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Forage Radish Cover Crop Suppresses Winter Annual Weeds in Fall and Before Corn Planting

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ABSTRACT

Forage radish (*Raphanus sativus* L. var. *longipinnatus*) is a new winter cover crop in the Mid-Atlantic region. The objective of this project was to characterize the repeatability, amount, and duration of weed suppression during and after a fall-planted forage radish cover crop and to quantify the subsequent effect on no-till seeded corn (*Zea mays* L.). Forage radish cover crops were grown in 10 site-years in the coastal plain of Maryland and followed by a corn crop in seven site-years. Forage radish was compared to rye (*Secale cereale* L.) and no cover crop treatments. Early and typical corn planting dates along with contrasting herbicide management strategies were compared over four site-years. Forage radish produced 3.9 to 6.6 Mg ha^{-1} of shoot dry matter and 1.3 to 3.2 Mg ha^{-1} of fleshy root dry matter when planted before 1 September. Forage radish did not reduce population or grain yield in subsequent corn crops. Forage radish provided complete suppression of winter annual weeds in fall and early spring but the suppression did not persist into the subsequent cropping season. When forage radish cover crops were used in place of preplant burndown herbicide treatments to control weeds in early planted corn, some weeds were present at the time of corn emergence but corn yields were not reduced as long as emerged weeds were controlled with a postemergence herbicide. Strategies to use the weed suppression of forage radish cover crops should focus on fall weed suppression and the early spring preplant window of weed control.

Forage radish is a new winter annual cover crop in the Mid-Atlantic region. Early work with forage radish as a cover crop in this region included observations that it could provide dramatic fall and spring weed suppression (Weil and Kremen, 2007). However, questions remain about the repeatability, amount, and duration of this suppression as well as the diversity of weed species affected. Answering these questions could lead to the development of integrated weed management strategies that reduce the use of herbicides while providing other soil and environmental benefits.

Radish cover crops are members of the *Brassicaceae* family and behave differently than cover crops currently grown in the Mid-Atlantic region, such as rye (*Secale cereale* L.), oat (*Avena sativa* L.), winter wheat (*Triticum aestivum* L.), crimson clover (*Trifolium incarnatum* L.), and hairy vetch (*Vicia villosa* Roth) (Holderbaum et al., 1990; Maryland Department of Agriculture, 2009; Weil and Kremen, 2007). Current cover crop species are winter annuals that grow more slowly in the fall and produce most of their biomass in the spring. They must be terminated in the spring before subsequent crop planting and develop higher C/N ratios when left to grow longer in the spring. Thus they require timely management to reduce the potential for delayed planting and immobilization of N needed by the subsequent crop.

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Unlike the above-mentioned cover crops, forage radish emerges quickly and grows rapidly in the fall (Weil et al., 2009). This may help inhibit undesirable winter annual weed growth. It also has a large white fleshy tap root that may protrude aboveground as much as 10 to 15 cm. Forage radish is sensitive to frost and typically winter-kills with prolonged exposure to temperatures below −4°C (Weil et al., 2009). Forage radish roots and shoots have a low C/N ratio. Its residues decompose rapidly during the freeze–thaw cycles that characterize winters in the Mid-Atlantic region and leave little residue on the soil surface the following spring. As a result, a unique low residue and weed-free seed bed is created for planting in the early spring following forage radish cover crops. These characteristics could make forage radish cover crops useful for farmers who are interested in the benefits of fall cover crops but want to avoid excessive spring crop residues or for organic farmers who wish to reduce preplant tillage without the use of prohibited herbicides.

Few studies have described weed suppression by radish cover crops. In the Netherlands, fodder radish (*Raphanus sativus* L. cultivar Brutus) suppressed the growth of weeds while it grew in the fall (Kruidhof et al., 2008). Oilseed radish (*Raphanus sativus* L. var. *oleiformis*) suppressed the fall growth of volunteer winter wheat in Ontario, Canada (Swanton et al., 1996). Oilseed radish also suppressed weeds in vegetable crop rotations in western New York (Stivers-Young, 1998) and in the Great Lakes Region of Michigan (Wang et al., 2008). Weed management using cover crops in the *Brassicaceae* family was reviewed by Haramoto and Gallandt (2004), but their review did not address radish cover crops.

Abbreviations: BARC-NF, USDA Beltsville Agricultural Research Center North Farm; BARC-SF, USDA Beltsville Agricultural Research Center South Farm; CMREC, University of Maryland Central Maryland Research and Education Center; WREC, University of Maryland Wye Research and Education Center.

The objectives of this study were to: (i) evaluate the reliability of weed suppression by forage radish cover crops, (ii) quantify the amount and duration of weed suppression by forage radish cover crops, (iii) characterize the weed species affected by forage radish cover crops, (iv) determine the impact of forage radish cover crops on subsequent corn yield, and (v) evaluate the optimum corn seeding dates and herbicide treatments to best use the weed suppression provided by forage radish cover crops.

MATERIALS AND METHODS

Site Description and Experimental Design

Experiments were conducted over a 4-yr period at four locations within the coastal plain of Maryland for a total of 10 site-years. The locations were: USDA Beltsville Agricultural Research Center North Farm (BARC-NF) (39°01'51" N, 76°55'58" W; 40 m elevation), the USDA Beltsville Agricultural Research Center South Farm (BARC-SF) (39°00'56" N, 76°56'29" W; 30 m elevation), the University of Maryland Central Maryland Research and Education Center (CMREC) (39°00'41" N, 76°49'55" W; 40 m elevation), and the University of Maryland Wye Research and Education Center (WREC) (38°54'52" N, 76°08'13" W; 3 m elevation). Soil at BARC-NF were Matawan (fine-loamy, siliceous, semiactive, mesic Aquic Hapludults)– Hammonton (coarse-loamy, siliceous, semiactive, mesic Aquic Hapludults) loamy sand in Field A, B (block 1 and 2), and C (block 1 and 2) and Ingleside (coarse-loamy, siliceous, semiactive, mesic Typic Hapludults)–Hammonton loamy sand in Field B (block 3 and 4) and Field C (block 3 and 4). At BARC-SF, soils were Codorus (fine-loamy, mixed, active, mesic Fluvaquentic Dystrudepts) silt loam in Field D, E, F, and G. The soils at CMREC were Cedartown (siliceous, mesic Psammentic Hapludults)–Galestown (siliceous, mesic Psammentic Hapludults)–Matawan (fine-loamy, siliceous, semiactive, mesic Aquic Hapludults) loamy sand in Field H and Ingleside–Hammonton loamy sand in Field I. At WREC, the soil was a Nassawango (fine-silty, mixed, semiactive, mesic Typic Hapludults) silt loam in Field J. Organic matter of all soils in the study ranged from 1.3 to 2.0%. All fields had a management history of conventional tillage with the exception of Field H and I at CMREC that had been no-till for at least the previous 6 yr. Crop rotations at BARC-SF, BARC-NF, and WREC included corn, soybean [*Glycine max* (L.) Merr.], winter wheat, and vegetable crops, while CMREC was corn, winter wheat, and soybean.

The fall weed communities common to all locations were common chickweed (*Stellaria media* L. Vill*)*, henbit (*Lamium amplexicaule* L.), and speedwell (*Veronica officinalis L*.). Common spring weed communities included common chickweed, henbit, speedwell, shepherd's purse (*Capsella bursa-pastoris* L. Medik), and storksbill (*Erodium cicutarium* L.). Common lambsquarters (*Chenopodium album* L.) was the dominant fall and spring weed in Field E, F, and G at BARC-SF. Horseweed (*Conyza canadensis* L. Cronq) was an important spring weed in Field A at BARC-NF.

Randomized complete block experiments with four replicates were established at BARC-NF in 2005, BARC-SF in 2005 and 2007, CMREC in 2006 and 2007, and WREC in 2007 to evaluate weed suppression following fall plantings of forage radish compared to rye (cultivar Wheeler) or a no-cover crop control. The effects of these cover crop treatments on subsequent corn crops (Pioneer 38B84, glyphosate tolerant) were quantified in all years except 2005. Plot size was 3 by 9 m for both sites in 2005 and 6 by 9 m for all other site-years. Forage radish and rye seeding rates were 14 and 135 kg ha^{-1}, respectively. Corn was no-till seeded into cover crop residues at a rate of 74,000 seeds ha^{-1} with 76 cm row spacing in all experiments.

A second set of more detailed studies were established at BARC-NF and BARC-SF in 2006 and 2007 to study the interaction of corn seeding date and herbicide management strategies with weed suppression following forage radish winter cover crops. At BARC-SF, three treatments were contrasted: forage radish, rye, and no cover crop treatments. Due to space restrictions, forage radish and no cover crop were the only treatments at BARC-NF. Corn was planted on two dates: early and typical. The target for the early corn planting date was in early to mid-April once soil temperature reached 10°C and soil was sufficiently dry for planting to occur. The target for the typical corn planting date was approximately 2 wk after the first planting date in late April or early May, which approximated the average planting date for farmers in the area of each experiment. A third treatment factor was plus or minus application of a postemergence herbicide. The experimental design of this study within each site year was a split-split plot with four randomized complete block replicates. Corn planting date was the main plot (12 by 12 m), cover crop treatment was the subplot (6 by 12 m), and herbicide treatment was the sub-subplot (3 by 12 m).

Field Management

BARC-NF and BARC-SF

Based on soil tests, 50 kg ha^{-1} N, 44 kg ha^{-1} P, and 84 kg ha^{-1} K were applied to Field A and 45 kg ha^{-1} N, 40 kg ha^{-1} P, 75 kg ha^{-1} K were applied to Field D before cover crop planting in August 2005. In August of 2006, 62 kg ha^{-1} N, 39 kg ha^{-1} P, and 101 kg ha^{-1} K were applied to Field B and Field E. In the fall of 2007, 94 kg ha^{-1} K was applied to Field C, Field F, and Field G. Preplant incorporated fertilizer applications were applied to both cover crop and no cover crop treatments based on the P and K needs of the subsequent corn crop and to ensure adequate cover crop nutrition and growth. The amount of N applied with the P and K fertilizer was based on the types of compound fertilizers on hand with the aim to provide sufficient N in the surface soil to ensure vigorous cover crop growth on these low organic matter soils with little N in the top 15 cm and no history of manure application (data not shown). Agricultural limestone was applied to Field B and Field C in August before cover crop planting at rates of 3.1 and 1.0 Mg ha^{-1} $CaC0_3$ equivalence, respectively. An offset disk was used to prepare seedbeds for planting and to incorporate fertilizer and lime before cover crop planting.

Cover crops were seeded using a conventional grain drill with disk openers and 19 cm row spacing in late August. Planting dates and other field operations are listed in Table 1. Irrigation was used to stimulate cover crop germination when conditions were unusually dry. Forage radish cover crops grew vegetatively in the fall until they were damaged by frost in mid- to late November and gradually winter-killed as temperatures became progressively colder in January and February. Rye cover crops grew vegetatively in the fall, overwintered, and grew substantially in early spring. Rye was terminated at or before booting (Zadocks stage 43 and approximately 40 cm tall) along with weeds growing in no cover crop treatments with glyphosate (N-(phosphonomethyl)glycine) (1.12 kg ha^{-1} a.i.) before corn planting (Table 1). In the spring of 2008, rye termination for the second planting date was delayed until the day after planting due to unseasonably wet conditions (Table 1). Forage radish treatments were not sprayed with herbicide before planting corn as it had already winter-killed and facilitated observations of the timing of spring weed emergence.

At the time of corn planting, granulated fertilizer was banded 5 cm to the side of the seed furrow. The rates of banded fertilizer were 22 kg ha^{-1} N, 20 kg ha^{-1} P and 37 kg ha^{-1} K in 2006 for Field B and Field E, and 23 kg ha^{-1} N in 2007 for Field C and Field F. For all site-years, N was side dressed when the corn was in the V6 stage (Ritchie et al., 1996) at 111 kg ha^{-1} N as UAN solution dribbled on the soil surface between rows. For treatments receiving herbicide, weeds were sprayed when corn was in the V1-V3 stage with glyphosate (3.4 kg ha^{-1} a.i.), atrazine (6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine) (1.74 kg ha^{-1} a.i.), and metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide) (1.34 kg ha^{-1} a.i.) (Table 1). This mixture controlled existing vegetation and provided residual control of later emerging weeds.

CMREC

In 2006, a soybean crop was mowed at a vegetative stage in early August and left to decompose to provide an organic N source before cover crop planting at CMREC Field H. This soybean dry matter contained 56 kg ha^{-1} of total N and had a C/N ratio of 13. In 2007, cover crops were planted after barley. Following soil tests, 7 kg ha^{-1} N was applied as UAN along with 2 kg ha^{-1} B to both cover crop and no cover crop treatments before cover crop planting. Cover crops were planted using a no-till drill with disk openers and 16 cm row spacing (Table 1). Forage radish cover crops were damaged by frost in mid- to late November and most plants winter-killed with progressively cold temperatures in January and February. Rye overwintered and was terminated, along with weeds growing in no cover crop treatments, before corn planting using paraquat (1,1'-dimethyl-4,4'-bipyridinium ion) (0.84 kg ha^{-1} a.i.) tank mixed with 2,4-D [(2,4-dichlorophenoxy) acetic acid] (0.40 kg ha^{-1} a.i.), (Table 1).

At the time of planting, fertilizer was placed in furrow at a rate of 5 kg ha^{-1} N, 5 kg ha^{-1} P, 4 kg ha^{-1} K and banded 5 cm below and 5 cm to the side of the seed furrow at a rate of 27 kg ha^{-1} N and 6 kg ha^{-1} S. The corn was side dressed when in the V6 stage at a rate of 127 kg N ha^{-1} as UAN solution knifed into the soil at a depth of 10 cm between every second corn row (Table 1). Weeds in the corn were controlled on 9 May 2007 and 15 May 2008 at the V1 to V3 stage by spraying glyphosate (1.12 kg ha^{-1} a.i.), metolachlor (1.47 kg ha^{-1} a.i.), atrazine (1.47 kg ha^{-1} a.i.), and mesotrione (2-(4-mesyl-2-nitrobenzoyl)-3-hydroxycylohex-2-enone) (0.19 kg ha^{-1} a.i.) (Table 1).

WREC

The field was in weedy fallow for 1 yr before the experiment. Cover crops were planted on 31 August using a no-till drill with disk openers and 16 cm row spacing (Table 1). Forage radish cover crops were damaged by frost in mid- to late November and most plants winter-killed with progressively cold temperatures in January. However at this location, approximately 20% of forage radish plants overwintered due to mild winter

Table 1. Field operations and sampling dates for cover crop experiment sites at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF), the Central Maryland Research and Education Center (CMREC), and the Wye Research and Education Center (WREC).

Location	BARC-NF					BARC-SF						CMREC		WREC
Field	A	B		C		D	E		F		G	H	I	J
Year	2005–06	2006–07		2007–08		2006–07	2006–07		2007–08		2007–08	2006–07	2007–08	2007–08
Corn seeding date	–	Early	Typical	Early	Typical	–	Early	Typical	Early	Typical	–	–	–	–
Cover crop planting	25 Aug.	31 Aug.	31 Aug.	28 Aug.	28 Aug.	25 Aug.	31 Aug.	31 Aug.	28 Aug.	28 Aug.	28 Aug.	12 Sept.	28 Aug.	31 Aug.
Fall cover rating†	4 Nov.	20 Nov.	20 Nov.	1 Dec.	1 Dec.	4 Nov.	20 Nov.	20 Nov.	10 Dec.	10 Dec.	10 Dec.	–	1 Dec	30 Nov.
Cover crop dry matter harvest	19 Nov.	6 Nov.	6 Nov.	17 Nov.	17 Nov.	19 Nov.	6 Nov.	6 Nov.	21 Nov.	21 Nov.	21 Nov.	8 Nov.	16 Nov.	16 Nov.
Early spring cover rating†	18 Mar.	20 Mar.	20 Mar.	20 Mar.	20 Mar.	–	28 Mar.	28 Mar.	21 Mar.	21 Mar.	21 Mar.	21 Mar.	20 Mar.	24 Mar.
Preplant herbicide application to terminate rye and weeds in no cover	–	30 Mar.	30 Mar.	11 Apr.	16 May	–	30 Mar.	30 Mar.	11 Apr.	16 May	11 Apr.	10 Apr.	10 Apr.	9 Apr.
April/May spring cover rating†	26 Apr.	30 Apr.	30 Apr.	25 Apr.	25 Apr.	–	25 Apr.	25 Apr.	2 May	2 May	2 May	4 May	21 Apr.	18 Apr.
Plant corn	–	24 Apr.	10 May	11 Apr.	15 May	–	24 Apr.	10 May	11 Apr.	15 May	11 Apr.	23 Apr.	16 Apr.	16 Apr.
Ground cover rating after corn planting†	–	30 Apr.	–	25 Apr.	30 May	–	25 Apr.	–	2 May	30 May	–	–	–	–
Post-plant herbicide application in corn	–	23 May	23 May	24 May	10 June	–	23 May	23 May	24 May	10 June	24 May	9 May	15 May	27 May
V4 cover rating†	–	27 May	7 June	30 May	12 June	–	28 May	7 June	30 May	30 May	–	–	–	–
Corn sidedress fertilizer	–	7 June	17 June	11 June	24 June	–	7 June	17 June	11 June	24 June	11 June	6 June	9 June	18 June
V8 cover rating†	–	14 June	28 June	19 June	1 July	–	22 June	26 June	20 June	12 June	–	–	–	–
Harvest corn grain	–	12 Sept.	12 Sept.	10 Sept.	22 Sept.	–	12 Sept.	12 Sept.	22 Sept.	23 Sept.	16 Sept.	17 Sept.	9 Sept.	–

† Visual rating of percent ground cover for weeds, cover crop leaf canopy, or cover crop residues.

temperatures and the field's close proximity to the Chesapeake Bay, which further moderated cold temperatures. Rye cover crops, weeds growing in no cover crop treatments, and forage radish cover crops that had overwintered were killed before corn planting with glyphosate (1.69 kg a.i. ha^{-1}) (Table 1).

Nitrogen was sprayed on the soil surface immediately after corn planting at 22 kg ha^{-1} N. Nitrogen was side dressed at 134 kg ha^{-1} N as UAN solution dribbled on the soil surface between rows when the corn was in the V6 stage. Weeds in the corn were controlled on 27 May 2008 by spraying glyphosate (1.69 kg a.i. ha^{-1}), metolachlor (0.98 kg a.i. ha^{-1}), atrazine (0.98 kg a.i. ha^{-1}), and mesotrione (0.13 kg a.i. ha^{-1}) in all treatments (Table 1).

Field Sampling

Cover crop biomass samples were taken in November near the time of maximum fall dry matter accumulation but before the first frost that injured forage radish (Table 1). Two 0.25 m^2 quadrats were sampled from each plot. The fleshy forage radish tap root was pulled from the soil and separated from the shoot foliage in the field. Samples were dried at 60°C before weighing.

Visual ratings of weed cover were chosen as the measure of weed abundance as this method is most predictive of weed influence on crop productivity in relatively large plots with a heterogeneous distribution of weeds (Teasdale and Cavigelli, 2010; Teasdale et al., 2004). To avoid edge effects, percent ground cover ratings were performed on weeds within the central area of the plots while weeds within the outer 30 cm edge of each plot were omitted from the rating. When corn was present, ratings were performed on weeds within the center two corn rows of each four row plot. Visual ratings of percent ground cover were made in November to evaluate fall cover crop growth and weed suppression. Percent ground cover ratings were also made in March before early corn planting date treatments and in late April or early May near the time of typical corn planting date treatments (Table 1). In the corn planting date experiment, percent ground cover ratings were taken to evaluate weed suppression at the following corn stages: emergence, V4, and V8. Specific dates for each of these ratings are listed in Table 1.

Corn grain yield and dry matter were determined by hand harvesting in September at physiological maturity (determined by black layer development in corn kernels) (Table 1). Fresh weights and plant population of corn plants were measured for two 3 m lengths from the center two rows of each plot. Three representative corn plants were selected at random from each 3 m harvest row (six plants per plot), fresh weights measured, and dried to determine moisture content of the plants with their ears. After drying, the ears of these six plants were shelled to quantify corn grain yield. The ratio of grain to the fresh weight of the six plants was used to calculate grain yield for each plot using the fresh weight of plants harvested from the two 3 m rows. Moisture content of the shelled grain was measured (MT3 Grain Moisture Meter, Farmex, CO) to report yields at 15.5% moisture.

$$Y_{15.5} = Y_{\mathrm{h}} \times [(100 - M_{\mathrm{h}})/(100 - 15.5)] \qquad [1]$$

where $Y_{15.5}$ is corn yield at 15.5% moisture, Y_{h} is the weight of the grain at the harvest moisture content, and M_{h} is the percentage grain moisture content at harvest.

Statistical Analysis

Two statistical analyses were conducted. The first compared cover crop productivity and its impact on weeds and corn production over 10 site-years. For experiments with multiple corn planting dates, only data for the earliest planting date was included in this first analysis. The second analysis was limited to four site-years and the impact of corn planting date and herbicide management on weeds and corn production.

Analysis 1

Cover crop dry matter means and standard deviations were calculated using the means procedure of SAS version 9.1 (SAS Institute, Cary, NC). Percent ground cover ratings for cover crops, cover crop residues, and weed cover were analyzed by ANOVA using the mixed model procedure of SAS version 9.1. Due to unbalanced treatments, treatment means were compared only within sites. Cover crop treatment was considered a fixed effect and block was considered a random effect in the statistical model. Corn yields and plant populations were analyzed by ANOVA using the mixed model procedure of SAS. Cover crop treatment was considered a fixed effect and block was considered a random effect in the statistical model.

Analysis 2

For the management experiment, a pooled ANOVA was conducted for the forage radish and no cover crop treatments common to all site-years using the mixed model procedure of SAS. This analysis took into account the split-split plot design of the experiment. In the statistical models cover crop and corn planting date were considered fixed factors while blocks within site-years and site-year were considered random. When statistical differences between treatments were identified by ANOVA, means comparisons were made using Fisher's Least Significant Difference test. Following the initial analysis an ANOVA was conducted to evaluate the interaction between corn planting date and site for corn grain yields.

RESULTS AND DISCUSSION

Analysis 1: Characterizing Forage Radish Weed Suppression and Impact on a Subsequent Corn Crop

Cover Crop Dry Matter Production

When planted before 1 September, forage radish emerged within 2 to 4 d of planting, grew rapidly, and formed a closed canopy within 4 to 6 wk. When planted before 1 September, forage radish dry matter production ranged from 3.9 to more than 6.6 Mg ha^{-1} for shoots and 1.3 to more than 3.2 Mg ha^{-1} for the fleshy tap roots (Table 2). Total fall dry matter production for both shoots and the fleshy tap roots ranged from 5.6 to more than 8.4 Mg ha^{-1}. Forage radish dry matter production was lowest for CMREC Field H, which had the latest planting date (12 September). Additional studies in the Mid-Atlantic region with forage radish have shown that planting dates delayed later than 1 September reduce forage radish fall canopy cover and dry matter production (Lawley, 2010).

In the fall, the amount of forage radish shoot dry matter was similar to or greater than that of rye in five site-years when both cover crops were planted in late August (Table 2). However, rye is typically planted during October in the Mid-Atlantic as it is a

Table 2. Cover crop and weed dry matter for experiments at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF), the Central Maryland Research and Education Center (CMREC), and the Wye Research and Education Center (WREC). Means followed by standard deviation in parentheses.

Location	Field	Year	Planting date	Harvest date (fall/spring)	Forage radish			Rye shoots		Weeds in no cover
					Fall shoot	Fall root	Fall total	Fall	Spring	Fall
					Mg ha^{-1}					
BARC-NF	A	2005–06	25 Aug.	19 Nov.	4.5(0.8)	2.3(0.7)	6.8(1.2)	–	–	1.4(0.7)
	B	2006–07	31 Aug.	6 Nov.	4.3(0.9)	1.3(0.4)	5.6(1.2)	–	–	2.3(0.7)
	C	2007–08	28 Aug.	17 Nov.	4.1(0.9)	1.5(0.5)	5.6(1.4)	–	–	2.1(1.4)
BARC-SF	D	2005–06	25 Aug.	19 Nov.	3.9(0.5)	2.8(0.9)	6.7(1.3)	–	–	2.5(0.9)
	E	2006–07	31 Aug.	6 Nov.	6.7(1.1)	1.8(0.5)	8.5(1.5)	4.7 (1.6)	–	3.4(1.0)
	F	2007–08	28 Aug.	21 Nov./29 Mar.	4.1(0.9)	2.4(1.0)	6.5(1.8)	4.1(0.9)	4.5 (0.9)	2.7(1.4)
	G	2007–08	28 Aug.	21 Nov./29 Mar.	5.2 (1.1)	2.2(1.1)	7.4(1.5)	5.4(0.9)	4.2(1.6)	3.6(2.6)
CMREC	H	2006–07	12 Sept.	8 Nov.	2.2(0.6)	0.8(0.2)	3.0(0.8)	1.5(0.5)	-†	0.1(0.1)
	I	2007–08	28 Aug.	16 Nov./29 Mar.	4.9(0.5)	3.2(0.5)	8.1(0.8)	4.5(0.6)	3.3(1.0)	2.2(0.3)
WREC	J	2007–08	31 Aug.	16 Nov./24 Mar.	5.4(0.8)	2.7(0.5)	8.1(1.0)	4.3(0.2)	2.8(0.7)	2.9(0.7)

† Rye shoot biomass was not collected in spring for CMREC Field H.

time better suited for typical corn and soybean rotations. Thus, fall dry matter production of rye in this study is much greater than the typical rye dry matter production for the region. However, it represents the potential fall productivity of rye when planted early. Weed pressure in plots without a cover crop varied widely among the 10 fields included in the study. Weed dry matter measured in November ranged from 0.1 to more than 3.6 Mg ha^{-1} (Table 2).

Corn Performance

There was no difference in corn yields among cover crop treatments in six out of seven site-years (Table 3). Corn yield was significantly lower following forage radish at CMREC Field H in 2007. However, this was also the site-year that had the lowest forage radish cover crop dry matter production due to late planting (Tables 1 and 2). Among all site years, corn yields were lowest at CMREC and BARC-NF in 2007 due to drought conditions. Corn growing at these two locations in loamy sand soils showed greater signs of drought stress than the corn at BARC-SF growing in alluvial silt loam soils in 2007.

There was no difference in corn population between forage radish and no cover crop treatments in six out of seven site-years. Corn population was 24% higher following forage radish compared with no cover at Field C in 2008. Corn plant populations were significantly lower following rye than both forage radish and no cover crop treatments in two out of five site-years (Table 3). Reduced populations following rye cover crops were attributed to residue interference with seed placement and emergence. Wet conditions before corn planting in 2008 for Fields F and G delayed rye termination until corn planting (Table 1). This resulted in a dense mass of rye residue that interfered with planting and reduced corn population by 13 and 25% for Fields F and G, respectively, when compared to the no cover crop treatment (Table 3). These results highlight the tradeoffs between cover crops that winterkill vs. those that overwinter, as well as the influence of weather conditions on cover crops performance and management. Cover crops, such as forage radish, that do not overwinter, will provide less residue, simplify spring seeding, provide warmer soils, and may allow for more timely planting of subsequent crops than an overwintering cover crop such as rye.

Weed Suppression

Forage radish provided complete suppression of weeds during the fall cover crop growing season (Table 4). When planted by 1 September, rye cover crops also had very low weed cover in the late fall. Average percent weed cover in no cover crop control plots ranged from 8 to 96% ground cover over nine site-years. Winter annual weeds that grew in no cover treatments but were suppressed by forage radish and rye cover crops included chickweed, henbit, speedwell, shepherd's purse, and storksbill.

Stivers-Young (1998) observed that an oilseed radish cover crop suppressed common chickweed and henbit in the fall and early spring. Kruidhof et al. (2008) found radish cover crops reduced fall weed dry matter by more than 70% and attributed these reductions to the rapid growth and canopy development of the radish. They observed that early season light interception by cover crops was important for suppression of tall growing weeds like common

Table 3. Yields and plant populations for early seeded corn following three cover crop treatments at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF), the Central Maryland Research and Education Center (CMREC). Means within site-year followed by the same letter are not statistically different (α = 0.05).

Location	Field	Year	Corn planting date	Corn grain yield			Corn population		
				Forage radish	No cover	Rye	Forage radish	No cover	Rye
				Mg ha^{-1}			1000 plants ha^{-1}		
BARC-NF	B	2007	24 Apr.	5.5a	6.4a	–	75a	76a	–
	C	2008	11 Apr.	8.3a	6.7a	–	72a	54b	–
BARC-SF	E	2007	24 Apr.	9.8a	9.7a	11.3a	76a	72a	73a
	F	2008	11 Apr.	13.1a	12.9a	11.9a	72a	67a	58b
	G	2008	11 Apr.	12.2a	13.0a	10.8a	69a	74a	59b
CMREC	H	2007	23 Apr.	3.7b	5.1a	4.8a	66a	71a	68a
	I	2008	16 Apr.	10. 3a	11.7a	11. 5a	76a	80a	78a

Table 4. Visual rating of percent weed ground cover in late fall, late March, and the typical time of spring corn planting for experimental sites at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF), the Central Maryland Research and Education Center (CMREC), and the Wye Research and Education Center (WREC). Means within a field and rating period followed by the same letters are not statistically different (α = 0.05).

		Percentage of ground covered by weeds		
Location	Field	Forage radish	No cover crop	Rye
			%	
		Late fall		
BARC-NF	A	0b	40a	–
	B	0b	83a	–
	C	0b	24a	–
BARC-SF	D	0c	78a	–
	E	0c	94a	10b
	F	0b	96a	0b
	G	0b	94a	0b
CMREC	I	0b	8a	0b
WREC	J	0b	47a	0b
		Late March		
BARC-NF	A	0b	84a	–
	B	1b	39a	–
	C	0b	71a	–
BARC-SF	E	0c	71a	7b
	F	3b	99a	1b
	G	1b	97a	0b
CMREC	H	22b	53a	4c
	I	0b	22a	0b
WREC	J	2b	55a	0b
		Typical time of corn planting		
BARC-NF	A	37c	95a	–
	B	19	-†	–
	C	11b	87a	–
BARC-SF	E	3	-†	-†
	F	37ab	75a	0b
	G	11	-†	-†
CMREC	H	63	-†	-†
	I	4	-†	-†

† Weeds sprayed with herbicides before typical time of corn planting.

lambsquarters but that late light interception was more important for suppression of short statured weeds like common chickweed.

Weeds remained absent in forage radish plots throughout the winter and into March. Average percent weed cover ranged from 0 to 3% in late March for eight out of nine site-years (Table 4). The highest percent weed cover in March occurred at Field H where forage radish was planted late (12 September) and therefore produced far less fall growth than in other site-years. Previous research has also shown that progressively later plantings of forage radish become progressively less competitive with weeds and result in greater fall and spring weed cover than early plantings (Lawley 2010). The first weeds to emerge in spring for forage radish cover crop treatments were winter annual weeds, such as common chickweed and henbit. These were the same species that grew during the fall and winter months in no cover crop treatments.

With the exception of Field H (where cover crop planting was late), weed suppression in March was similar for forage radish and rye cover crop treatments for all site-years, despite the fact that rye cover crops were alive and growing in March while forage radish cover crops had winter-killed. Forage radish treatments had only 20 to 50% ground cover, all provided by its residues, while rye had 40 to 75% ground cover from its living canopy plus 20 to 45% from residues.

At the time of typical corn planting, percent weed cover in forage radish cover crops ranged from 3 to 63% over eight site years (Table 4). Three site-years within the corn planting date experiment (Field A, C, and F) provided the opportunity to compare forage radish and no cover crop treatments that had not been sprayed with herbicides before the typical time for corn planting in late April or early May (Table 4). Comparisons of these two treatments revealed that forage radish continued to have lower weed cover than no cover crop treatments. However, with percent weed cover ratings of up to 63%, it was evident that forage radish cover crops did not provide residual weed suppression that persisted into the growing season of subsequent warm season crops.

Winter annual species (common chickweed, henbit, and speedwell) continued to dominate forage radish treatments at the time of typical corn planning in late April and early May. Horseweed was suppressed in forage radish treatments at BARC-NF in Field A during the spring of 2006. In late April of 2006, mean ground cover by horseweed of 4% in no cover crop treatments were reduced to 0% in forage radish treatments. This observation suggests that cover crops may be a tool to manage herbicide resistant horseweed. Further observations of horseweed suppression were limited by the absence or low abundance of horseweed in fields at other locations and further study is needed. Common lambsquarters emergence in Field E, F, and G was stimulated in the spring following forage radish cover crops compared to no cover crop treatments (data not shown). This contrasted with the fall suppression of common lambsquarters in forage radish cover crop relative to no cover crop treatments. The stimulation of lambsquarters emergence in early spring following forage radish cover crops has been documented in other controlled field experiments where lambsquarters was introduced following forage radish and no cover crop treatments (Lawley, 2010).

These trends in the timing and duration of forage radish weed suppression were similar to those reported by other researchers with similar radish cover crops. Fodder radish did not suppress spring weed growth in the Netherlands (Kruidhof et al., 2008). Oilseed radish suppressed weeds in vegetable crop rotations until late March or early April in western New York, (Stivers-Young, 1998) and until early July in central Michigan (Wang et al., 2008).

Analysis 2: Management to Use Forage Radish Weed Suppression

The second study focused on the interaction of cover crop, corn seeding date, and herbicide management strategies to determine whether early corn planting could take advantage of the early spring window of forage radish weed suppression. An initial analysis to evaluate the ability of forage radish cover crops to provide weed suppression in subsequent crops was conducted focusing on forage radish cover crop treatments with no herbicide application in the following corn crop. Overall, percent weed cover was lower for earlier corn planting dates at the time of crop emergence as well as at the V4 and V8 stages (Table 5). Average weed cover ratings for individual site-years during corn emergence ranged from

2 to 24% for early planted corn and from 57 to 88% for typical corn planting dates. This data agrees with our conclusion that forage radish cover crops did not provide weed suppression that persisted into the following growing season. If left uncontrolled, these weeds resulted in an average corn yield reduction of more than 25 and 60% for early and typical corn planting dates respectively, when compared to treatments where weeds were controlled with a postemergence herbicide treatment. In light of this large yield reduction from treatments without postemergence herbicide, the remainder of this paper will deal only with treatments including a postemergence herbicide.

The hypothesis that forage radish cover crops could be used in place of a preplant burndown herbicide before planting corn was tested by comparing forage radish treatments that received postemergence weed control but no preplant weed control, to no cover crop treatments that received both preplant and in-crop weed control. When averaged over all four site-years, weed cover ratings at the time of corn emergence were higher in forage radish treatments that received no preplant herbicide than in the no cover treatments that did receive preplant herbicide (Table 6). Differences between these forage radish and no cover crop treatments were much greater at the typical than early corn planting date.

These trends in weed cover at the time of corn emergence did not match trends in corn yield or corn plant population (Table 6). Averaged over four site-years, there were no significant differences in corn yield between forage radish treatments that received in-crop weed control but no preplant weed control compared to no cover crop treatments that received both preplant and in-crop weed control for both early and typical corn planting dates (Table 6). Corn biomass was lower in forage radish than in no cover crop treatments for the typical planting date treatment and this result may have been due to increased weed pressure at the time of corn emergence. Corn population was higher in the forage radish cover crop treatment relative to no cover crop treatment for the early planting date, but these treatments had similar corn populations at the typical planting date (Table 6). Weed cover ratings suggest that only the early planting of corn would be favorable when eliminating a burndown herbicide application following forage radish cover crops to reduce early season weed competition in corn. However, corn yields suggest that forage radish cover crops could be used in place of a preplant burndown herbicide at either early or typical planting dates without sacrificing yield.

In this study, weeds were controlled by the postemergence herbicide application in forage radish plots within 2 to 6 wk of planting (Table 1). Zimdahl (2004) summarizes several studies that define a period of 3 to 6 wk after planting during which corn can tolerate early season weed competition without yield loss as long as adequate weed control is maintained throughout the remainder of the growing season. The timing of weed control in this study was within this range of tolerance to weed competition and residual herbicides provided good weed suppression for the remainder of the corn growing season. Thus, despite inadequate weed control at the typical corn planting date in the forage radish treatment, weed competition did not persist long enough to negatively impact corn yield.

Weeds are not the only yield limiting factor to consider when identifying optimal corn planting dates. Dean and Weil (2009) and Kremen (2006) found that nitrate was released by forage radish cover crop residues early in the spring. This nitrate was observed to increase shoot dry matter production in V6 corn and 2-wk-old soybean crops (Kremen, 2006) but nitrate was also found to leach below the rooting zone of young plants in sandy coarse textured soils following early season rains (Dean and Weil, 2009; Kremen, 2006). In this study, early corn planting at BARC-NF (with loamy sand textured soils), reduced grain yields by 32% compared to corn planted on the typical date when averaged over 2 yr (Table 7). This trend was reversed at of BARC-SF (with silt loam textured soils) where early

Table 5. Visual rating of percent weed cover following forage radish cover crops without herbicide treatments for early and typical corn planting dates at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF). Weed cover was assessed after corn emergence and when corn was in the V4 and V8 stage. Means were pooled over four site-years with the exception of the typical corn planting date at emergence that was pooled over two site-years. Means followed by the same letter within corn stage are not statistically different (α = 0.05).

Corn stage	Percentage of ground covered by weeds	
	Early corn planting	Typical corn planting
	%	
Emergence	8a	72b†
V4	46a	68b
V8	36a	61b

† Percentage ground covered by weeds for forage radish and no cover crop treatments at time of typical corn planting are described by location in Table 4.

Table 6. Visual rating of percent weed cover at time of corn emergence, corn grain yield, total aboveground corn dry matter, and corn population for early and typical corn planting dates following forage radish, and no cover crop treatments with in-crop weed control at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF). Means were pooled over four site-years. Means followed by the same letters are not statistically different (α = 0.05).

Corn planting date	Forage radish with no preplant burndown	No cover crop with preplant burndown
Percent of ground covered by weeds at corn emergence		
	%	
Early	10b	0c
Typical	73a	1c
Corn grain yield		
	Mg ha^{-1}	
Early	9.2b	9.0b
Typical	9.8a	10.9a
Total above ground corn dry matter		
	Mg ha^{-1}	
Early	15.5b	15.2b
Typical	15.9b	18.0a
Corn population		
	1000 plants ha^{-1}	
Early	74a	67b
Typical	71ab	73ab

Table 7. Effect of planting date on corn yield by site averaged over 2 yr at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF). Means followed by the same letters are not statistically different (α = 0.05).

Location	Soil texture	Corn grain yield	
		Early corn planting	Typical corn planting
		Mg ha^{-1}	
BARC-NF	loamy sand	6.7b	9.8a
BARC-SF	silt loam	11.5a	10.3b

seeded corn yields were 11% greater than corn planted on the typical planting date averaged over 2 yr. Opposing yield trends for early and typical corn planting dates at the two sites suggest that there may be trade-offs other than weed control efficacy to consider when making decisions about early planting.

CONCLUSIONS

Forage radish cover crops produced a large amount of dry matter in fall, similar in quantity to that produced by rye when both cover crops were planted in late August. Forage radish, when compared to rye or no cover crop treatments, did not reduce plant population or yield in following corn crops. Forage radish provided nearly complete weed suppression in the fall and early spring but this suppression did not persist into the corn growing season. Winter annual weeds, such as common chickweed and henbit, were suppressed by forage radish cover crops in the fall and early spring. All experiments were conducted with sufficient fertility to optimize forage radish growth in fall. Additional research is required to define fertility requirements that would ensure sufficient forage radish growth and leaf canopy development to achieve a high degree of weed suppression.

When a forage radish cover crop was planted in a timely manner, it could be used in place of a preplant burndown herbicide to provide relatively weed-free conditions for early planted corn. Corn yields were not reduced as long as emerged weeds (common chickweed, henbit, speedwell, and lambsquarters) at the time of or shortly after corn emergence were controlled with a postemergence herbicide. However, if forage radish planting is delayed and growth suboptimal, it can be expected that preplant tillage or burndown herbicides will be needed to control weeds sufficiently to avoid corn yield reduction. Thus, strategies to control weeds with a forage radish cover crop should focus on early cover crop planting to maximize fall weed suppression and planting crops as early in spring as possible to avoid emerging weeds as soils warm.

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