ABSTRACT

Title of Document: WEED SUPPRESSION BY FORAGE RADISH WINTER COVER CROPS.

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Forage radish (*Raphanus sativus* L. var. *longipinnatus*) is a new winter cover crop in the Mid-Atlantic region. This study had three objectives: 1) to characterize the repeatability, amount, and duration of weed suppression during and after a fall-planted forage radish cover crop 2) to quantify its subsequent effect on direct seeded corn, and 3) to identify the mechanisms of this weed suppression.

Forage radish cover crops were grown in ten site-years and followed by a corn crop in seven site-years in the coastal plain of Maryland. Forage radish was compared to rye (*Secale cereale* L.), oat (*Avena sativa* 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 did not reduce population or yield in subsequent corn crops. Forage radish provided complete suppression of winter annual weeds in the fall and early spring but the suppression did not persist into the following cropping season. When forage radish cover crops were used in place of pre-plant burn down 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 if emerged weeds were controlled with a postemergence herbicide.

Controlled environment bioassays involving cover crop amended soil, aqueous plant extracts, and aqueous soil extracts along with a field experiment involving planted weed seeds did not provide evidence of allelopathy. In a residue moving experiment, no difference in spring weed suppression was observed if forage radish residues were removed prior to killing frost in November or left in place to decompose in three of four site-years. These results were supported by planting date experiments where fall ground cover and spring weed suppression was greatest for earlier planting dates of forage radish cover crops. Thus, rapid and competitive fall growth, rather than allelopathy, is the most likely mechanism of weed suppression by forage radish winter cover crop. Strategies to utilize the weed suppression of forage radish cover crops should focus on fall weed suppression and the early spring pre-plant window of weed control.

WEED SUPPRESSION BY FORAGE RADISH WINTER COVER CROPS.

By

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Dedication

To my parents: Sheron and Michael Van Den Bosch. I am glad to be “old enough” to enjoy the pieces of you that I see in me. Your example and love gave me a foundation that enabled me to be inquisitive, make choices, take risks, set goals, work hard, and start building a life of my own.

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Table of Contents

Dedication ii
Acknowledgements iii
Table of Contents v
List of Tables viii
List of Figures xi
Chapter 1: Introduction 1
Background and problem definition 1
Justification for research 2
General research approach 3
General research objectives and hypothesis 4
References 6
Chapter 2: Literature review 7
Introduction 7
Using cover crops to control weeds 10
Weed suppression by Brassica cover crops 10
Weed suppression by forage radish and fall planted radish cover crops 11
Amount and duration of weed suppression following radish cover crops 12
Weed species suppressed by radish cover crops 13
Mechanisms of cover crop weed suppression 14
Competition 14
Allelopathy 15
Altered soil conditions 16
Challenges to identifying the mechanisms of cover crop weed suppression 17
Do cover crops provide selective weed suppression? 18
Mechanisms of Brassica cover crop weed suppression 19
Mechanisms of forage radish cover crop weed suppression 20
Impact of Brassica cover crops on following crops 21
Conclusions 22
References 23
Chapter 3: Forage radish winter cover crops suppress winter annual weeds in fall and prior to corn planting 30
Abstract 30
Introduction 31
Materials and methods 33
Site description and experimental design 33
Field management 34
Field sampling 38
Statistical analysis 39
Results and discussion 41
Cover crop dry matter production 41
Corn performance 41
Weed suppression 42
Corn management to utilize forage radish weed suppression 44

Conclusions ... 48
References ... 49
Chapter 4: The mechanism of forage radish weed suppression ... 66
Abstract ... 66
Introduction ... 67
Materials and methods ... 70
Site description and field management ... 70
Experiment 1: Aqueous plant and soil extracts ... 71
Plant sample harvest and preparation ... 71
Soil sample collection and preparation ... 71
Extract preparation and incubation ... 72
Experiment 2: Soil bioassay ... 73
Soil sampling and sample preparation ... 73
Incubation, germination, and biomass ... 73
Experiment 3: Planted weed seed emergence ... 74
Statistical analysis ... 75
Experiment 4: Residue moving ... 75
Statistical analysis ... 76
Experiment 5: Cover crop seeding date ... 77
Site management and field sampling ... 77
Soil moisture and temperature following forage radish cover crops ... 77
Results and discussion ... 78
Experiment 1: Aqueous plant and soil extracts ... 78
Plant tissue extracts ... 78
Soil extracts ... 79
Experiment 2: Soil bioassay ... 80
Seed germination and seedling biomass ... 80
Experiment 3: Weed seed bioassay ... 82
Experiment 4: Residue moving ... 84
Effect on soil conditions ... 86
Experiment 5: Cover crop planting date ... 86
Conclusions ... 88
References ... 90
Chapter 5: Conclusions ... 108
Objective 1: Characterization of weed suppression following forage radish winter cover crops ... 108
Objective 2: Impact of forage radish cover crops on subsequent corn crop performance ... 109
Objective 3: Mechanism of forage radish weed suppression ... 109
Recommendations ... 110
Appendix 1: Weather summary ... 112
Appendix 2: Field names and selected soil properties ... 113
Appendix 3: Observation of horseweed (*Conyza canadensis* L.) suppression following forage radish cover crops ... 114
Appendix 4: Impact of forage radish cover crop on spring soil conditions ... 115
Appendix 5: Natural weed seed bank study ... 116

Objectives 116
Hypothesis..... 116
Materials and methods 116
Site descriptions 116
Soil sampling 116
Tray preparation and management..... 117
Emergence counts 117
Statistical analysis..... 117
Results and discussion 118
Conclusions..... 120
Reference 120
Appendix 6: Sample SAS code..... 123

List of Tables

Table 3.1: Soil properties and field history 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). 50
Table 3.2: 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). 51
Table 3.3: 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. 52
Table 3.4: 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). 53
Table 3.5: Visual rating of percent weed cover in late fall for 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). Means within a field and rating category followed by the same letters are not statistically different (α=0.05). 54
Table 3.6: Dominant weed species present in the no cover crop treatments that were absent in forage radish and rye treatments for all site-years 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). 55
Table 3.7: Visual rating of percent weed cover in late March for 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). Means within site-year followed by the same letter are not statistically different (α=0.05). 56
Table 3.8: Visual rating of cover crop leaf canopy and residue ground cover in late March for 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). Means within site-year followed by the same letter are not statistically different (α=0.05). 57
Table 3.9: Visual rating of percent weed cover around the typical time of spring corn planting time for un-sprayed treatments in 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 within field and rating type followed by the same letter are not statistically different (α=0.05). 58
Table 3.10: 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 crop stage are not statistically different (α=0.05). 59
Table 3.11: Visual rating of percent weed cover at time of corn emergence, corn yields, and plant populations for early and typical corn planting dates following forage radish, rye, 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 with the exception of rye cover crop treatment means that was pooled over two years at one site. Means followed by the same letters are not statistically different (α=0.05). 60
Table 3.12: Effect of planting date on corn yield differed by site at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF). 61
Table 3.13: Influence of forage radish, rye, and no cover crop treatments on corn yield and plant population at the USDA Beltsville Agricultural Research Center South Farm (BARC-SF) in 2007 and 2008. Means followed by the same letters are not statistically different (α=0.05). 62
Table 4.1: Location and selected soil properties for experiments at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF). 93
Table 4.2: Management history and cover crop planting dates for experiment sites at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF). 94
Table 4.3: Residue treatments for Experiment 4. 95
Table 4.4: Mean fall dry matter of forage radish shoot and fleshy root tissue used to create residue moving treatments in November at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF) in 2006 and 2007. 96
Table 4.5: Electrical conductivity (EC) of extracts prepared from plant tissues harvested on 7 Nov, 2005 and plant residues harvested on 24 March, 2006. 98
Table 4.6: Effect of forage radish cover crop residue treatment on mean percent weed cover in early spring and at planting time at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF)..... 105
Table A2.1: Research farm field names and selected soil properties 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. 113

Table A3.1: Horseweed (*Conyza canadensis* L.) and total weed suppression following forage radish cover crops in Field-A at the Beltsville Agricultural Research Center during the winter and spring of 2006. 114
Table A5.1: Natural weed seed bank emergence in soils sampled during May 2006 following forage radish, rye, rapeseed, and no cover crop treatments at the USDA Beltsville Agricultural Research Center North Farm (NE-6) and the Lower Eastern Shore Research and Education Center (LESREC) in Salisbury, MD.... 121
Table A5.2: Natural weed seed bank emergence in soils sampled in March, 2007 following forage radish, oat, and no cover crop treatments at the USDA Beltsville Agricultural Research Center North Farm (NE-1N) and South Farm (SG-10A). 122

List of Figures

Figure 2.1: The winter annual weed yellow rocket (*Barbarea vulgarix* R.Br.) did not growing among forage radish cover crop residues (right) in March, 2005 at the Beltsville Agricultural Research Center. The low residue spring seed bed following forage radish cover crop residues contrasts with the rye (*Secale cereale* L.) cover crop growing to the left. 27
Figure 2.2: Natural logarithm of the response ratio [*ln*(yield of corn following winter cover crops/yield of corn following no cover crop) (L_i) for biculture (10 observations), grass (68 observations), and legume winter cover crops (82 observations) from treatments in 36 studies. Horizontal bars represent variance. Response ratios greater than zero indicate a yield benefit from cover crops (Miguez and Bollero, 2005). 28
Figure 2.3: Light interception (LI) of different cover crop species over time (days after sowing – DAS) for Experiment A (A) and Experiment B (B). Fodder radish (closed triangles) and winter oilseed rape (open triangles) demonstrated faster canopy development than winter rye (closed squares), white lupin (open squares), alfalfa (open diamonds), and Itialian ryegrass (closed diamonds) (Kruidhof et al., 2008). 29
Figure 3.1: Forage radish cover crop growth on November 18, 2007 at the USDA Beltsville Agricultural Research Center. Cover crop was planted on August..... 63
Figure 3.2: No weed cover following forage radish cover crops (A) on March 29th, 2007 at the Beltsville Agricultural Research Center South Farm (BARC-SF). No cover crop treatment was dominated by speedwell (*Veronica officinalis L.*), common chickweed (*Stellaria media* L. Vill), and henbit (*Lamium amplexicaule* L.) 64
Figure 3.3: Lower weed cover on April 26, 2008 in early corn planting date (April 11) treatment compared to weed cover dominated by common lambsquarters on May 23, 2008 in the typical planting date (May 16) treatment. 65
Figure 4.1: Relative germination and root length of lettuce (*Lactuca sativa* L.) seedlings grown in aqueous plant tissue extracts. Germination and root lengths are expressed as a percent of the distilled water control. Extracts were prepared from fresh forage radish shoot, forage radish root, and oat shoot tissues collected on 7 Nov, 2005 and from plant residues collected on 24 March, 2006. Bars represent standard deviation. 97
Figure 4.2: Relationship between lettuce (*Lactuca sativa* L.) performance and electrical conductivity of aqueous plant tissue extracts and a distilled water control. Extracts were prepared from forage radish root (FR), forage radish shoot (FS), and oat shoot (OS) and compared to a distilled water control (C). Plant tissues were harvested November 7, 2005 and residues harvested March 24, 2006..... 99
Figure 4.3: Relative root length of lettuce (*Lactuca sativa* L.) seedlings grown in aqueous soil extracts. Root lengths are expressed as a percent of the distilled water control. Soil extracts were prepared from surface soil samples (0-5 cm) collected from forage radish, oat, and no cover crop field treatments on 28 March and 30 May, 2006. Bars represent standard deviation. 100

Figure 4.4: Effect of soil samples collected below decomposing forage radish residues (FR) or no cover crop (NO) on lettuce and (Lactuca *sativa* L.) and tomato (*Solanum lycopersicum* L) germination and seedling biomass. Soils were sampled from fields at the USDA Beltsville Agricultural Research Center North Farm (NF) and South Farm (SF). Significant differences ($\alpha = 0.05$) between pairs of FR and NO treatments for North Farm and South Farm are indicated by NF* or SF* respectively. 101
Figure 4.5: Initial gravimetric soil moisture and soil nitrate content of soils sampled from forage radish (FR) and no cover crop (NO) treatments at the USDA Beltsville Agricultural Research Center North Farm and South Farm. Significant differences ($\alpha = 0.05$) between pairs of FR and NO treatments for North Farm and South Farm are indicated by NF* or SF* respectively. No samples were available to measure soil nitrate for Field-E for the 28 February sampling date. 102
Figure 4.6: Mean cumulative weed emergence of planted weed seeds and lettuce seeds below decomposing forage radish cover crop, decomposing oat cover crop, and no cover crop control treatments in 2006 at the USDA Beltsville Agricultural Research Center North Farm. Bars represent standard deviation. 103
Figure 4.7: Mean emergence of common lambsquarters (*Chenopodium album* L.) below decomposing forage radish residues and a no cover crop control for three site-years at the USDA Beltsville Agricultural Research Center. Letters represent differences between cover crop treatments within a site. Bars represent standard deviation. 104
Figure 4.8: Effect of forage radish cover crop on average daily maximum (max) and minimum (min) soil temperature and average daily soil moisture relative to no cover crop the following spring (March to May 2006) in field Field-B at the USDA Beltsville Agricultural Research Center North Farm. 106
Figure 4.9: Influence of cover crop planting date on fall cover crop canopy and weed suppression the following March in 2007 and 2008 at the USDA Beltsville Agricultural Research Center North Farm (Field-A and Field-B) and South Farm (Field-F and Field-E). Error bars represent stand deviation. 107
Figure A1.1: Average daily air temperature and cumulative rainfall during the cover crop and corn growing season at the USDA Beltsville Agricultural Research Center during the 2006-07 and 2007-08 seasons. 112
Figure A4.1: Average daily maximum and minimum soil temperature, average daily soil moisture tension, and daily rainfall in forage radish and no cover crop treatments at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF) in spring 2007. 115

Chapter 1: Introduction

Background and problem definition

Weed control remains one of the major challenges to crop production. Herbicides and tillage are the two most widely used methods to control weeds because they can provide effective and in some cases selective control of weeds. However, both of these measures can have negative impacts on agroecosystems. As an alternative, integrated weed management (IWM) employs multiple weed management strategies. These practices may not provide sufficient control when used individually, but allow for reduced use of herbicides and tillage (Swanton and Murphy, 1996). Combining these multiple weed control strategies is often described as synchronizing "many little hammers" that act synergistically to achieve an overall control strategy (Liebman and Gallandt, 1997). Cover crops can be used as one of the "little hammers" in an IWM tool kit with the added advantage of providing many other agronomic and soil benefits.

The mechanisms by which cover crops reduce weed seed germination and seedling growth include: competition, allelopathy, and altered soil conditions (Creamer et al., 1996; Hoffman and Regnier, 2006; Teasdale et al., 2007). These mechanisms are not mutually exclusive and multiple mechanisms may contribute to weed suppression. A better understanding of the mechanisms of cover crop weed suppression will allow farmers to increase the efficacy

and consistency of this weed management tool or identify when conditions require supplemental weed control measures to be taken.

To increase cover crop adoption by farmers in the Chesapeake Bay watershed, research is needed to evaluate alternative cover crop species with novel characteristics that may improve their fit with the range of cropping systems used in the Mid-Atlantic region. Forage radish is a new winter annual cover crop in the Mid-Atlantic region. It has unique characteristics that makes it distinct from many other 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; MDA, 2009; Weil and Kremen, 2007)

When planted in late August, forage radish emerges quickly and produces biomass rapidly in the fall (Weil et al., 2009). It has a large, white, and fleshy tap root that may protrude aboveground as much as 10 to 15 cm. Forage radish is sensitive to frost and winterkills with prolonged exposure to temperatures below -4°C (Weil et al., 2009). Forage radish cover crop 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. Because of this rapid decomposition, forage radish cover crops create a unique low residue and weed-free seed bed for planting in the early spring.

Justification for research

Early work with forage radish as a cover crop in the Mid-Atlantic region included observations that it could provide dramatic fall and spring weed suppression (Weil and Kremen,

2007). Although cover crops are rarely planted solely for weed suppression, this characteristic along with other soil quality and nutrient cycling benefits may make forage radish an attractive alternative for cropping systems in the Mid-Atlantic region. To effectively develop reliable weed management strategies utilizing forage radish winter cover crops, research is needed to quantify the amount and duration of the weed suppression it provides as well as the type of weed species it is capable of suppressing. Having a better understanding of the mechanisms of forage radish cover crop weed suppression will also help develop strategies to maximize weed suppression and identify situations when alternative weed management strategies will be required.

General research approach

A series of field, growth chamber, and laboratory experiments were conducted between January 2005 and March 2009 to evaluate the ability of forage radish cover crops to suppress weeds, its impact on a subsequent corn crop, and the underlying mechanism of its suppression. Field experiments occurred at four sites within the coastal plain of Maryland. Comparisons were made to control treatments that included oat, rye, and no cover crop.

Field experiments were conducted over ten site-years to evaluate the effect of forage radish cover crops on the amount and duration of weed suppression, the weed species suppressed, and impact on a subsequent corn crop. Six experiments that employed a variety of experimental approaches were used to study the mechanism of forage radish weed suppression. These approaches utilized both the controlled environment of lab and growth chamber experiments as well as field experiments.

Much of the published allelopathy work has neglected to include the soil, which may influence the movement and availability of allelochemicals to interact with weed seeds in the soil seed bank (Cheng, 1992). Therefore, in this study, soil bioassays along with aqueous extracts were used to evaluate allelopathic potential using lettuce and tomato as test species (Rice et al., 2005). To test for allelopathy under field conditions, lettuce and a selection of weed seeds were planted below cover crop residues.

To compare the effects of competition and allelopathy on weed suppression in fall and spring, cover crop residues were removed or added among forage radish and no cover crop plots. Different cover crop seeding dates were also used to vary the amount and timing of cover crop growth in fall. The effects of cover crop residues on spring soil conditions were also monitored.

General research objectives and hypothesis

Objective 1: To characterize the repeatability, amount, and duration of weed suppression during and after a fall-planted forage radish winter cover crops.

Hypotheses:

1. Forage radish winter cover crops will consistently cause complete weed suppress compared to no cover treatments during the fall.
2. Forage radish winter cover crops will consistently provide complete weed suppression after they have winterkilled and are decomposing during the winter.
3. Forage radish winter cover crops will consistently suppress weeds in the spring to the same extent as a spring oat cover crop, which leaves much more residue.

4. Forage radish winter cover crops suppress weeds in the spring to the same extent as an actively growing rye cover crop.
5. Weed suppression by forage radish will control winter annual weeds better than summer annual weeds.

Objective 2: To quantify the effect of fall-planted forage radish cover crops on a subsequent corn crop.

1. Corn population and yields of direct seeded corn following forage radish cover crops will not be lower than following no cover crop.
2. Weed pressure will be lower in early planted corn compared to a typical planting date.

Objective 3: To determine if the weed suppression mechanism of forage radish cover crops is due to allelopathy, competitive fall growth, or altered soil conditions.

1. If weed suppression is due allelopathy, forage radish tissues and amended soil contain water soluble allelopathic compounds that will reduce lettuce seed germination and seedling growth.
2. The allelopathic effects of forage radish residue and soil will decline from winter to spring.
3. If weed suppression is mainly due to allelochemical release while forage radish cover crops decompose, removing cover crop residues following the first frost will reduce weed suppression the following spring.

4. If weed suppression is due to competition during the fall cover crop growing season, removing cover crop residue before the first frost will not reduce weed suppression the following spring.
5. If weed suppression is due to competition during the fall cover crop growing season, earlier fall planting dates of forage radish cover crops will increase their ability to suppress weeds the following spring.

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Chapter 2: Literature review

Introduction

The state government of Maryland is using cost share programs to promote the use of cover crops on farms in Maryland to improve water quality in the Chesapeake Bay watershed. Despite cost share incentives of $99 to $210 per hectare in 2009 (MDA, 2009), cover crop acreage in Maryland remained around 93,000 ha, which represents 12 % of all agricultural cropland in the state (MDA, 2010). In 2009, Maryland's new strategic action plan set a two-year goal to prevent the addition of 1,700,000 kg of nitrogen and 91,254 kg of phosphorus from reaching the Chesapeake Bay over 2008 levels (MDA, 2010). This program proposes to use cover crops to account for 46% of these reductions by nearly doubling cover crop acreage to 186,000 ha.

As of February 22, 2010, implementation of the cover crop portion of this program remains at 18 % compared to 100% completion for the nutrient management plan enforcement and manure transport portions of the program (StateofMaryland, 2010). Incentives and cost share programs alone may not be sufficient to meet cover crop program goals if farmers do not perceive cover crops to provide sufficient agronomic benefits. Research is needed to quantify how cover crops benefit farmers through cropping system management, productivity, and profitability.

In addition to broader environmental services, cover crops provide multiple agronomic benefits. These benefits have been reviewed by several authors (Dabney et al., 2001; Hartwig

and Ammon, 2002; SAN, 2007; Weil and Kremen, 2007). Cover crops cycle nutrients, such as nitrate, that may be susceptible to leaching outside of the main growing season (Dean and Weil, 2009; Rasse et al., 2000; Robertson and Vitousek, 2009). Legume cover crops may also fix additional nitrogen that becomes available during subsequent growing seasons (Clark et al., 1997a).

Cover crops reduce soil degradation due to wind and water erosion at a field scale (Dabney, 1998). They also enhance soil quality by providing living plant roots outside of the traditional growing season and additional plant residues that can increase soil organic matter. This provides additional habitat and food sources for the food web of macro and microorganisms that live in the soil (Hartwig and Ammon, 2002). Over time, cover cropping can increase soil aggregate stability, macroporosity, aeration, water infiltration, and water retention, especially when used in combination with conservation tillage (Dabney, 1998).

Cover crops are also used to manage pests in agroecosystems (Hartwig and Ammon, 2002). *Brassica* cover crops have been used to suppress a variety of plant pests, such as pathogens, nematodes, and weeds (Brown and Morra, 1997). Studies have shown cover crops to have a range of effects on subsequent crop yield. In a meta analysis combining the results of 36 studies, Miguez and Bollero (2005) found that hairy vetch cover crops had a positive effect on subsequent crop yield while rye cover crops had either no impact or an overall positive impact on subsequent crop yield. Both cover crop species and cover crop management strategies can influence subsequent crop performance and yield (Clark et al., 1997b).

To increase cover crop adoption by farmers in the Chesapeake Bay watershed, research is also needed to evaluate alternative cover crop species with novel characteristics that may

improve their fit with the range of cropping systems used in the Mid-Atlantic region. Forage radish (*Raphanus sativus* L. var. *longipinnatus*), and certain cover crops in the *Brassicaceae* family, such as rapeseed (*Bassica napus* L.), oilseed radish (*Raphanus sativus* L. var. *oleiformis*), and white or yellow mustard (*Sinapus alba* L.), are new winter annual cover crops in the Mid-Atlantic region. They have different characteristics than other 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; MDA, 2009; Weil and Kremen, 2007).

When planted in late August, forage radish emerges quickly and produces biomass rapidly in the fall (Weil et al., 2009). It 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 winterkills with prolonged exposure to temperatures below -4°C (Weil et al., 2009). Forage radish cover crop 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. Because of this rapid decomposition, forage radish cover crops create a unique low residue and weed-free seed bed for planting in the early spring.

Early work with forage radish as a cover crop in the Mid-Atlantic region included observations of dramatic fall and spring weed suppression (Figure 2.1) (Weil and Kremen, 2007). Although cover crops are rarely planted solely for weed suppression, this characteristic along with the other potential benefits of this new cover crop may make forage radish an attractive alternative for cropping systems in the Mid-Atlantic region. This literature review will focus on the use of forage radish and other *Brassica* cover crops to suppress weeds in

agricultural production systems, the mechanisms of cover crop weed suppression, and their impact on the productivity of subsequent crops. The term radish will be used in this literature review to refer to the several sub-species, populations, or cultivars of *Raphaus sativus* that have a similar large swollen tap root and leaf morphology, such as forage radish, oilseed radish, and fodder radish (*Raphanus sativus* cv. Brutus).

Using cover crops to control weeds

Weed control remains one of the major challenges to crop production. Herbicides and tillage are the two most widely used methods to control weeds because they can provide effective and in some cases selective control of weeds. However, both of these measures can have negative impacts on agroecosystems. As an alternative, integrated weed management (IWM) employs multiple weed management strategies. These practices may not provide sufficient control when used individually, but allow for reduced use of herbicides and tillage (Swanton and Murphy, 1996). Combining these multiple strategies is often described as synchronizing "many little hammers" that act synergistically to achieve an overall control strategy (Liebman and Gallandt, 1997). Cover crops can be used as one of the "little hammers" in an integrated weed management tool kit with the added advantage of providing many of the other agronomic and soil benefits.

Weed suppression by Brassica cover crops

One group of cover crops that is being used to suppress weeds is the *Brassicacea* family. Haramoto and Gallandt (2004) published a recent review of *Brassica* cover crops for weed

management. These cover crops are planted as winter annual cover crops or as early spring cover crops that are terminated prior to establishing the main cash crop. Most of the research to date has focused on using *Brassica* cover crops in vegetable cropping systems.

Krishnan et al. (1998) found rapeseed (*Brassica napus* L.), brown mustard (*Brassica juncia* L.), and white mustard (*Sinapis alba* L.) to reduce weed emergence and biomass production in subsequent soybean (*Glycine max* L.) crops when used as green manures under both greenhouse and field conditions. Weed species suppressed included kochia (*Kochia scoparia* L. Schrad.), shepherd's-purse (*Capsella bursa-pastoris* L.), redroot pigweed (*Amaranthus retroflexus* L.), and green foxtail (*Setaria viridis* L. Beauv.). Boydston and Hang (1995) found rapeseed cover crops to reduce weed biomass by up to 96% in subsequent potato crops compared to fallow treatments under field conditions. Al-Khatib et al. (1997) found rapeseed and white mustard reduced weed biomass in green pea (*Pisum sativum* L.).

Weed suppression by forage radish and fall planted radish cover crops

Few studies have described weed suppression of radish cover crops compared to other *Brassica* cover crops. Oilseed radish, turnip (*Brassica rapa* L.), and fodder radish, have been grown as winter annual cover crops and have been observed to suppress weeds in several field studies. Like forage radish, these cover crops are typically planted in the late summer or early fall and winterkill while in a vegetative stage during the fall or winter months. In the spring their residues remain in the field and may be managed with tillage to prepare a seed bed or left undisturbed using direct seeding (Charles et al., 2006; Kruidhof et al., 2008; Wang et al., 2008; White and Weil, 2010).

Amount and duration of weed suppression following radish cover crops

In general, research reports of radish cover crop species grown in temperate regions indicate that they suppress weeds both during the fall cover crop growing season and during the early spring after they winterkill. In central Michigan, oilseed radish cover crops reduced spring weed biomass by 98% in early May compared to 70% for hairy vetch and rye cover crops (Charles et al., 2006). Total weed density in early May was also lower following oilseed radish than following any other cover crop treatment tested. However, weed suppression did not persist after seed bed preparation for celery transplants in late spring. At the time of celery transplants in June and July, total weed density following oilseed radish was higher or equivalent to all cover crop and control treatments.

Wang et al. (2008) evaluated the effects of fall cover crops, including oilseed radish, on weeds in onions in central Michigan. Cover crops were seeded in August and incorporated with tillage then saturated with water using irrigation in October to promote biofumigation. Weed density in the onion crop following oilseed radish was reduced by 30 % in late June and early July compared to the no cover crop control. Wang et al. (2008) observed that all cover crop treatments, including oilseed radish, reduced recoverable weed seeds in the soil seed bank by approximately 75% compared to the no cover crop control. However, the viability of recovered seeds in the soil seed bank was not evaluated.

In New York, Stivers-Young (1998) reported almost 100% early spring weed suppression following oilseed radish over two seasons and following forage turnip (*Brassica rapa* L.) when added as a treatment in the second season). This dramatic suppression occurred only when cover

crops were planted in August. It occurred to a lesser extent when crops were planted in September.

In the Netherlands, Kruidhof et al. (2008) evaluated the ability of fodder radish (*Raphanus sativus* cv. 'Brutus') to compete with weeds in the fall and the allelopathic potential of its residues when incorporated in the spring. When grown as a fall cover crop, fodder radish reduced fall weed biomass by a minimum of 70% compared to no cover crop (Kruidhof et al., 2008). No differences in spring weed emergence were detected between fodder radish and no cover crop treatments. Fodder radish did not inhibit the spring emergence of sugar beet and lettuce seeds that were used as indicator species for allelopathy.

Weed species suppressed by radish cover crops

Radish cover crops most commonly suppress winter annual weed species. In Michigan, Charles et al. (2006) observed oilseed radish cover crops suppressed the fall and early spring growth of common chickweed (*Stellaria media* L. Vill.), prostrate pigweed (*Amaranthus blitoides* S. Wats), shepherd's purse (*Capsella bursa-pastoris* L. Medik), common purslane (*Portulaca oleracea* L.), and yellow nutsedge (*Cyperus esculentus* L.).

In central Michigan, Wang et al. (2008) observed that oilseed radish and mustard cover crops suppressed nearly all weed species growing in the no cover crop treatments during the fall cover crop growing season. This resulted in reduced weed seed production. In the following onion crop, there was a 65% reduction in redroot pigweed (*Amaranthus retroflexus* L.) density following oilseed radish and the other cover crop treatments. None of the cover crop treatments used by Wang et al. (2008) were able to reduce population densities of yellow nutsedge, common purslane, or wild mustard (*Sinapis arvensis* L.) during the onion growing season.

In New York, oilseed radish cover crops provided nearly 100% early spring suppression of henbit (*Lamium amplexicaule* L.), malva (*Malva moschata* L.), and common chickweed (Stivers-Young, 1998). In Ontario, Canada, oilseed radish also produced sufficient biomass in two of three site-years to suppress fall growth of volunteer winter wheat (*Triticum aestivum*) by 75% (Swanton et al., 1996).

Mechanisms of cover crop weed suppression

The mechanisms by which cover crops reduce weed seed germination and seedling growth include: competition, allelopathy, and altered soil conditions (Creamer et al., 1996; Hoffman and Regnier, 2006; Teasdale et al., 2007). These mechanisms are not mutually exclusive and multiple mechanisms may contribute to weed suppression. A better understanding of the mechanism of cover crop weed suppression may allow the development of more effective and consistent weed management tools or to identify when conditions require supplemental weed control measures to be taken.

Competition

All plants require sunlight, water, carbon dioxide and mineral nutrients. The ability of plants to preferentially acquire or tolerate low levels of these resources may give them a competitive advantage (Tilman, 1997). Several characteristics contribute to the ability of cover crops to compete with weeds. These include low dormancy, uniform emergence, rapid emergence, fast growth, closed canopy architecture, and biomass production (Kruidhof et al., 2008; Mohler, 2001). Kruidhof et al. (2008) compared the light interception of contrasting cover crop species canopies as a measure of the rate of canopy development and competitive ability

(Figure 2.3). The time to reach 50% of maximum light interception was shorter for foddor radish and oilseed radish than for alfalfa (*Medicago sativa* L.) and Italian rye grass (*Lolium multiflorum* L.). Cover crop management practices, such as planting date or seeding rate, along with the relative time of weed emergence will also influence the relative ability of cover crops to compete with weeds (Hoffman and Regnier, 2006; Teasdale et al., 2007).

Allelopathy

Some plant species produce substances called allelochemicals that impact the germination, growth, and development of other plants when they are released into the environment (Chou, 1999; Inderjit and Keating, 1999; Rizvi et al., 1992; Weston, 1996). This phenomenon is called allelopathy (Rice, 1984). Allelochemicals are diverse in their chemical properties and modes of action (Brown and Morra, 1997; Inderjit and Keating, 1999). Allelochemicals may affect both germinating seeds and seedlings. Several plant species commonly used as cover crops have documented allelopathic effects and may be managed to maximize allelopathic suppression of weeds (Anaya, 1999; Chou, 1999; Weston, 1996).

The distribution and concentration of allelochemicals in the soil may be influenced by the amount of plant biomass, concentrations of allelochemicals within plant tissues, residue management practices, the chemical properties of allelochemicals, soil properties and allelochemical fate in the soil environment (Cheng, 1992; Mamolos and Kalbutji, 2001; Teasdale, 2003). Allelochemicals released from residues that are decomposing on the soil surface may be more concentrated than those released from incorporated residues (Liebman and Mohler, 2001). Given the number of variables influencing allelochemical production and fate in the

environment, it is not surprising that field trials often show inconsistent results and that laboratory experiments are criticized as being artificial and unrepresentative.

Altered soil conditions

Cover crops and their residues may result in physical, biological, or chemical changes in the soil environment (Mohler, 1996). Thus, they can influence the availability of sites for weed seed germination and seedling establishment. Liebman and Mohler (2001) reviewed the impact of soil factors, such as temperature, light, water, and soil fertility, on weed germination and seedling emergence. Plant species have evolved to require different soil conditions for seed after ripening, dormancy breaking, and germination (Baskin and Baskin, 2001). Thus, soil factors may influence weed-crop interactions before competitive interactions even begin (Liebman and Mohler, 2001).

Growing cover crop canopies as well as the residues of terminated cover crops intercept solar radiation, influencing the quantity and quality of light reaching the soil surface as well as soil temperature (Kruidhof et al., 2008; Teasdale and Mohler, 1993). Shading decreases the magnitude of temperature fluctuations. Weeds have evolved to use a variety of signals to break seed dormancy. These include the magnitude of temperature fluctuations and exposure to light in the red spectrum of wavelengths (Baskin and Baskin, 2001). Cover crops interfere with these signals and suppress weeds reliant on these signals within the growing cover crop or during residue decomposition (Gallandt et al., 1999; Liebman and Mohler, 2001; Teasdale, 2003).

Cover crops and their residues can also alter soil nutrient availability. Some weed species, such as common lambsquarters, or biotypes of common lambsquarters use nutrients as a signal to promote germination (Bouwmeester and Karssen, 1993). Growing cover crops take up

nutrients leftover after cash crop production and/or those being mineralized from crop residues or manure. Decomposing cover crop residues with high carbon to nitrogen ratios may also tie up soil nutrients. Depleting soil nutrients may decrease the competitive advantage of weeds emerging with crops. In contrast, cover crops with low carbon to nitrogen ratios may be a source of nutrients. By changing the amount, timing, form, and spatial variability of nutrients in the soil, cover crops can impact weed germination and growth during the growing season of cover and subsequent crops.

Challenges to identifying the mechanisms of cover crop weed suppression

Several studies have documented the occurrence of cover crop weed suppression, often as part of a larger study looking at multiple cover crop benefits. Few studies are designed to identify the mechanisms of cover crop weed suppression. This may be due to the challenge of experimentally isolating the mechanisms responsible for cover crop weed suppression, especially under field conditions. For example, cover crops and their residues may change multiple soil factors including nutrient, temperature, moisture, and light conditions in addition to releasing allelopathic compounds (Teasdale et al., 2007).

In theory, competition is distinguished from allelopathy because it involves removing essential factors from the environment while allelopathy involves adding chemical compounds to the environment (Zimdahl, 2004). In practice, it is difficult to design treatments that isolate these two effects (Williamson, 1990).

Identifying the mechanism of cover crop weed suppression would allow farmers to target their management practices to increase the efficacy and consistency of weed suppression and to determine when supplemental weed control measures would be required. For example, if

allelopathy was the mechanism of weed suppression, cover crops may be managed to maximize allelochemical production through varietal selection. Timing of cover crop termination may also be scheduled when the plants contain maximum allelochemical concentrations and weed seeds are most likely to be exposed. However, if competition was the mechanism, management could be targeted towards maximizing biomass production during or prior to weed emergence and may involve varietal selection and seeding practices to maximize early season biomass production.

Do cover crops provide selective weed suppression?

Selective herbicides provide effective weed control when they kill weeds and cause negligible damage to crops. Concerns are often raised by farmers about the negative impact of weed suppressive cover crops on subsequent cash crops. Some allelopathic cover crop species, such as rapeseed, have been found to suppress both weeds and subsequent crop species (Horricks, 1969). Other allelopathic cover crop species have selectively suppressed weed species without negative impacts on subsequent crops (Haramoto and Gallandt, 2005). Ideally, cover crop management strategies would selectively suppress weeds and enhance crop performance.

Mohler (1996) discussed the use of crop residues and mulches to selectively suppress weeds in subsequent crops. Larger seeded species (typically crops) have greater energy reserves that allow them to germinate from deeper in the soil. As allelochemicals are sometimes more concentrated near the soil surface, especially under no-till conditions, preferential protection is provided for larger crop seeds planted deeper in the soil than for weed seeds that are typically germinating closer to the soil surface (Mohler, 1996). Greater energy reserves also give large

seeded species greater ability to push through cover crop residues that may physically inhibit emergence.

Liebman and Sundberg (2006) describe larger seeded species as more tolerant of environmental stresses and plant competition. Seeds of small-seeded species tend to have longer and thinner roots that increase their absorptive surface per unit area. This may make them more vulnerable to allelochemicals and other environmental stresses. Liebman and Sundberg (2006) also hypothesized that larger seed size may provide seeds with the ability to metabolically detoxify allelochemicals. Similar to selective herbicides, cover crops may suppress some species or biotypes more effectively than others. Different requirements for breaking dormancy may exist among annual weeds due differences that have evolved among species or biotypes. These factors could include a range of environmental factors including soil nitrate levels, soil temperature, and exposure to red light. Mechanisms that target germinating weed seeds and seedlings, such as allelopathy are less likely to provide suppression of perennial weeds.

Mechanisms of Brassica cover crop weed suppression

Several studies have shown evidence to support allelopathy as the mechanism of weed suppression by *Brassica* crop and cover crop species (Al-Khatib et al., 1997; Boydston and Hang, 1995; Krishnan et al., 1998; Turk and Tawaha, 2003). Haramoto and Gallandt (2004) and Boydston and Al-Khatib (2006) reviewed *Brassica* cover crops and weed management, focusing on allelopathy as the mechanism of this weed suppression, and on the hydrolysis products of glucosinolates as the allelochemicals responsible.

Glucosinolates are secondary plant metabolites commonly found in *Brassica* species. Glucosinolates are hydrolysed by the enzyme myrosinase into products that have biological activity against weed seeds, pathogens, insects, and nematodes (Brown and Morra, 1995; Brown and Morra, 1997; Chew, 1988). Isothiocyanates (ITCs) are one of these reaction products. They are volatile and short lived when released in soil (Al-Turki and Dick, 2003; Borek et al., 1996). Isothiocyanates inhibit seed germination and seedling growth in a variety of weed and test crop species (Bialy et al., 1990; Brown and Morra, 1995; Brown and Morra, 1996; Petersen et al., 2001; Turk and Tawaha, 2003).

Mechanisms of forage radish cover crop weed suppression

Currently the mechanism to explain weed suppression following forage radish and other radish type winter cover crops is not known. As a member of the *Brassica* family, forage radish may suppress weeds via the breakdown products of glucosinolate hydrolysis. Glucosinolates in forage radish tissues include 4-methylsulfinyl-3-butenyl and 4-methylthio-3-butenyl (Ishii et al., 1989). However, no studies could be found that test this glucosinolate for allelopathic activity. Kruidhof et al. (2008) did not find evidence of allelopathy when incorporating winter killed fodder radish residues the following spring and conducting a field bioassay with lettuce and sugar beet as test species.

In addition to allelopathy, fall competition and altered soil conditions are other possible mechanisms to explain forage radish weed suppression. Forage radish emerges quickly when planted in late August and can rapidly form a closed leaf canopy given sufficient available nutrients and water (Weil et al., 2009). Several authors have hypothesized that the rapid growth

of radish cover crop species is responsible for fall weed suppression during the cover crop growing season (Kruidhof et al., 2008; Stivers-Young, 1998; Wang et al., 2008). Fall competition may also increase weed suppression by reducing fall weed seed production. Wang et al. (2008) observed that all fall cover crops, including oilseed radish, decreased weed seeds in the seed bank the following spring.

Due to the low amounts of residue left in the spring following forage radish winter cover crops, physical inhibition of seedling establishment due to residue effects may be the least likely mechanism for weed suppression. Residue decomposition may alter soil conditions, such as nutrient levels, soil temperature, and soil moisture, which may play a role in weed suppression. For example, Dean and Weil (2009) found that nitrates were released by decomposing forage radish residues early in the spring.

Impact of Brassica cover crops on following crops

Forage radish and other *Brassica* cover crops are relatively new cover crops in the Mid-Atlantic region. Unlike other common cover crops in the Mid-Atlantic region, such as rye, crimson clover, and hairy vetch, less is known about the yield response of crops following forage radish and other cover crops in the *Brassicacea* family. No publications could be found that describe the impact of forage radish cover crop on the large-hectarage grain crops in the Mid-Atlantic region, such as corn, soybean, and winter wheat. In Nebraska, brown and white mustard grown as early spring green manure crops suppressed early season weed growth without reducing soybean yields when herbicides were used to provide in-crop weed control (Krishnan et al., 1998).

Research with *Brassica* cover crops has primarily focused on horticulture crops, such as potatoes, green pea, celery, and onions. Potato yield following spring terminated winter rapeseed cover crops was equal to or greater than no cover crop treatments over two site-years in Washington (Boydston and Hang, 1995). Incorporated rapeseed winter cover crops reduced green pea yields in Washington while white mustard cover crops increased green pea yields (Al-Khatib et al., 1997). Yield reductions following rapeseed were due to the physical interference of rapeseed residues with stand establishment. Celery and onion yields following oilseed radish winter cover crops were equal to or greater than no cover crop treatments over two site-years in Michigan (Charles et al., 2006; Wang et al., 2008).

Conclusions

Forage radish is a new cover crop in the Mid-Atlantic region with unique characteristics that may provide new opportunities for farmers that are being encouraged to plant a cover crop to provide environmental benefits within the Chesapeake Bay watershed. Forage radish can provide a range of benefits to cropping systems, including weed suppression. Other *Brassica* cover crops have been observed to suppress winter annual weeds in the fall and early spring. Cover crops can suppress weeds by a number of mechanisms. The mechanisms of forage radish cover crop weed suppression are not currently understood. Research is needed to evaluate the repeatability, amount, and duration of forage radish weed suppression and to identify the mechanisms of this weed suppression in order to develop management practices to best take advantage of this weed suppression in the Mid-Atlantic region.

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Figure 2.1: The winter annual weed yellow rocket (*Barbarea vulgarix* R.Br.) did not growing among forage radish cover crop residues (right) in March, 2005 at the Beltsville Agricultural Research Center. The low residue spring seed bed following forage radish cover crop residues contrasts with the rye (*Secale cereale* L.) cover crop growing to the left.

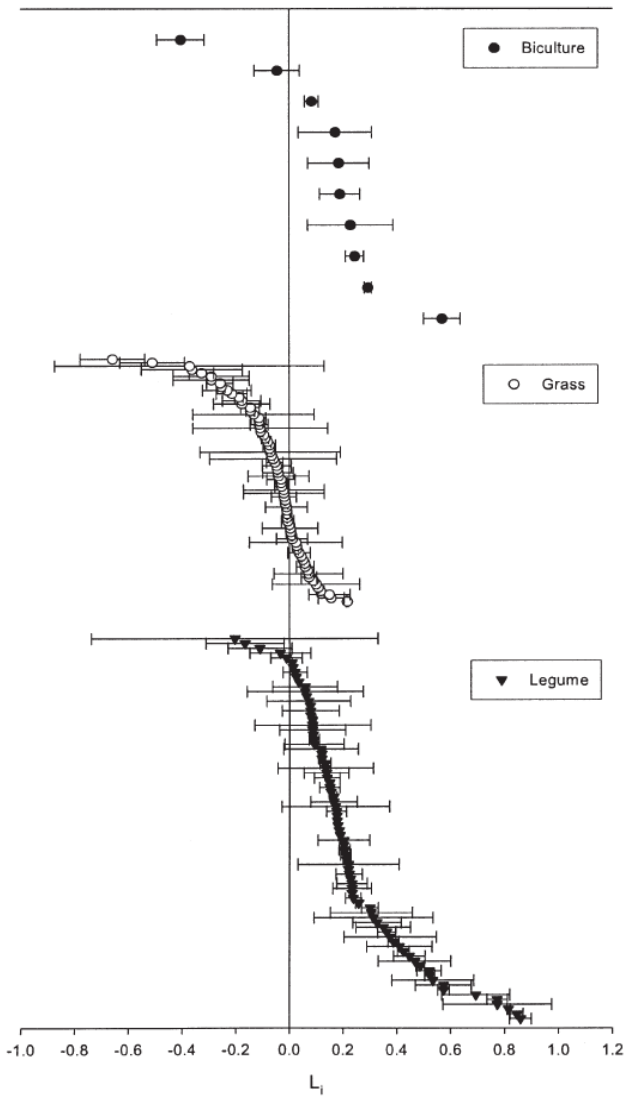

Figure 2.2: Natural logarithm of the response ratio [*ln*(yield of corn following winter cover crops/yield of corn following no cover crop) (L_i) for biculture (10 observations), grass (68 observations), and legume winter cover crops (82 observations) from treatments in 36 studies. Horizontal bars represent variance. Response ratios greater than zero indicate a yield benefit from cover crops (Miguez and Bollero, 2005).

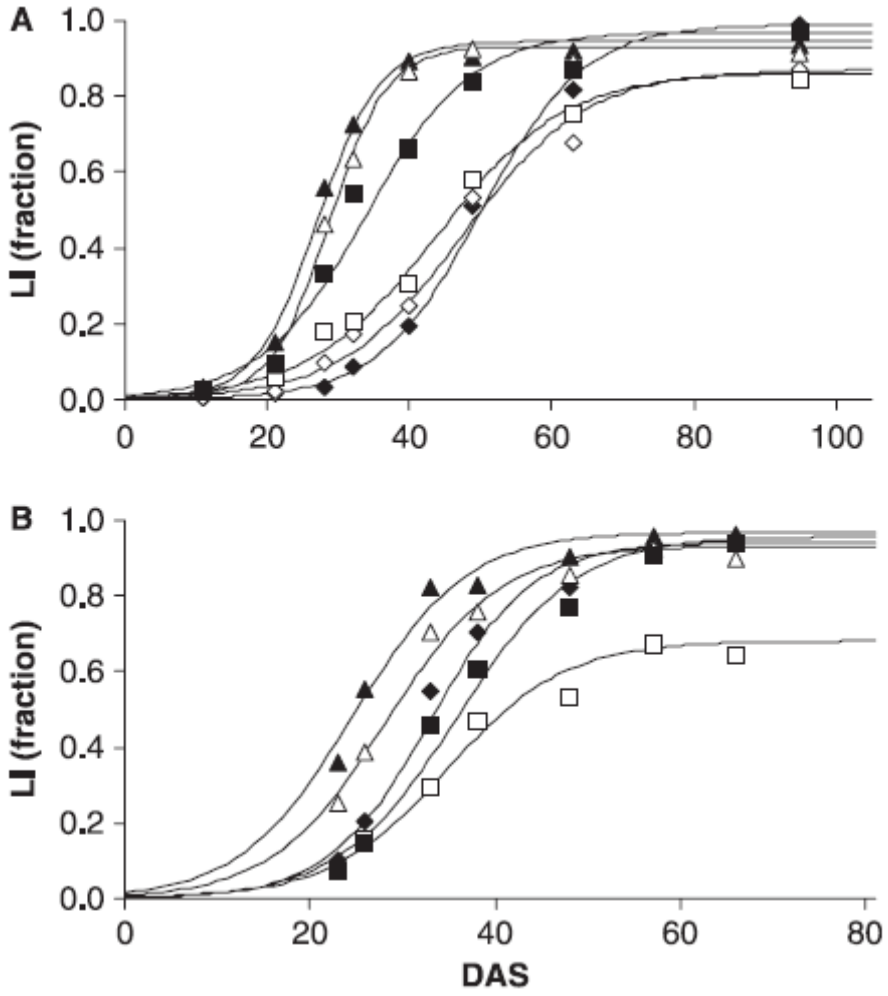

Figure 2.3: Light interception (LI) of different cover crop species over time (days after sowing – DAS) for Experiment A (A) and Experiment B (B). Fodder radish (closed triangles) and winter oilseed rape (open triangles) demonstrated faster canopy development than winter rye (closed squares), white lupin (open squares), alfalfa (open diamonds), and Itialian ryegrass (closed diamonds) (Kruidhof et al., 2008).

Chapter 3: Forage radish winter cover crops suppress winter annual weeds in fall and prior to corn planting

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 direct seeded corn (*Zea mays* L.). Forage radish cover crops were grown in ten site-years in the coastal plain of Maryland and were followed by a corn crop in seven of those site-years. Forage radish was compared to rye (*Secale cereale* L.), oat (*Avena sativa* 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 3900 to 6600 kg ha^{-1} of shoot dry matter and 1300 to 3200 kg 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 the 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 utilize the weed suppression of forage radish cover crops should focus on fall weed suppression and the early spring preplant window of weed control.

Introduction

Forage radish is a new winter annual cover crop in 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; MDA, 2009; Weil and Kremen, 2007). Current cover crop species winter annuals that grow more slowly in the fall and produce most of their biomass in spring. They must be terminated in the spring prior to subsequent crop planting and have higher carbon to nitrogen ratios when left to grow longer in the spring. Forage radish emerges quickly and grows rapidly in the fall (Weil et al., 2009). It has a large white fleshy tap root that may protrude aboveground as much as 10 to 15 cm. Forage radish typically winterkills, has a lower carbon to nitrogen ratio, and decomposes rapidly in the fall.

Forage radish is sensitive to frost and winterkills with prolonged exposure to temperatures below -4 ^{o}C (Weil et al., 2009). Forage radish cover crop 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. Because of this rapid decomposition, forage radish cover crops create a unique low residue and weed-free seed bed for planting in the early spring. These characteristics may 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. cv. 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 recently reviewed by Haramoto and Gallandt (2004), but their review did not address radish cover crops.

The objectives of this study were to: 1) evaluate the reliability of weed suppression by forage radish cover crops, 2) quantify the amount and duration of weed suppression by forage radish cover crops, 3) characterize the weed species affected by forage radish cover crops, 4) determine the impact of forage radish cover crops on subsequent corn yield, and 5) evaluate the

optimum corn seeding dates and herbicide treatments to best utilize the weed suppression provided by forage radish cover crops.

Materials and methods

Site description and experimental design

Experiments were conducted over a four-year period at four locations within the coastal plain of Maryland for a total of ten site-years. The locations were: USDA Beltsville Agricultural Research Center North Farm (BARC-NF), the USDA Beltsville Agricultural Research Center South Farm (BARC-SF), the University of Maryland Central Maryland Research and Education Center (CMREC), and the University of Maryland Wye Research and Education Center (WREC). Soil properties for each site-year are described in Table 3.1. The fall and early spring weed communities existing at these locations were dominated by common chickweed (*Stellaria media* L. Vill), henbit (*Lamium amplexicaule* L.), common lambsquarters (*Chenopodium album* L.), and shepherd's purse (*Capsella bursa-pastoris* L. Medik).

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 (cv. Wheeler) or spring oat (cv. Ogle) (oat was used instead of rye at BARC-NF and BARC-SF in 2005). The effects of these cover crop treatments on subsequent corn crops were quantified in all years except 2005. Plot size was 3 x 9 m for both sites in 2005 and 6 x 9 m for all other site-years.

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. Rye and no cover crop treatments were the control treatments at BARC-SF. Due to space restrictions, no cover crop was the only control treatment at BARC-NF. 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 m x 12 m), cover crop treatment was the sub plot (6 m x 12 m), and herbicide treatment was the sub-sub plot (3 m x 12 m).

Field management

BARC-NF and BARC-SF: The seven fields at BARC-NF and BARC-SF had a history of conventional tillage and crop rotations that include corn, soybean (*Glycine max* L. Merr), winter wheat, and vegetable cops. 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 prior to 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 based on the P and K needs of the subsequent corn crop and to ensure adequate cover crop nutrition and growth. Nitrogen applied with the P and K fertilizer provided some nitrogen in the upper part of the soil profile for cover crop establishment as the fields in this study had 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 prior to cover crop planting at a rate of 3.1 Mg ha^{-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 prior to 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 3.2. Forage radish was seeded at a rate of 14 kg ha^{-1}, rye at a rate of 135 kg ha^{-1}, and oat at 90 kg ha^{-1}. Irrigation was used to stimulate cover crop germination when conditions were unusually dry. The 2005 spring oat cover crop reached the heading stage, or Zadocks stage 59 (Zadoks et al., 1974), by the time it was killed by frost in late November. Forage radish cover crops grew vegetatively in the fall until they were damaged by frost in mid to late November and gradually winterkilled with temperatures that 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 prior to 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.) prior to corn planting (Table 3.2). 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 3.2). Forage radish treatments were not sprayed with herbicide prior to planting corn as it had already winterkilled and facilitated observations of the timing of spring weed emergence.

Corn (Pioneer 38B84, glyphosate tolerant) was direct seeded into cover crop residues at a rate of 74,000 seeds ha^{-1} with 76 cm row spacing. 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 ^{o}C and soil was sufficiently dry for planting to occur. The target for the typical corn planting date was approximately two weeks 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. At 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, nitrogen 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-N9-(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 3.2).

CMREC The two sites at CMREC had a history of no-till management for at least the previous six years and a typical crop rotation of corn- soybean-winter wheat. In 2006, a soybean crop was mowed at a vegetative stage in early August and left to decompose to provide an organic N source prior to 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. Cover crops were planted using a no-till drill with disk openers and 16 cm row spacing (Table 3.2). Forage radish was seeded at a rate of 14 kg ha^{-1} and rye at a rate of 135 kg ha^{-1}. Forage radish cover crops were damaged by frost in mid to late November and most plants winterkilled with progressively cold temperatures in January and February. Rye overwintered and was terminated, along with weeds growing in no cover crop treatments, prior to corn planting with paraquat

(1,1'-dimethyl-4,4'-bipyridinium ion) (0.84 kg ha^{-1} a.i..) and 2,4-D ((2,4-dichlorophenoxy) acetic acid) (0.40 kg ha^{-1} a.i.), (Table 3.2).

Corn (Pioneer 38B84, glyphosate tolerant) was direct seeded into cover crop residues at a rate of 74,000 seeds ha^{-1} with 76 cm row spacing (Table 3.2). At 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 3.2). Weeds in the corn were controlled on 9 May, 2007 and 15 May, 2008 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 3.2).

WREC: This site had a history of conventional tillage, a vegetable crop rotation, and irrigation. The field was in weedy fallow for one year prior to the experiment. Cover crops were planted on 31 August using a no-till drill with disk openers and 16 cm row spacing (Table 3.2). Forage radish was seeded at a rate of 14 kg ha^{-1} and rye at a rate of 135 kg ha^{-1}. Forage radish cover crops were damaged by frost in mid to late November and most plants winterkilled with progressively cold temperatures in January. However at this location, approximately 20 % of forage radish plants overwintered due to mild winter 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 prior to corn planting with glyphosate (1.69 kg a.i. ha^{-1}) (Table 3.2).

Corn (Pioneer 38B84, glyphosate tolerant) was direct seeded into cover crop residues at a rate of 74,000 seeds ha^{-1} with 76 cm row spacing (Table 3.2). Nitrogen was sprayed on the soil surface immediately after planting at 22 kg ha^{-1} N. Nitrogen was side dressed at 40 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 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 3.2).

Field sampling

Cover crop biomass samples were taken in November near the time of maximum fall dry matter accumulation but prior to the first frost that injured forage radish (Table 3.2). 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 ^{o}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 as 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 prior to early corn planting date treatments and in late April or early May near the time of

typical corn planting date treatments (Table 3.2). 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 3.2.

Corn grain yield and dry matter were determined by hand harvesting in September at physiological maturity (determined by corn kernels reaching black layer) (Table 3.2). Fresh weights 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, USA) in order to report yields at 15.5% moisture.

$$Y_{15.5} = Y_h*[(100- M_h) / (100-15.5)] \qquad \text{Equation 1}$$

Where $Yield_{15.5}$ 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 percent grain moisture content at harvest.

Corn plant populations were calculated based on the number of plants in the two 3 m harvest rows.

Statistical analysis

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.

Yields and plant populations for all experiments that had a corn crop 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. For experiments with multiple corn planting dates, only data for the earliest planting date was included in the combined analysis. The pooled analysis for all site-years was run as a split-plot design with site as the main plot and cover crop treatment as the sub-plot. Site-year and block within site-year were considered random effects in the statistical model.

For the corn planting date 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. A separate analysis was conducted to compare cover crop treatments that included rye for the two years at BARC-SF. Year and block within year were considered random effects. A third ANOVA was conducted to evaluate the interaction between years and cover crop treatments by site. Year and cover crop treatment were considered fixed effects while blocks within years were considered random effects. When statistical differences between treatments were identified by ANOVA, means comparisons were made using Fisher’s Least Significant Difference test.

Results and discussion

Cover crop dry matter production

When planted prior to 1 September, forage radish was observed to emerge within two to four days of planting, grow rapidly, and form a closed canopy within four to six weeks. When planted prior to 1 September, forage radish dry matter production ranged from 3900 to over 6600 kg ha^{-1} for shoots and 1300 to over 3200 kg ha^{-1} for the fleshy tap roots (Table 3.3 and Figure 3.1). Total fall dry matter production for both shoots and the fleshy tap roots ranged from 5600 to over 8400 kg ha^{-1}. Forage radish dry matter production was lowest for CMREC Field-H, which had the latest planting date (12 September).

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 3.3). However, rye is typically planted during October in the Mid-Atlantic as it is a 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. Oat was grown at two sites in the fall of 2005. Its fall dry matter production was greater than forage radish. Weed pressure varied widely among the ten fields included in the study. Weed dry matter measured in November ranged from 130 to over 3600 kg ha^{-1} (Table 3.3).

Corn performance

There was no difference in corn yields among cover crop treatments in six out of seven site-years (Table 3.4). 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 (Table 3.2 and 3.3). 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 3.4). Reduced populations following rye cover crops were attributed to residue interference with seed placement and emergence

Weed suppression

Forage radish provided complete suppression of weeds during the fall cover crop growing season (Table 3.5 and Figure 3.1). When planted by 1 September, rye cover crops also had very low or no 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 henbit, common chickweed, and shepherd's purse (Table 3.5 and Table 3.6). Fall growth of the cool-season summer annual weed, common lambsquarters, was suppressed in Field-E, Field-F, and Field-G where it was known to be a dominant weed in the soil seed bank. Dominant weed species present in the no cover crop treatments, that were absent in forage radish and rye cover crops treatments, for all experiment sites are listed in Table 3.6.

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 light interception by cover crops was important for suppression of tall growing weeds like common lambsquarters but was not more important than late light interception for suppression of short statured weeds like common chickweed.

Weeds remained absent in forage radish plots throughout the winter and into March (Figure 3.2). Average percent weed cover ranged from 0-3 % in late March for eight out of nine site-years (Table 3.7). 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. 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, weed suppression in March was similar for forage radish and rye cover crop treatments for all site-years. This was surprising as rye cover crops were alive and growing in March but forage radish cover crops had winterkilled. Forage radish treatments had only 23 to 53 % ground cover, all provided by its residues, while rye had 42 to 76 % from its living canopy plus 23 to 46 % from its residues (Table 3.8).

At the time of typical corn planting, percent weed cover in forage radish cover crops range from 3 to 63 % over eight sight years (Table 3.9). 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 3.9). Comparisons of these two treatments revealed that forage radish continued to have lower weed cover than no cover crop treatments. However,

percent weed cover ratings of up to 63 % it was evident that forage radish cover crops would not provide residual weed suppression that could persist 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. Fall growth of common lambsquarters, was suppressed in Field-E, F, and G where it was known to be a dominant weed in the soil seed bank. However, common lambsquarters emergence in these three fields was stimulated the following spring following forage radish cover crops compared to no cover crop treatments (Table 3.9).

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).

Corn management to utilize forage radish weed suppression

To evaluate the ability of forage radish cover crops to provide weed suppression in subsequent crops, forage radish cover crop treatments with no herbicide application in the

following corn crop were compared over the four site-years of the planting date study. 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 3.10). 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 (data not shown) (Figure 3.3). Percent weed cover ratings were highest when corn was in the V4 stage and decreased at the V8 stage due to the shading effect of the corn canopy. 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 over 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 in-crop 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 than in the no cover and rye treatments (Table 3.11). Differences between forage radish and no cover crop treatments were much greater at the typical 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 3.11). 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 3.11). 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. Forage radish cover crop treatments did not have lower corn stand densities relative to no cover crop treatments and had the highest plant stand densities for the early planting date (Table 3.11). Weed cover ratings suggest that earlier planting of corn would be favorable when eliminating a burndown herbicide application following forage radish cover crops in order 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- 6 weeks of planting (Table 3.2). Zimdahl (2004) discusses two concepts that can be used to evaluate weed management decisions in young corn. The first is a critical weed-free period that ranges from the first 3-5 weeks after planting to prevent yield reductions. The second is a period of 3-6 weeks 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 the range of tolerance to weed competition and residual herbicides provided good weed suppression for the remainder of the corn growing season.

Weeds were not the only yield limiting factor to consider in this study. On loamy sand textured soils of BARC-NF, planting corn on the early date reduced grain yields by 32 % compared to corn planted on the typical date when averaged over two years (Table 3.12). This trend was reversed in the silt loam textured soils of BARC-SF where early seeded corn yields were 11 % greater than corn planted on the typical planting date averaged over two years. 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.

Comparisons between forage radish and rye cover crops were possible for BARC-SF site-years. Trends between cover crops at BARC-SF were driven by the management of rye cover crops. Wet conditions prior to the time of typical corn planting in 2008, delayed rye termination until corn planting (Table 3.2). This resulted in a dense mass of rye residue that interfered with planting and reduced corn population and yield by 30% and 25 % respectively, when compared to the no cover crop treatment (Table 3.). These results highlight the tradeoffs between cover crops that winterkill versus 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 are less likely to provide residue to cover the soil and conserve soil moisture from evaporation during drought periods in summer, but they simplify spring seeding, provide warmer soils, and may allow for more timely planting of subsequent crops.

Conclusions

Forage radish cover crops produced a large amount 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. In three of ten site-years, common lambsquarters was suppressed by forage radish in the fall but its emergence was stimulated the following spring.

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 at the time of or shortly after corn emergence are controlled with a postemergence herbicide. However, if forage radish planting was delayed and growth sub-optimal, 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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Table 3.1: Soil properties and field history 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).

Farm	Field	Latitude	Longitude	Soil Series	Soil Taxonomy Subgroups	Surface soil textural class	Soil organic matter (%)	Previous crop	Previous tillage system
BARC-NF	A	39° 01’ 51” N	76° 55’ 58” W	Matawan-Hammonton	Aquic Hapludults	loamy sand	1.3	sweet corn	conventional
	B	39° 01’ 52” N	76° 55’ 59” W	Matawan-Hammonton (Rep 1, 2) Ingleside-Hammonton (Rep 3, 4)	Aquic Hapludults, Typic Hapludults	loamy sand	2.0	weedy fallow	conventional
	C	39° 01’ 53” N	76° 56’ 01” W	Matawan-Hammonton (Rep 1, 2) Ingleside-Hammonton (Rep 3, 4)	Aquic Hapludults, Typic Hapludults	loamy sand	2.0	fallow	conventional
BARC-SF	D	39° 00’ 56” N	76° 56’ 29” W	Codorus	Fluvaquentic Dystrudepts	silt loam	1.2	cucumber	conventional
	E	39° 00’ 51” N	76° 56’ 30” W	Codorus	Fluvaquentic Dystrudepts	silt loam	1.5	fallow	conventional
	F	39° 00’ 48” N	76° 56’ 27” W	Codorus	Fluvaquentic Dystrudepts	silt loam	2.2	fallow	conventional
	G	39° 00’ 48” N	76° 56’ 27” W	Codorus	Fluvaquentic Dystrudepts	silt loam	2.2	fallow	conventional
CMREC	H	39° 00’ 41” N	76° 49’ 55” W	Cedartown-Galestown-Matawan	Psammentic Hapludults, Aquic Hapludults	loamy sand	1.9	soybean	no-till
	I	39° 00’ 40” N	76° 49’ 56” W	Ingleside-Hammonton	Typic Hapludults, Aquic Hapludults	loamy sand	1.9	barley	no-till
WREC	J	38° 54’ 52” N	76° 08’ 13” W	Nassawango	Typic Hapludults	silt loam	1.4	fallow	conventional

Table 3.2: 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	2007-07	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 March	20 March	20 March	20 March	20 March	-	28 March	28 March	21 March	21 March	21 March	21 March	20 March	24 March
Terminate rye and weeds in no cover	-	30 March	30 March	11 April	16 May	-	30 March	30 March	11 April	16 May	11 April	10 April	10 April	9 April
April/May spring cover rating†	26 April	30 April	30 April	25 April	25 April	-	25 April	25 April	2 May	2 May	2 May	4 May	21 April	18 April
Plant corn	-	24 April	10 May	11 April	15 May	-	24 April	10 May	11 April	15 May	11 April	23 April	16 April	16 April
Emergence cover rating after corn planting	-	30 April	-	25 April	30 May	-	25 April	-	2 May	30 May	-	-	-	-
Herbicide 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 Jun	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

Table 3.3: 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	Forage radish			Rye shoots		Oat shoots	Weeds in no cover
					Fall shoot	Fall root	Fall total	Fall	Spring	Fall	Fall
					kg ha^{-1}						
BARC-NF	A	2005	25 Aug	19 Nov	4457(821)	2319(733)	6775(1208)	-	-	7405(1420)	1379(680)
	B	2006	31 Aug	6 Nov	4262(865)	1338(449)	5600(1268)	-	-	-	2309(709)
	C	2007	28 Aug	17 Nov	4104(862)	1499(510)	5603(1288)	-	-	-	2129(1421)
BARC-SF	D	2005	25 Aug	19 Nov	3902(530)	2829(916)	6730(1369)	-	-	7907(1040)	2515(910)
	E	2006	31 Aug	6 Nov	6667(1143)	1782(527)	8449(1458)	4683(1642)	-	-	3422(987)
	F	2007	28 Aug	21 Nov	4103(912)	2363(976)	6465(1765)	4101(867)	4532(946)	-	2653(1443)
	G	2007	28 Aug	21 Nov	5206(1081)	2215(1117)	7680(1546)	5429(906)	4180(1627)	-	3645(2551)
CMREC	H	2006	12 Sept	8 Nov	2179(560)	815(239)	2994(755)	1483(452)	-	-	136(144)
	I	2007	28 Aug	16 Nov	4910(467)	3208(475)	8118(750)	4481(648)	3258(1032)	-	2164(257)
WREC	J	2007	31 Aug	16 Nov	5353(837)	2737(462)	8090(962)	4261(223)	2832(727)	-	2890(717)

Table 3.4: 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	Yield (kg ha^{-1})			Corn Plant population (1000 plants ha^{-1})		
				Forage radish	No cover	Rye	Forage radish	No cover	Rye
BARC-NF	B	2007	24 April	5417a	6428a	-	75a	76a	-
	C	2008	11 April	8270a	6668a	-	72a	54b	-
BARC-SF	E	2007	24 April	9811a	9680a	11364a	76a	72a	73a
	F	2008	11 April	13120a	12938a	11848a	72a	67a	58b
	G	2008	11 April	12173a	12998a	10808a	69a	74a	59b
CMREC	H	2007	23 April	3746b	5138a	4892a	66a	71a	68a
	I	2008	16 April	10293a	11738a	11495a	76a	80a	78a

Table 3.5: Visual rating of percent weed cover in late fall for 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). Means within a field and rating category followed by the same letters are not statistically different (α=0.05).

		Cover crop			
Location	Field	Forage radish	No cover crop	Rye	Oat
		Total weeds (percent ground cover)			
BARC-NF	A	0b	40a	-	1a
	B	0b	83a	-	-
	C	0b	24a	-	-
BARC-SF	D	0c	78a	-	1b
	E	0c	94a	10b	-
	F	0b	96a	0b	-
	G	0b	94a	0b	-
CMREC	I	0b	8a	0b	-
WREC	J	0b	47a	0b	-
		Winter annual weeds (percent ground cover)			
BARC-NF	B	0b	83a	-	-
	C	0b	23a	-	-
BARC-SF	E	0c	54a	4b	-
	F	0b	79a	0b	-
	G	0b	84a	0b	-
CMREC	I	0b	2a	0b	-
WREC	J	0b	32a	0b	-
		Summer annual weeds (percent ground cover)			
BARC-NF	B	0	0	-	-
	C	0a	1a	-	-
BARC-SF	E	0b	38a	6b	-
	F	0b	15a	0b	-
	G	0	0	0	-
CMREC	I	0b	4a	0b	-
WREC	J	0b	15a	0b	-
		Cover crop canopy (percent ground cover)			
BARC-NF	A	100a	-	-	93a
	B	100a	-	-	-
	C	100a	-	-	-
BARC-SF	D	100a	-	-	96b
	E	100a	-	90b	-
	F	100a	-	100a	-
	G	100a	-	100a	-
CMREC	I	100a	-	100a	-
WREC	J	100a	-	91b	-

Table 3.6: Dominant weed species present in the no cover crop treatments that were absent in forage radish and rye treatments for all site-years 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	Fall	Spring
BARC-NF	common chickweed (*Stellaria media* L. Vill) henbit (*Lamium amplexicaule* L.)	common chickweed henbit speedwell (*Veronica officinalis L.*) horseweed (*Conyza canadensis* L. Cronq) shepherd's purse (*Capsella bursa-pastoris* L. Medik)
BARC-SF	common chickweed common lambsquarters (*Chenopodium album* L.)	common chickweed henbit storksbill (*Erodium cicutarium* L.)
CMREC	common chickweed henbit	common chickweed henbit
WREC	speedwell common lambsquarters	common chickweed henbit speedwell shepherd's purse

Table 3.7: Visual rating of percent weed cover in late March for 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). Means within site-year followed by the same letter are not statistically different (α=0.05).

		Cover crop			
Location	Field	Forage radish	No cover crop	Rye	Oat
		Total weeds (percent ground cover)			
BARC-NF	A	0b	84a	-	4b
	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	-
		Winter annual weeds (percent ground cover)			
BARC-NF	A	0b	84a	-	3
	B	1b	38a	-	-
	C	0b	67a	-	-
BARC-SF	E	0c	66a	7b	-
	F	3b	98a	1b	-
	G	1b	92a	0b	-
CMREC	H	22b	46a	4c	-
	I	0b	13a	0b	-
WREC	J	1b	46a	0b	-
		Summer annual weeds (percent ground cover)			
BARC-NF	A	0	0	-	0
	B	0	0	-	-
	C	0	0	-	-
BARC-SF	E	0	0	0	-
	F	0	0	0	-
	G	0	0	0	-
CMREC	H	0	0	0	-
	I	0b	8a	0b	-
WREC	J	1b	9a	0b	-

Table 3.8: Visual rating of cover crop leaf canopy and residue ground cover in late March for 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). Means within site-year followed by the same letter are not statistically different (α=0.05).

		Cover Crop			
Location	Field	Forage radish	No cover crop	Rye	Oat
		Cover crop canopy (percent ground cover)			
BARC-NF	A	-	-	-	-
	B	-	-	-	-
	C	-	-	-	-
BARC-SF	E	-	-	60	-
	F	-	-	76	-
	G	-	-	67	-
CMREC	H	-	-	43	-
	I	-	-	53	-
WREC	J	-	-	42	-
		Cover crop residue (percent ground cover)			
BARC-NF	A	34b	-	-	89a
	B	40	-	-	-
	C	53	-	-	-
BARC-SF	E	43a	-	27b	-
	F	48a	-	23b	-
	G	52a	-	33b	-
CMREC	H	23b	-	35a	-
	I	53a	-	37b	-
WREC	J	50a	-	46b	-

Table 3.9: Visual rating of percent weed cover around the typical time of spring corn planting time for un-sprayed treatments in 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 within field and rating type followed by the same letter are not statistically different (α=0.05).

		Cover Crop			
Location	Field	Forage radish	No cover crop	Rye	Oat
		Total weeds (percent ground cover)			
BARC-NF	A	37c	95a	-	70b
	B	19	-†	-	-
	C	11b	87a	-	-
BARC-SF	E	3	-	-	-
	F	37ab	75a	0b	-
	G	11	-	-	-
CMREC	H	63	-	-	-
	I	4	-	-	-
		Winter annual weeds (percent ground cover)			
BARC-NF	A	37c	92a	-	70b
	B	19	-	-	-
	C	10b	82a	-	-
BARC-SF	E	0	-	-	-
	F	11b	75a	0c	-
	G	3	-	-	-
CMREC	H	63	-	-	-
	I	3	-	-	-
		Summer annual weeds (percent ground cover)			
BARC-NF	A	0	0	-	0
	B	0	-	-	-
	C	1a	0a	-	-
BARC-SF	E	2	-	-	-
	F	25a	0b	0b	-
	G	7	-	-	-
CMREC	H	0	-	-	-
	I	0	-	-	-
		Cover crop residue (percent ground cover)			
BARC-NF	A	9	-	-	-
	B	11	-	-	-
	C	34	-	-	-
BARC-SF	E	16	-	-	-
	F	8	-	-	-
	G	5	-	-	-
CMREC	H	-	-	-	-
	I	8	-	-	-

† Weeds sprayed with herbicides or treatment no present in experiment

Table 3.10: 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 crop stage are not statistically different (α=0.05).

	Early Corn planting date	Typical Corn planting date
Crop Stage	Weed ground cover (%)	
emergence	8a	72b
V4	46a	68b
V8	36a	61b

Table 3.11: Visual rating of percent weed cover at time of corn emergence, corn yields, and plant populations for early and typical corn planting dates following forage radish, rye, 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 with the exception of rye cover crop treatment means that was pooled over two years at one site. Means followed by the same letters are not statistically different (α=0.05).

Cover crop Corn planting date	Forage radish with no preplant burndown	No cover crop with preplant burndown
	Weed cover at corn emergence	
Early	10b	0c
Typical	73a	1c
	Corn grain yield (kg ha^{-1})	
Early	9155b	8993b
Typical	9828a	10851a
	Corn (kg ha-1	
Early	15546b	15155b
Typical	15920b	18035a
	Corn plant population (1000 plants ha^{-1})	
Early	74a	67b
Typical	71ab	73ab

Table 3.12: Effect of planting date on corn yield differed by site at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF).

Corn planting date	Early	Typical
Site	Corn grain yield (kg ha^{-1})	
BARC-NF	6696b	9808a
BARC-SF	11509a	10346b

Table 3.13: Influence of forage radish, rye, and no cover crop treatments on corn yield and plant population at the USDA Beltsville Agricultural Research Center South Farm (BARC-SF) in 2007 and 2008. Means followed by the same letters are not statistically different (α=0.05).

Cover crop Year	Forage radish	No cover crop	Rye
	Corn grain yield (kg ha^{-1})		
2007	9352b	9933b	10815b
2008	12087a	13358a	10022b
	Corn plant population (1000 plants ha^{-1})		
2007	76a	71ab	72ab
2008	68b	69ab	48c

Figure 3.1: Forage radish cover crop growth on November 18, 2007 at the USDA Beltsville Agricultural Research Center. Cover crop was planted on August

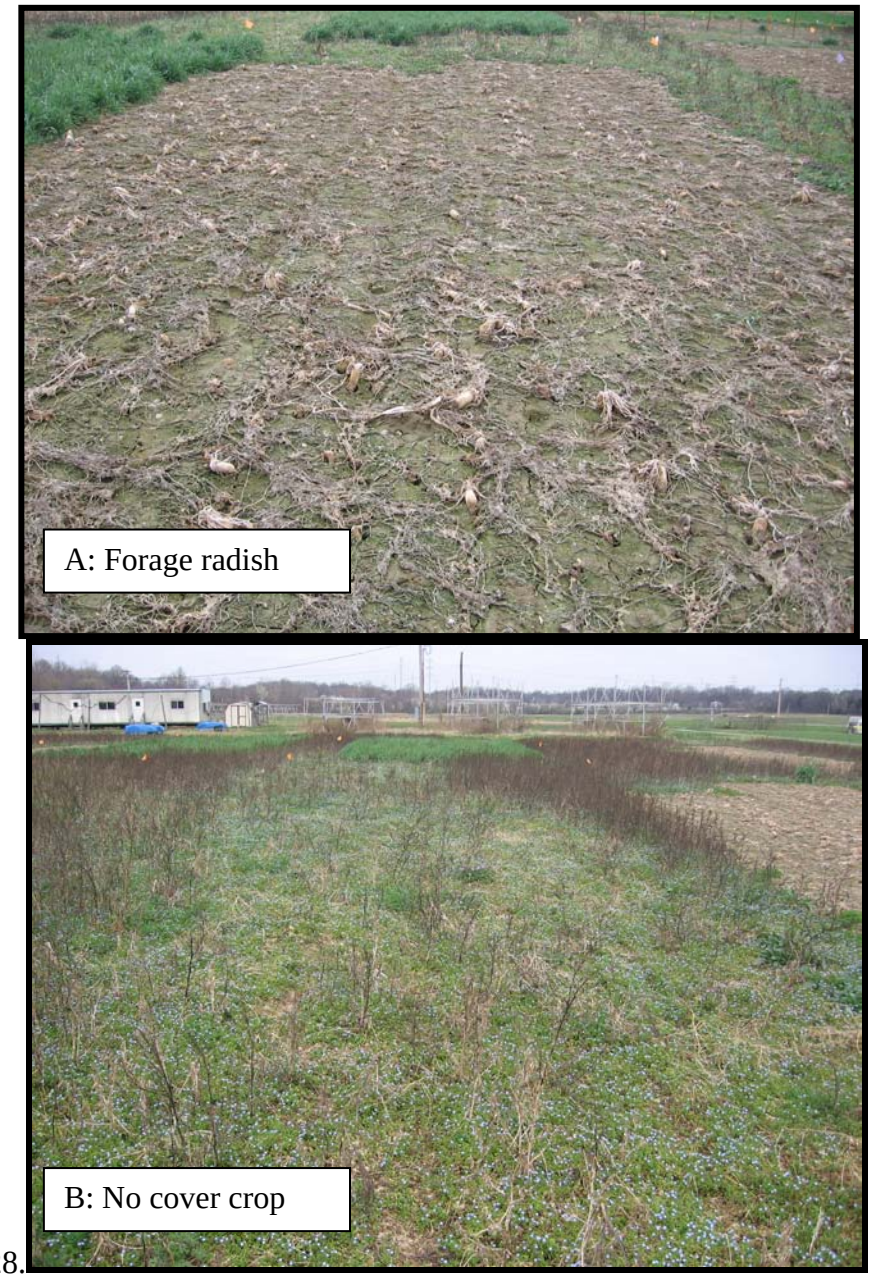

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Figure 3.2: No weed cover following forage radish cover crops (A) on March 29th, 2007 at the Beltsville Agricultural Research Center South Farm (BARC-SF). No cover crop treatment was dominated by speedwell (*Veronica officinalis L.*), common chickweed (*Stellaria media* L. Vill), and henbit (*Lamium amplexicaule* L.)

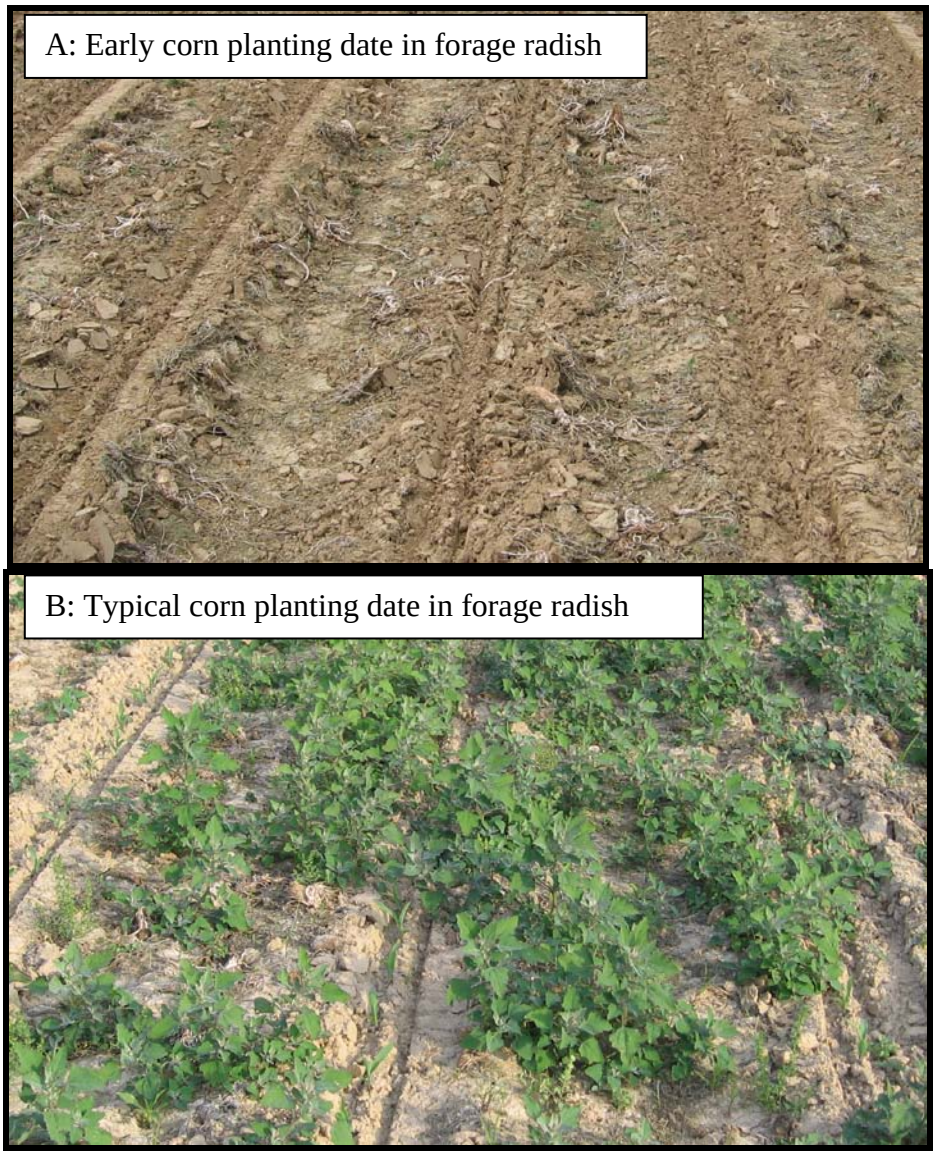

Figure 3.3: Lower weed cover on April 26, 2008 in early corn planting date (April 11) treatment compared to weed cover dominated by common lambsquarters on May 23, 2008 in the typical planting date (May 16) treatment.

Chapter 4: The mechanism of forage radish weed suppression

Abstract

In the Mid-Atlantic region, forage radish (*Raphanus sativus* L. var. *longipinnatus*) winter cover crops planted prior to 1 September suppress winter annual weeds from fall until early April. Little is known about the mechanism of this weed suppression. Previous research with other *Brassica* cover crops suggests that allelopathy and/or resource competition could play a role. Controlled environment bioassays involving cover crop amended soil, aqueous plant extracts, and aqueous soil extracts along with a field experiment involving planted weed seeds did not provide evidence of allelopathy. Rather, forage radish amended soils in soil bioassays and aqueous extracts of amended soil often stimulated seedling germination and growth. In residue moving experiments, no difference in spring weed suppression was observed if forage radish residues were removed prior to killing frost in November or left in place to decompose in three of four site-years. These results were supported by planting date experiments in which fall ground cover and spring weed suppression was greatest for earlier planting dates of forage radish cover crops. Thus, rapid and competitive fall growth, rather than allelopathy, is the most likely mechanism of weed suppression by forage radish winter cover crops.

Introduction

In the Mid-Atlantic region of the USA, forage radish winter cover crops planted prior to 1 September suppress winter annual weeds from fall through to early April (Chapter 3). This weed suppression may be utilized by farmers to provide preplant weed control for a subsequent crop while taking advantage of the other soil and nutrient benefits of cover crops (Chapter 3). In contrast to the repeatability of preplant weed suppression observed following forage radish winter cover crops in the coastal plain of Maryland (Chapter 3), researchers report that weed suppression by other cover crops and their residues is inconsistent (Forcella et al., 2003; Teasdale, 2003; Teasdale et al., 2007). Knowledge of the mechanisms involved could be used to improve cover crop management strategies to suppress weeds and help predict when alternative weed management strategies will be needed.

Little is known about the mechanism of weed suppression following forage radish winter cover crops. Similar winterkill-susceptible radishes planted in the late summer or early fall have been observed to suppress weeds in several field studies. Oilseed radish (*Raphanus sativus* L. var. *oleiformis*) winter cover crops suppressed winter annual weeds in vegetable rotations from fall planting until March/April in on-farm studies conducted in western New York (Stivers-Young, 1998). In Michigan, oilseed radish reduced early spring weed density and biomass prior to vegetable crops and also reduced recoverable weed seeds in the soil seed bank compared to a no cover crop control (Charles et al., 2006; Wang et al., 2008). In Ontario, Canada, oilseed radish also produced sufficient biomass in two of three site-years to suppress fall growth of volunteer winter wheat (*Triticum aestivum* L.) by 75 % (Swanton et al., 1996).

When planted by early August in the Netherlands, fodder radish (*Raphanus sativus* cv. Brutus) reduced fall weed biomass by 65 to 95% when grown as a fall cover (Kruidhof et al., 2008). However, fodder radish in this study had no effect on the natural weed population or lettuce (*Lactuca sativa* L.) and sugar beet (*Beta vulgaris* L.) test crops during May. No data were reported on earlier spring weed suppression. The authors suggested cover crop competitiveness, allelopathy, and reduced weed seed production as mechanisms for this weed suppression.

Several studies have supported allelopathy as the mechanism of weed suppression for *Brassica* cover crop species (Al-Khatib et al., 1997; Boydston and Hang, 1995; Krishnan et al., 1998; Turk and Tawaha, 2003). Haramoto and Gallandt (2004) as well as Boydston and Al-Khatib (2006) reviewed *Brassica* cover crops and weed management, focusing on allelopathy as the mechanism of this weed suppression, and on the hydrolysis products of glucosinolates as the allelochemicals responsible.

Glucosinolates are secondary plant metabolites commonly found in *Brassica* species. Glucosinolates are hydrolysed by the enzyme myrosinase into products with demonstrated biological activity against weed seeds, pathogens, insects, and nematodes (Brown and Morra, 1995; Brown and Morra, 1997; Chew, 1988). Isothiocyanates (ITCs) are reaction products that are volatile and short lived when released in soil (Al-Turki and Dick, 2003; Borek et al., 1996). ITCs have been shown to inhibit seed germination and seedling growth in a variety of weed and test crop species (Bialy et al., 1990; Brown and Morra, 1995; Brown and Morra, 1996; Petersen et al., 2001; Turk and Tawaha, 2003)

Forage radish and other radish cover crops in the *Brassica* family behave differently than many of the other *Brassica* cover crops when planted as cover crops in

the fall. Forage radish is sensitive to frost and winterkills with prolonged exposure to temperatures below -4 ^{o}C (Weil et al., 2009). Forage radish cover crop residue decomposes rapidly during the freeze-thaw cycles that characterize winters in the Mid-Atlantic region, leaving little residue on the soil surface the following spring. Because of this rapid decomposition, forage radish cover crops create a unique low residue and weed-free seed bed for planting in the early spring.

These characteristics of forage radish cover crops also create challenges for studying the mechanism of forage radish weed suppression. In the Mid-Atlantic, forage radish shoots are first damaged by frost in late November or early December but shoots re-grow until the growing point, often protected by surrounding foliage, is finally damaged by colder temperatures in January or February. Thus it is difficult to define a distinct termination date, control the termination event, or create one treatment event with the potential to release a single high dose of allelochemicals.

The objective of this study was to determine the mechanism(s) of observed weed suppression by forage radish cover crops. Three main mechanisms of weed suppression were hypothesized: 1) allelopathy, 2) competitive fall growth, and 3) altered soil conditions that influence weed germination and emergence. Five experiments were conducted including both controlled environment and field experiments. Controlled environment bioassays involving cover crop amended soil, aqueous plant extracts, and aqueous soil extracts along with a field experiment involving planted weed seeds were used to evaluate allelopathic potential of forage radish. Field experiments to compare the effects of competitive fall growth and allelopathy, involved manipulated cover crop

residues and planting dates. The effects of cover crop residues on spring soil conditions were also monitored.

Materials and methods

Site description and field management

All field experiments were conducted over a four year period at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF) in the coastal plain of Maryland (Table 4.1). Plant and soil samples for laboratory and growth chamber bioassays were collected from these field experiments. All fields included in this project have a history of conventional tillage and crop rotation that included corn, soybean, vegetable crops, winter wheat and cover crops such as hairy vetch and winter rye.

The experimental design for all field experiments was a randomized complete block with four replicates. Pre-plant incorporated fertilizer applications made to ensure adequate cover crop nutrition and growth are summarized in Table 4.2. Lime was applied to Field-B and Field-A at a rate of 2.5 Mg ha^{-1} $CaC0_3$ prior to starting the experiment to raise soil pH to a target of 6.5.

Forage radish (*Raphanus sativus* L. var. *longipinnatus*) cover crop treatments were compared to no cover crop treatments in all experiments and a spring oat (*Avena sativa* L. cv. Ogle) cover crop treatment in 2005. Cover crops were seeded using a conventional grain drill with disk openers and 18 cm row spacing. With the exception of the forage radish planting date study (Experiment 5), all cover crops were seeded in late August (Table 4.2). Forage radish was seeded at a rate of 14 kg ha^{-1} and oat at 90 kg ha^{-1}.

Irrigation was used to stimulate cover crop germination in 2005 when conditions were unusually dry. The 2005 oat cover crop had reached panicle emergence by the time it was killed by frost in late November. Forage radish cover crops grew vegetatively in the fall until they were damaged by frost in mid to late November and gradually winter-killed with progressively cold temperatures in January and February.

Experiment 1: Aqueous plant and soil extracts

Plant sample harvest and preparation

Forage radish root, forage radish shoot, and oat shoot samples were harvested from field Field-A on 7 Nov, 2005 prior to frost damage. Mean biomass of sampled cover crops was 4457 kg ha^{-1}, 2319 kg ha^{-1}, and 7404 kg ha^{-1} for forage radish shoot, forage radish roots, and oat shoots respectively. Winterkilled plant residue samples were collected on 24 March, 2006. All plant shoot, root, and residue samples for both sampling dates were washed to remove soil, dried at 65 ^{o}C for two weeks, ground(<2 mm), and stored at 4 ^{o}C.

Soil sample collection and preparation

Soil samples from 0-5 cm depth were collected on 28 March and 30 May, 2006 below decomposing forage radish and oat residues as well as from the no cover crop control in Field-A. Samples were homogenized in the field to form one composite sample for each cover crop treatment. Soil samples were collected in the morning and kept on ice until they were extracted in the afternoon. The gravimetric soil water content at sampling was determined with a microwave (Weil, 2005).

Extract preparation and incubation

The extraction and incubation procedure was modified from Rice et al. (2005). Aqueous extractions of plant samples were prepared at 4 ^{o}C by shaking 15 g of dried ground plant material with 150 ml of distilled water at 100 rpm for 1 hour in a glass Erlenmeyer flask covered with parafilm. Soil extracts were prepared in a similar manner using field moist soil equivalent to 15 g of dry soil in 150 ml of distilled water. The slurry was filtered through six layers of cheese cloth and centrifuged (3040 x g) for ten minutes at 4 ^{o}C. The supernatant solution was filtered by Whatman #3 filter paper and then a 0.025 μm nylon membrane filter. Extract filtrate was kept on ice during filtration and prepared in dilutions with distilled water to extract:water proportions of 0.125, 0.25, 0.5, and 1.0 (full strength extract). Electrical conductivity of the crude extract was determined using a conductivity dip cell on samples that had been stored in the freezer and thawed at 4 ^{o}C for 24 hours.

Fifty lettuce seeds were placed on top of Whatman #1 filter paper moistened with 2.5 ml of extract in each of four replicate 100 mm diameter x 15 mm deep petri dishes. Petri dishes were sealed with parafilm and incubated for 48 hours at 25 ^{o}C on trays set at a 45° angle to allow geotropism to facilitate seedling measurements. After 48 hours of incubation, seed germination was assessed. Shoot and root length were measured on 10 randomly chosen seedlings. Relative root length was calculated as:

$$\text{Relative root length} = (RL_t / RL_c) \times 100$$

Where RL_t is the length in mm of the root in the treatment and RL_c is the length of the root for the control treatment for each replicate.

Experiment 2: Soil bioassay

Soil sampling and sample preparation

Soils for this bioassay were collected from fields Field-B and Field-E (Table 4.1 and Table 4.2). Mean forage radish biomass accumulation on 6 November, 2006 for Field-B was 4262 kg ha^{-1} and 1338 kg ha^{-1} for forage radish shoots and forage radish roots, respectively. Biomass accumulation for Field-E was 5046 kg ha^{-1} and 1138 kg ha^{-1} for forage radish shoots and forage radish roots, respectively, on 6 November, 2006.

Twenty soil cores 5 cm in diameter and 5 cm deep were collected from surface soils in each replicate of forage radish and no cover crop treatments in each field. Soil cores from each plot were composited and stored in a cooler on ice in the two fields. Soils were sampled on 18 January, 2006, 28 February, 2007, and 30 March, 2007 representing early, intermediate, and late stages of cover crop residue decomposition.

Fifty lettuce (*Lactuca sativa* L. cv. Great Lakes) and tomato seeds (*Solanum lycopersicum* L. cv. Rutgers) seeds were each placed above 300 g of field moist soil in a 10 cm long x 8 cm wide x 10 cm deep plastic pot and covered by an additional 100 g of soil. Soil from each field plot was potted and sub samples were reserved to determine gravimetric soil moisture content and soil nitrate content using the salicylic-acid method (Cataldo et al., 1975). Soil samples had to be air dried for a period of 24 hours at room temperature on 28 February because they were too wet for potting.

Incubation, germination, and biomass

The potted seeds were incubated for five weeks in a growth chamber at 23 ^{o}C, 50 % relative humidity, and 17 hours day^{-1} of light at an average light intensity of 250 photons m^{-2} ms^{-1}. To reduce the possibility of water soluble allelochemicals being

leached through the soil, the pots were watered using capillary rise from water maintained in a saucer below each pot. Pots were arranged in the growth chamber in a pattern that reflected the randomized complete block design of the field experiment where the soil samples were collected.

Germination counts were made weekly. At the end of the first week, seedlings were thinned to eight plants. Those eight plants were thinned to four at the end of two weeks. Any additional lettuce or weed seeds that emerged were counted and pulled. At the end of the five week study, the four seedlings were cut and their aboveground biomass was dried and weighed. Data were analyzed by ANOVA using the Mixed model procedure of SAS version 9.1 (SAS Institute, Cary, NC). Data for lettuce and tomato were analyzed separately. Comparisons were made between pairs of cover crop treatments within sampling date and site. Cover crop treatments were considered fixed effects and block was considered random. When the ANOVA indicated significant differences between cover crop treatments ($P < 0.05$), mean comparisons were made using Fisher's Least Significant Difference test.

Experiment 3: Planted weed seed emergence

After forage radish cover crops were initially damaged by frost and oat cover crops were winter-killed, 2.2 ml of each of the following weed seeds were sown under cover crop residues in individual 1 m rows between rows of cover crops (19 cm spacing) on 5 January, 2006. The weeds planted were common chickweed (*Stellaria media* (L.) Vill.), fall panicum (*Panicum dichotomiflorum* Michx.), green foxtail (*Setaria viridis* (L.) Beauv.), henbit (*Lamium amplexicaule* L.), horseweed (*Conyza canadensis* (L.) Cronq.), common lambsquaters (*Chenopodium album* L.), redroot pigweed (*Amaranthus*

retroflexus L.) and common ragweed (*Ambrosia artemisiifolia* L.). Lettuce (*Lactuca sativa* L.) was also planted because it was being used as a test species in other experiments. In 2008, common lambsquarters seeds were planted on 1 February in a similar manner into forage radish and no cover treatments in existing experiments in Field-C at the North Farm and Field-F at the South Farm (Table 4.1).

Weed seed emergence counts were taken on a weekly or biweekly basis from January through June and seedlings were pulled after counting. Plots were weeded by hand between rows of planted weed seeds. Volume rather than seed number was chosen as the measure for spreading seeds due to the fine nature of horseweed seeds that made them impractical to count.

Statistical analysis

Mean cumulative weed emergence and standard deviation was calculated using the Means procedure of SAS. Data for common lambsquarters emergence were analyzed by ANOVA in the Mixed procedure of SAS. In the model, blocks were considered random factor and cover crop treatment was considered a fixed factor. Data for each site-year was analyzed separately.

Experiment 4: Residue moving

The residue moving experiment was conducted at Field-B and Field-E in 2006 and Field-C and Field-F in 2007 (Table 4.2). Forage radish was planted over the plot area on 31 August, 2006 and 28 August, 2007 at both locations. Weeds were controlled in the no cover crop treatments by hand hoeing on 14-15 September, 2006, and by spraying glyphosate (N-(phosphonomethyl)glycine) (1.12 kg ha^{-1} a.i.) on 3 October, 2007. The experimental design was a randomized complete block with four replicates. Plot size was

3 m by 3 m. All residue moving treatments and treatment codes are described in Table 4.3. Two no cover crop treatments were included as control treatments: 1) weedy no cover crop treatments (NO-weedy) that did not get weeded for the duration of the experiment, and 2) fall-weeded no cover crop treatments (NO-fall weeded) that were hand weeded in October, and November. No cover crop plots that received additions of forage radish residues (NO-S_1R_1 and NO-S_1R_0) were weeded prior to treatment imposition in 2007 but not in 2006.

Residue treatments (Table 4.3) were imposed prior to a killing frost on 13 November, 2006 and 14 November, 2007. Cover crop biomass was measured at the time of residue treatment establishment (Table 4.4). Tarps and boards were used by workers to limit soil compaction when removing cover crop residues from the plots. Where forage radish plants were removed, the fleshy taproot was pulled from the ground with care taken to minimize soil disturbance. Visual ratings of percent weed ground cover was rated periodically in spring to evaluate weed suppression.

Statistical analysis

Data were analyzed by ANOVA using the Mixed procedure of SAS. Separate analyses were conducted for each rating period. Data from the two seasons were run in separate analyses due to unbalanced treatments between 2007 and 2008. In the model, block was considered a random effect within site. Cover crop treatment and site were considered fixed effects. A natural log transformation was used prior to analysis to improve homogeneity of variances. Back-transformed means were reported. When the ANOVA indicated significant differences between cover crop treatments ($P < 0.05$), mean comparisons were made using Fisher's Least Significant Difference test.

Experiment 5: Cover crop seeding date

Site management and field sampling

Weed suppression of forage radish cover crops was evaluated in four seeding date trials in 2007-08 and 2008-09, for a total of four site-years. These trials were located in Field-A, Field-B, Field-F, and Field-E. Forage radish cover crops were planted every seven days in 2008 from 28 August to 27 September. In 2009, forage radish was planted every ten days from 27 August to 13 October. Treatments were replicated four times and a no cover crop control treatment was included in the randomized complete block experimental design. All fields were tilled prior to establishing the experiment. In 2009, individual plots were also tilled prior to each cover crop seeding date to ensure a weed-free seed bed for each seeding date. Percent weed cover was rated in late March to evaluate the influence of cover crop seeding date on the ability of forage radish cover crops to suppress weeds.

Soil moisture and temperature following forage radish cover crops

Surface soil moisture and temperature were measured in forage radish and no cover crop treatments. Measurements were taken from March till May in all four reps of forage radish and no cover crop treatments for existing experiments in fields Field-B (2006) and Field-A (2007) at the North farm and field Field-E (2006) at the South farm of the Beltsville Agricultural Research Center in Beltsville, MD. Thermistor temperature sensors sealed in epoxy (Irrometer, Riverside, CA) were installed horizontally 2 cm below the soil surface and granular matrix soil moisture tension sensors (Watermark Sensors, Irrometer, Riverside, CA) were installed horizontally 5 cm below the soil surface. One of each type of sensor was installed in each of the two cover crop plots per

block. All sensors for one block were connected to the same data logger (Watermark Monitor 900M, Irrometer, Riverside, CA) that recorded every hour. Soil moisture and temperature data presented is the daily mean of three or four replicates, due to occasional sensor malfunction.

Results and discussion

Experiment 1: Aqueous plant and soil extracts

Plant tissue extracts

Lettuce seed germination and relative root length increased with the dilution of the full strength plant tissue extracts for all tissues sampled in November 2005 (Figure 4.1). The largest decline in relative germination occurred in forage radish root and shoot tissue extracts in proportions at or above 0.5 of the full strength extract. For extracts prepared from plant residues collected in March, lettuce germination declined only in full strength extracts prepared from forage radish root and shoot tissues. Extracts prepared from plant residue in March had a stimulatory effect on the relative root length of lettuce seedlings at extract proportions of 0.125 and 0.25 (Figure 4.1). Plant tissue extracts had little effect on the relative shoot length of lettuce in both November and March (data not shown).

Although these results might suggest allelopathic potential, it is likely that the negative effects of full-strength forage radish and oat extracts on lettuce germination and root growth were due to increasing salinity of the extract solutions (Table 4.5). Generally there was a trend of decreasing lettuce seed germination and root length with increasing electrical conductivity, with a threshold between 2-4 dSm^{-1} (Figure 4.2). Previous studies

have shown lettuce to be moderately sensitive to salinity with an initial threshold for yield decline at an electrical conductivity of 1.3 dS m^{-1} (Shannon and Grieve, 1999).

Extracts of both forage radish shoot and root tissues were included in the experiment to identify potential differentiation of the location of allelopathic compounds. However, this differentiation was not observed. Despite the very pungent odor and dark color of the forage radish root extract, both shoot and root tissues of forage radish had similar effects on lettuce. Both types of tissue extracts also had high electrical conductivity (Table 4.5). The root shoot tissue extract had a higher electrical conductivity and more inhibitory effect on lettuce seedlings than the shoot tissue extract. Oat was included as a treatment because it is another frost sensitive cover crop that is also reported to have allelopathic properties (Inderjit and Keating, 1999). Lettuce root response to oat tissue and residue extracts was similar to that of forage radish shoot extracts.

Soil extracts

Soil extracts were included in this experiment to test for potential retention of allelochemicals in the soil that could have a residual effect on weed seed germination and seedling growth. As forage radish tissues are not typically incorporated into the soil, it was thought that soil extracts might provide a more realistic bioassay treatment than those prepared from plant tissues. It was hypothesized that soil sampled beneath decomposing forage radish residues would decrease lettuce seed germination as well as root and shoot growth. It was also hypothesized that these effects would be greater in March, when weed suppression was observed, than in May, when there was no weed suppression (Chapter 3). Neither of the extracts prepared from cover crop amended soil

had a negative effect on lettuce. Both cover crop treatment extracts as well as the no cover crop control extract had a stimulatory effect on lettuce root length relative to the distilled water control in March and May (Figure 4.3). Unlike extracts prepared from plant tissues, relative root length of lettuce seedlings increased with increasing soil extract proportion. The soil extracts had very low EC, of less than 0.1 dS m^{-1}. None of the soil extracts had an effect on relative shoot length or lettuce seed germination (data not shown).

These results suggest that there were no alleochemicals present in the soil extracts and that non-cover crop factors were the cause of lettuce stimulation, such as nutrients released by organic matter decomposition or from the soil cation exchange. Results from the bioassay of plant tissue extracts can be explained by high EC levels, and thus only weakly suggest any potential for allelopathy. Certainly the results of the soil extract bioassay suggest that any inhibitory affect, whether due to allelopathy or osmotic potential, were not realized in the soil. Thus, aqueous extract bioassays did not present strong evidence in support of the allelopathy hypothesis for the occurrence of weed suppression following forage radish winter cover crop.

Experiment 2: Soil bioassay

Seed germination and seedling biomass

Much allelopathy research has overlooked the soil factors influencing the movement and availability of allelochemicals to interact with weed seeds in the soil (Inderjit, 2001). It was hypothesized that if forage radish was allelopathic, lettuce or tomato germination and seedling growth would be reduced in soils sampled below decomposing forage radish residues relative to a no cover crop control. It was also

hypothesized that the allelopathic effects of forage radish cover crops would be greater in January than in March. However, neither of these trends was observed. In all but one case, the significant differences between no cover crop and forage radish treatments, indicated a stimulatory effect of forage radish, rather than an inhibitory effect, causing improved lettuce seed biomass or tomato seed germination (Figure 4.4). Tomato seed germination was higher in forage radish treatments relative to the no cover crop control in January and March for soils sampled at Field-E. Lettuce seedling biomass was greater in forage radish treatments than in the no cover crop control in both January and February. These stimulatory effects of forage radish on lettuce and tomato agree with the findings of Experiment 1, using aqueous soil extracts of soils, and do not provide evidence to support the hypothesis that allelopathy was the mechanism of weed suppression by forage radish.

The stimulation of tomato seed germination and lettuce seedling biomass in forage radish treatments could be due to the higher nitrate content of the soil sampled from the forage radish treatment (Figure 4.5). By the time forage radish cover crops finally winter-killed, wet conditions made soil sampling and potting a challenge. Overall, lettuce and tomato seed germination was lower than expected, even in the control treatment, possibly due to wet conditions associated with the soils being water saturated at the time of sample collection (Figure 4.5) as well as the bottom-watering regime during the incubation. Taller pots might have provided a better balance of air and water filled pores when bottom watering during the bioassay.

A further limitation of this experiment is the change in temperature and moisture between the field and the germination test chambers which could have caused loss of

volatile allelochemicals, such as many ITCs. Petersen et. al. (2001) conducted soil bioassays to evaluate the allelopathic effect of turnip-rape (*Brassica rapa* (*Rapifera* Group)-*Brassica napus* L.) mulch and identified ITCs present in both the plant tissue and soil. The ITC concentration in their study was 2,300 times lower in the soil than in plant tissues and their disappearance from the soil was enhanced by saturated soil conditions and high temperatures. Sampling of soil for the bioassay also resulted in the separation of soil and plant residues, the potential source for a continued supply of newly forming ITCs as these residues decomposed.

Experiment 3: Weed seed bioassay

Weed and lettuce emergence was not suppressed by forage radish relative to the no cover crop control or the oat cover crop treatment (Figure 4.6). Weed emergence was higher in the forage radish treatment for several of the weeds species planted, including common chickweed, common lambsquarters, redroot pigweed, and common ragweed. Emergence of lettuce occurred much earlier (February) in forage radish treatments than the other two treatments (April) (Figure 4.6).

In the Netherlands, field bioassays with fodder radish winter cover crops did not detect any allelopathic effect on emergence of lettuce or sugarbeet (*Beta vulgaris* L.) test crops (Kruidhof et al., 2008). Brown and Morra (1996) observed delayed germination of lettuce seeds when exposed to water-soluble extracts of rapeseed plant tissues. However, field bioassays conducted by Haramoto and Gallandt (2005) did not find consistent reductions or delays in lettuce or tomato seed germination following rapeseed, mustard, or canola cover crops in Maine.

Stimulation of lettuce and weed seed emergence may have been due to higher soil nitrate levels in the forage radish treatment (Figure 4.5). Some weed species, such as common lambsquarters, use nutrients as a signal to promote germination (Bouwmeester and Karssen, 1993). Following further observations of increased common lambsquarters emergence from the natural weed seed bank in other field experiments (Chapter 3), common lambsquarters was introduced into two subsequent field experiments. The results of these field bioassays agree with these earlier observations in two out of three site-years (Figure 4.7).

The behavior of winter annual weed species observed in this bioassay contrast with the results of other field experiments (Chapter 3). In field experiments, it was observed that forage radish cover crops delayed emergence of winter annual weeds relative to no cover crop (Chapter 3). One of the differences between these field experiments and the field bioassay was the timing of weed seed introduction and spring vs. fall germination of weeds. Due to the freeze-thaw nature of winters in Maryland, the date for spreading weed seeds in this field bioassay was a compromise between two needs: 1) planting weed seeds early enough to get the best treatment exposure to the cover crop residues as they winterkill and 2) planting weed seeds when it was cold enough to prevent some species from germinating prior to sufficient exposure to cover crop residues.

In the field bioassay, winter annual weeds in both forage radish and no cover control plots were forced to establish in the spring, whereas they naturally would establish during the fall in the no cover crop plots. This introduction date also meant that

planted weeds in the forage radish treatment were influenced only by residue decomposition and not by the fall cover crop growth.

The results of this bioassay agree with several findings of the aqueous soil extract and soil bioassays. Forage radish stimulated the emergence of some weed seeds in the field bioassay, increased biomass production for some seedlings in the soil bioassay, and increased lettuce root length in the soil extract bioassay. Together, the results of these three experiments suggest that allelopathy is not a likely mechanism for forage radish weed suppression.

Experiment 4: Residue moving

To compare the influence of competitive fall growth to the influence of decomposing forage radish residues on spring weed emergence, forage radish cover crop residues were removed and transferred to no cover crop control areas (Table 4.3). As observed in other field experiments (Chapter 3), weed suppression following forage radish in all four site-years of this experiment was greater in forage radish treatments relative to no cover crop controls in March but not in April (Table 4.6). It was hypothesized that removing forage radish shoot and fleshy root tissues prior to a killing frost would decrease spring weed suppression if forage radish had allelopathic activity. It was also hypothesized that adding forage radish tissues to a no cover crop area would provide increased spring weed suppression following residue decomposition if forage radish had allelopathic activity.

Regardless of whether forage radish residues were removed prior to killing frost in November (FR-S_0R_0) or left in place to decompose (FR-S_1R_1), there was no difference between these two treatments in three of four site-years (Table 4.6). Adding forage radish

residues to no cover crop plots (NO-S_1R_1) resulted in an increase in weed cover compared to forage radish (FR-S_1R_1) in three of four site-years (Table 4.6). Equivalent amounts of forage radish biomass were present in both treatments but the architecture of cover crop residues was different. Forage radish roots and shoots added in NO-S_1R_1 were placed on the soil surface rather than inserted back into the soil. Thus root tissue was decomposing on top of the soil surface rather than in the large root channels. Despite differences in architecture, rapid residue decomposition in both treatments left little potential for physical weed suppression by residues the following spring.

Doubling forage radish residue (FR-S_2R_2) did not increase weed suppression in either early spring or at planting time (Table 4.6). Two treatments, FR-S_0R_1 and NO-S_1R_0, were included to identify potential differences in plant tissues containing allelochemicals. Percent weed cover was at least 20 % higher in the early spring following NO- S_1R_0 compared to FR-S_0R_1 in the spring of 2007. However, the most important comparisons for these treatments are to their relative controls over two site-years. NO-S_1R_0 was not statistically different than NO-S_1R_1. There was no difference between FR-S_0R_1 and FR-S_1R_1over two site-years. These comparisons suggest that there was no difference in the effect of root vs. shoot tissue on weed suppression.

The treatment NO-fall weeded provided the opportunity to evaluate weed emergence following the imposition of other residue moving treatments. Weed emergence in NO-fall weeded began after the last fall weeding in late November and continued through the winter. Thus, percent weed cover was higher in the fall-weeded no cover crop treatment the following spring than all forage radish treatments by as much as 20 %. These differences may have been due to soil disturbance as a result of the weeding

or due to the absence of a closed weed canopy that would interfere with light signals to break weed seed dormancy and stimulate emergence to the same degree as the forage radish canopy.

The results of this experiment provide evidence that the competitive fall growth of forage radish cover crops play a more important role in forage radish weed suppression than allelopathy. The residue moving experiment builds upon the findings of previous controlled environment and field studies in suggesting that allelopathy was not the mechanism behind forage radish weed suppression.

Effect on soil conditions

Only small differences in spring daily maximum and minimum soil temperatures were observed between forage radish and no cover crop treatments relative to soil conditions in no cover crop plots (Figure 4.8). Average daily soil moisture tended to be slightly dryer in forage radish cover crop plots than in no cover crop treatments (Figure 4.8). The residue of forage radish decomposes quickly in the early spring. Given that only small amounts of forage radish residue remain in the spring, it is not surprising that forage radish had relatively small effects on spring soil moisture and temperature conditions relative to no cover crop treatments. This soil data suggests that alteration to spring soil conditions is not a major mechanism of early spring forage radish weed suppression.

Experiment 5: Cover crop planting date

If competitive fall growth was the mechanism behind forage radish cover crop weed suppression, it was hypothesized that cover crop planting date would influence spring weed suppression. In an experiment designed to identify the optimum seeding date

of forage radish cover crops, ratings of fall cover crop ground cover and spring weed suppression were taken for four site-years. In the fall of 2007, there was no difference in percent fall cover crop ground cover among all cover crop planting dates due to a long and unseasonably warm fall (Figure 4.9). The following spring, weed suppression was still higher for earlier planting dates of forage radish cover crops at Field-A (Figure 4.9).

At both sites in the 2008 -09 season, later planting dates and associated lower fall cover crop ground cover resulted in higher percent ground cover by weeds the following March (Figure 9). However, weed cover was lower for the last planting date in the 2008-09 season. This seeding date was past the optimum for peak fall weed emergence and establishment. In 2008, cultivation was used prior to each cover crop planting date. Little time was left with suitable conditions for weed germination for this last planting date. This decline was not observed in the 2007-08 season as seeding concluded 17 days prior to the 2008-09 season and weeds were not controlled prior to each planting date.

In similar experiments with oilseed radish, Stivers-Young (1998) found no-measureable spring weed biomass following early plantings (25 August/ 3 September) and 115 to 150 kg ha^{-1} of weed biomass after later plantings (8 September/16 September) in western New York. In their experiment, the dominant weed species suppressed were henbit, malva (*Malva moschata* L.), and common chickweed. Kruidhof et al. (2008) compared the rate of canopy development to intercept light to the ability of six winter cover crop species to suppress weeds in the Netherlands. Early canopy development that brought about rapid reductions in light interception was more important for weed suppression than later canopy development. In two of the three experiments conducted by Kruidhof et al. (2008), two species that were similar to forage radish (fodder radish and

oilseed radish) had the most rapid canopy development to reduce light penetration through the canopy.

The findings of these two studies support the results of this forage radish seeding date experiment, as earlier planting dates that had earlier developing canopies also had the greatest ability to suppress weeds. Weed suppression was higher for earlier planting dates of forage radish cover crops in all four site-years. The results of this experiment support the hypothesis that fall competition is the mechanism behind the suppression of weeds following forage radish cover crops.

Conclusions

In the Mid-Atlantic forage radish winter cover crops planted prior to 1 September suppress winter annual weeds from fall planting until early April. The objective of this study was to identify the mechanism of forage radish weed suppression. Experiment 1 involving aqueous extracts of cover crop tissues, residues, and amended soil did not reveal any allelopathic activity that would limit seed germination or seedling establishment. The results of the soil bioassay in Experiment 2 also supported this conclusion. In fact, forage radish amended soils in both the soil bioassay and the aqueous extracts of amended soil stimulated seedling growth in both experiments. These results also agreed with the findings from Experiment 3, where forage radish cover crops did not inhibit emergence of winter-planted weed seeds in the field relative to a no cover crop control. Again, forage radish amended soil stimulated emergence of lettuce and common lambsquarters.

Experiments 4 and 5 involving residue moving and forage radish seeding dates targeted the competitive fall growth of forage radish cover crops. The growing cover crop canopy intercepts short-wave radiation, reduces the amount of light reaching the soil surface, the heat absorbed by the soil, and the evaporation of soil moisture (Teasdale, 2003; Teasdale et al., 2007). Light and alternating temperatures are signals used by weed seeds to identify favorable periods for germination and emergence (Baskin and Baskin, 2001). Weed seeds may have either a narrow or wide range of conditions that define their germination requirement. Cover crops and their residues may influence soil conditions and can influence the occurrence of the conditions (Teasdale and Daughtry, 1993). However, there was relatively little difference in soil moisture and temperature between forage radish and no cover crop treatments.

Cover crops may suppress weeds both while growing and/or during residue decomposition after they have been terminated. It is possible that more than one factor contributed to weed suppression following forage radish cover crops. Controlled environment bioassays involving cover crop amended soil and aqueous extracts along with field experiments utilizing planted seeds and natural weed seed banks did not provide evidence that allelopathy was the mechanism of weed suppression following forage radish winter cover crops in the Mid-Atlantic. Although it is not possible to eliminate allelopathy as a potential mechanism of forage radish weed suppression, results from the residue moving experiment and planting date experiment provided support that early and competitive fall growth of forage radish is the dominant mechanism for weed suppression. Thus, cover crop management strategies to maximize weed suppression following forage radish cover crops should ensure that crop rotations allow for early

planting of forage radish cover crops. If factors such as drought, low soil fertility, or early frost limit the rapid canopy development of forage radish winter cover crops in the late summer or early fall, alternative preplant weed control may be required the following spring.

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Table 4.1: Location and selected soil properties for experiments at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF).

Farm	Field	Latitude	Longitude	Soil Series	Soil Taxonomy Subgroups	Surface soil textural class	Soil organic matter (%)
BARC-NF	Field-A	39° 01’ 51” N	76° 55’ 58” W	Matawan-Hammonton	Aquic Hapludults	loamy sand	1.3
	Field-B	39° 01’ 52” N	76° 55’ 59” W	Matawan-Hammonton (Rep 1, 2) Ingleside-Hammonton (Rep 3, 4)	Aquic Hapludults, Typic Hapludults	loamy sand	2.0
	Field-C	39° 01’ 53” N	76° 56’ 01” W	Matawan-Hammonton (Rep 1, 2) Ingleside-Hammonton (Rep 3, 4)	Aquic Hapludults, Typic Hapludults	loamy sand	2.0
BARC-SF	Field-E	39° 00’ 51” N	76° 56’ 30” W	Codorus	Fluvaquentic Dystrudepts	silt loam	1.5
	Field-F	39° 00’ 48” N	76° 56’ 27” W	Codorus	Fluvaquentic Dystrudepts	silt loam	2.2

Table 4.2: Management history and cover crop planting dates for experiment sites at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF).

Location	BARC-NF					BARC-SF		
Field	Field-A		Field-B		Field-C	Field-E		Field-F
Year	2005-06	2007-08	2006-07	2008-09	2007-08	2006-07	2008-09	2007-08
Previous crop	sweet corn	fallow	fallow	fallow	fallow	fallow	corn silage	fallow
Fertilizer (N, P_2O_5, K_2O kg ha^{-1})	45, 40, 75	85, 0, 0	100, 18,50	20, 0, 0		61, 18, 83	90, 0, 0	85, 0, 0
Cover Crop Planting	25 Aug	several†	31 Aug	several	28 Aug	31 Aug	several	28 Aug

† Experiment 5: forage radish planting date study

Table 4.3: Residue treatments for Experiment 4.

Treatment ID	Fall cover crop	Treatment description
FR-S_0R_0	Forage radish (FR)	Shoots and fleshy tap roots removed
FR-S_1R_1		Shoots and roots remain in place
FR- S_2R_2		Add shoots and fleshy tap roots to an existing stand
FR- S_0R_1		Remove shoots only, roots remain
NO- S_1R_1	No cover crop (NO)	Add shoots and fleshy tap roots to plot with no growing forage radish
NO- S_1R_0		Add shoots only to plot with no growing forage radish
NO-weedy		No cover crop, weeds never controlled
NO-fall weeded		No cover crop, weeds periodically removed by hand in fall

Table 4.4: Mean fall dry matter of forage radish shoot and fleshy root tissue used to create residue moving treatments in November at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF) in 2006 and 2007.

Year	Location	Field	Forage radish shoot (kg ha^{-1})	Forage radish root (kg ha^{-1})
2006	BARC-NF	Field-B	6883	2581
		Field-C	4104	1499
2007	BARC-SF	Field-E	5495	1971
		Field-F	4103	2363

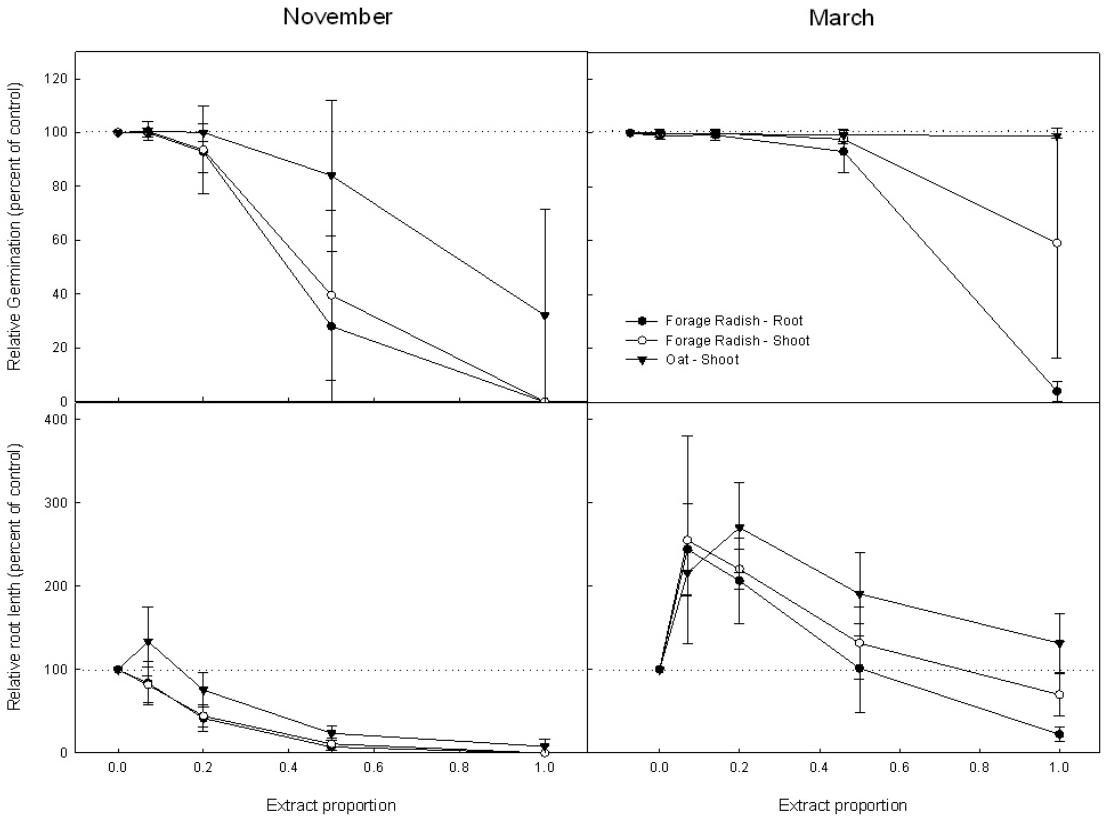

Figure 4.1: Relative germination and root length of lettuce (*Lactuca sativa* L.) seedlings grown in aqueous plant tissue extracts. Germination and root lengths are expressed as a percent of the distilled water control. Extracts were prepared from fresh forage radish shoot, forage radish root, and oat shoot tissues collected on 7 Nov, 2005 and from plant residues collected on 24 March, 2006. Bars represent standard deviation.

Table 4.5: Electrical conductivity (EC) of extracts prepared from plant tissues harvested on 7 Nov, 2005 and plant residues harvested on 24 March, 2006.

Cover crop	Plant tissue	Extract proportion	EC (ds m^{-1})	
			November	March
Forage radish	Root	1	8.72	9.47
Forage radish	Shoot	1	6.73	2.49
Oat	Shoot	1	2.86	1.71
Distilled water control	-	1	0.0121	0.00612

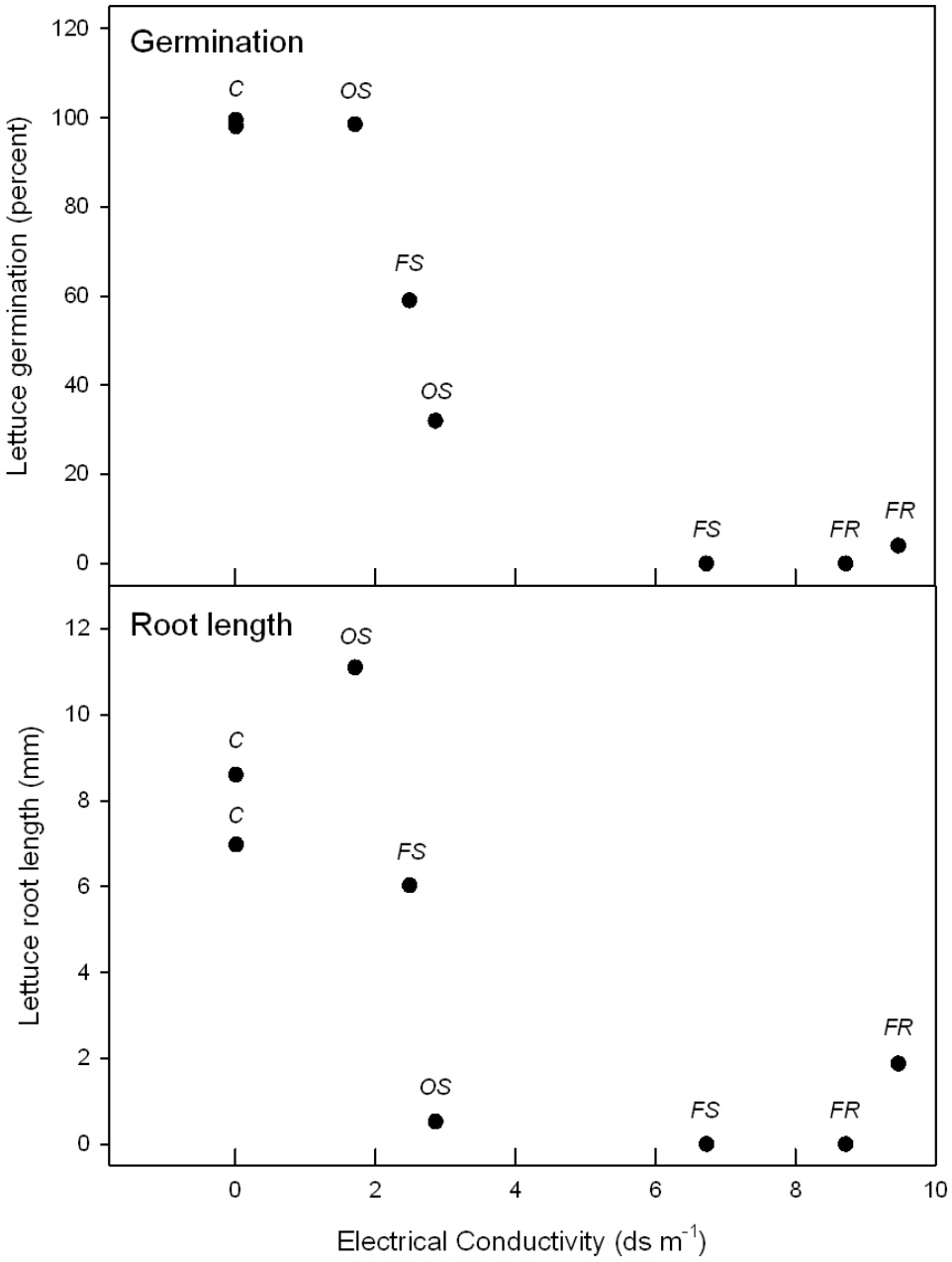

Figure 4.2: Relationship between lettuce (*Lactuca sativa* L.) performance and electrical conductivity of aqueous plant tissue extracts and a distilled water control. Extracts were prepared from forage radish root (FR), forage radish shoot (FS), and oat shoot (OS) and compared to a distilled water control (C). Plant tissues were harvested November 7, 2005 and residues harvested March 24, 2006.

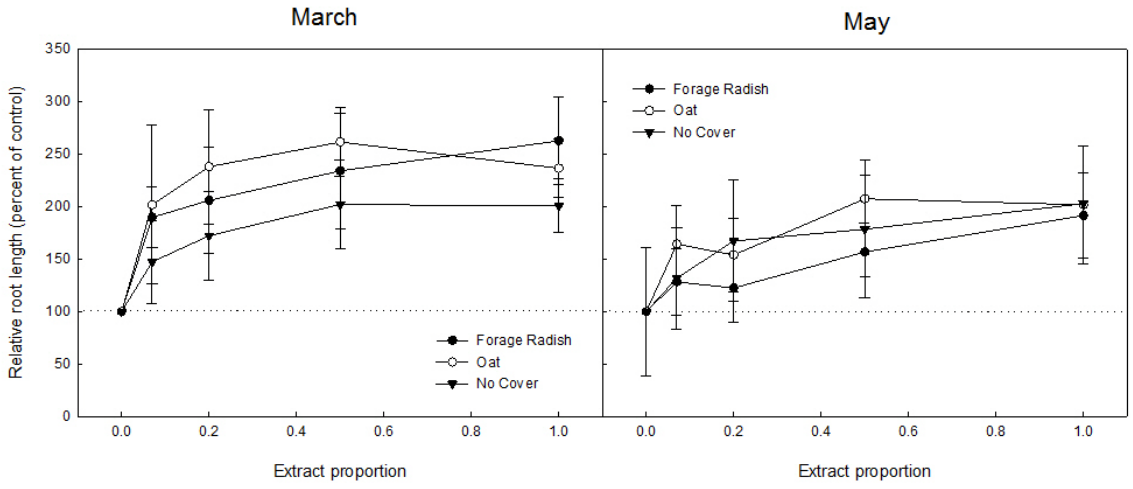

Figure 4.3: Relative root length of lettuce (*Lactuca sativa* L.) seedlings grown in aqueous soil extracts. Root lengths are expressed as a percent of the distilled water control. Soil extracts were prepared from surface soil samples (0-5 cm) collected from forage radish, oat, and no cover crop field treatments on 28 March and 30 May, 2006. Bars represent standard deviation.

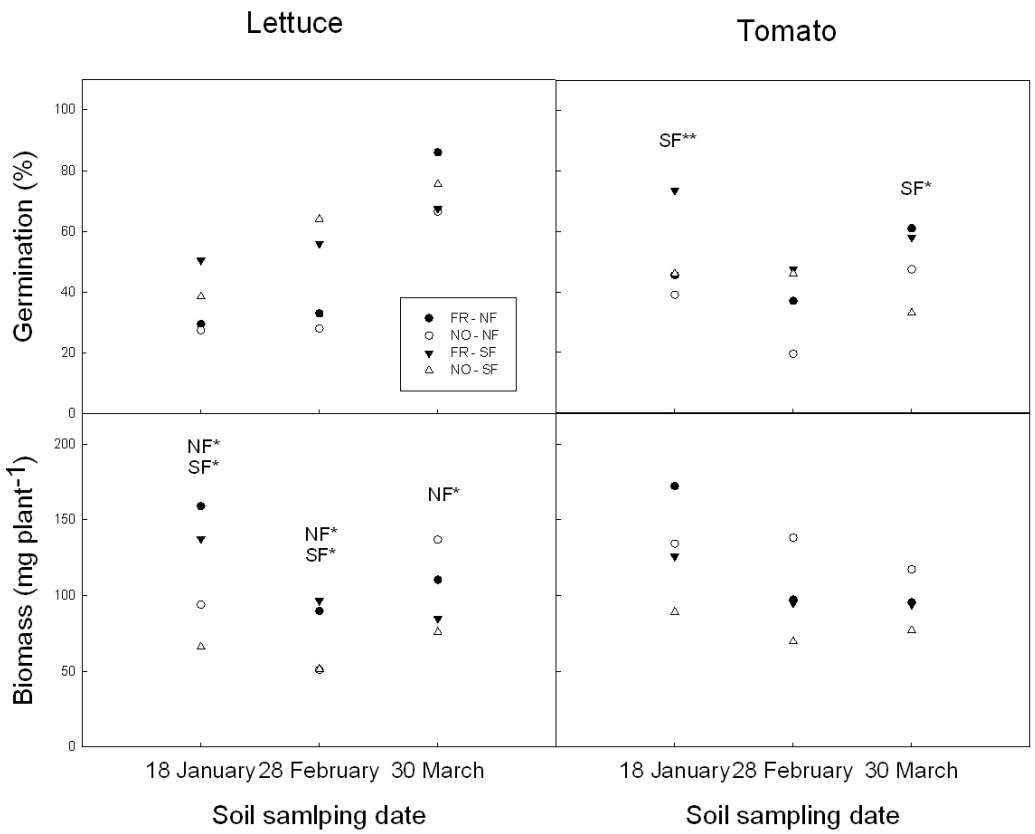

Figure 4.4: Effect of soil samples collected below decomposing forage radish residues (FR) or no cover crop (NO) on lettuce and (Lactuca *sativa* L.) and tomato (*Solanum lycopersicum* L) germination and seedling biomass. Soils were sampled from fields at the USDA Beltsville Agricultural Research Center North Farm (NF) and South Farm (SF). Significant differences ($\alpha = 0.05$) between pairs of FR and NO treatments for North Farm and South Farm are indicated by NF* or SF* respectively.

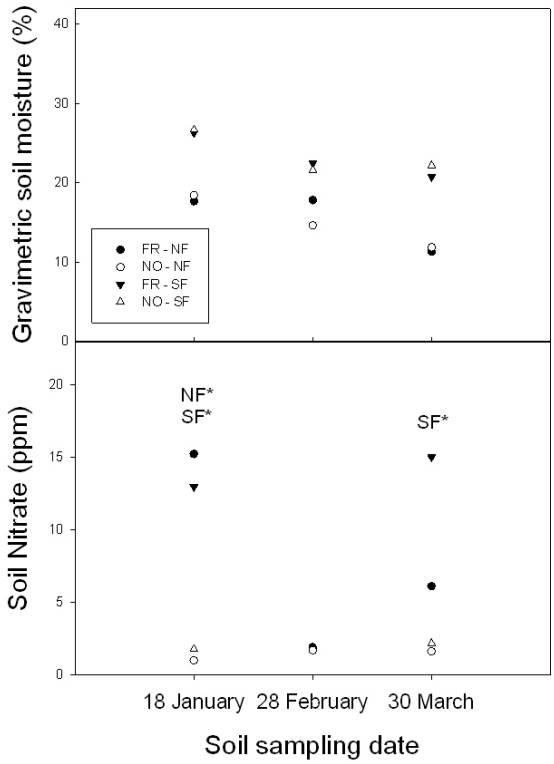

Figure 4.5: Initial gravimetric soil moisture and soil nitrate content of soils sampled from forage radish (FR) and no cover crop (NO) treatments at the USDA Beltsville Agricultural Research Center North Farm and South Farm. Significant differences (α = 0.05) between pairs of FR and NO treatments for North Farm and South Farm are indicated by NF* or SF* respectively. No samples were available to measure soil nitrate for Field-E for the 28 February sampling date.

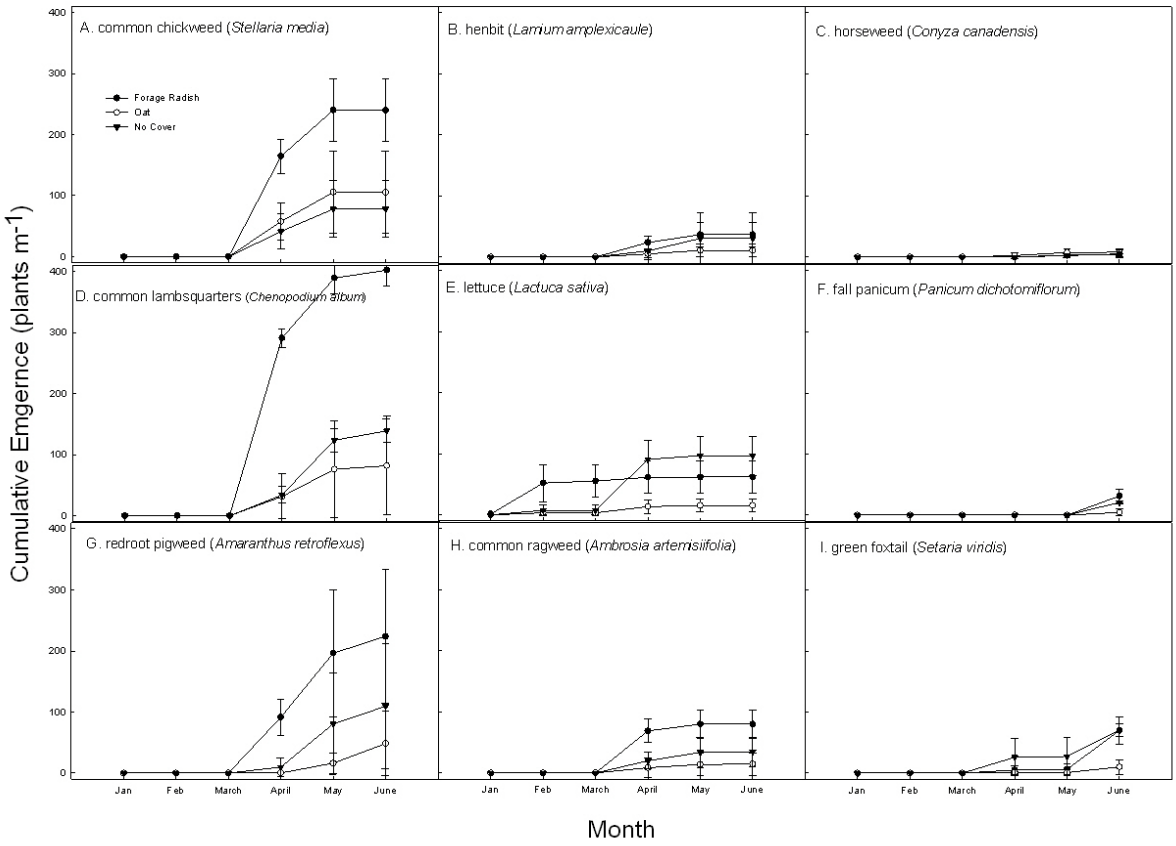

Figure 4.6: Mean cumulative weed emergence of planted weed seeds and lettuce seeds below decomposing forage radish cover crop, decomposing oat cover crop, and no cover crop control treatments in 2006 at the USDA Beltsville Agricultural Research Center North Farm. Bars represent standard deviation.

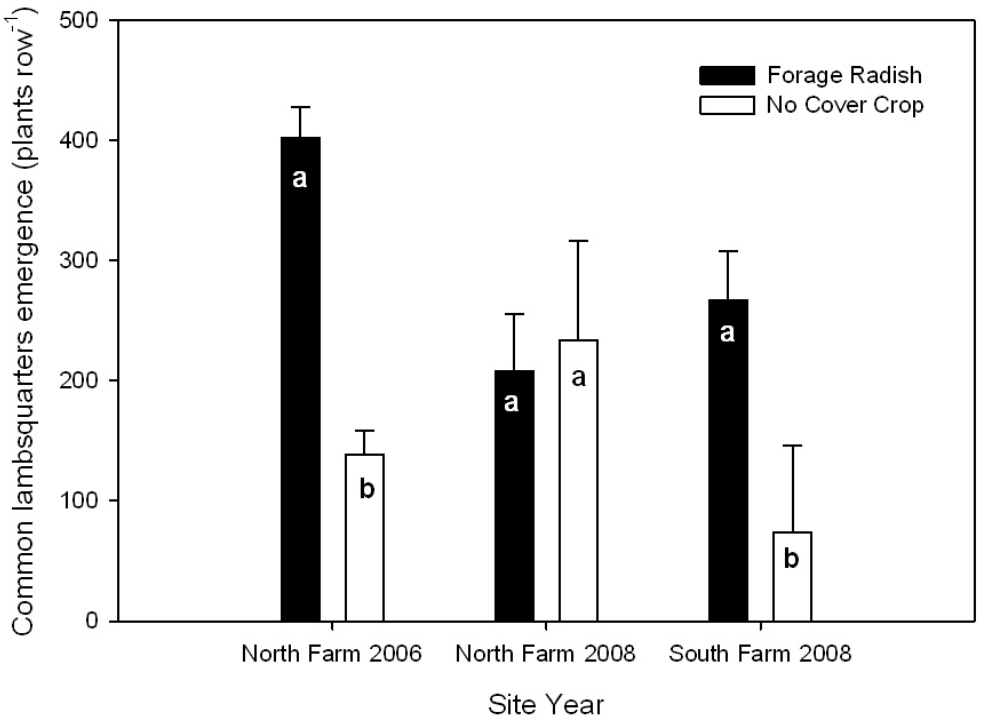

Figure 4.7: Mean emergence of common lambsquarters (*Chenopodium album* L.) below decomposing forage radish residues and a no cover crop control for three site-years at the USDA Beltsville Agricultural Research Center. Letters represent differences between cover crop treatments within a site. Bars represent standard deviation.

Table 4.6: Effect of forage radish cover crop residue treatment on mean percent weed cover in early spring and at planting time at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF).

Fall cover crop			Forage radish				No cover			
Residue treatment			FR[†]-S_0[±]R_0[§]	FR-S_1R_1	FR-S_2R_2	FR-S_0R_1	NO[†]-S_1R_1	NO-S_1R_0	NO-weedy	NO-fall-weeded
Location	Field	Date	Percent weed cover in early spring							
BARC-NF	A	20 Mar 2007	0.1a[¶]	0.3a	0.0a	0.0a	32b	38b	53c	5.8a
	B	7 April 2008	7.4b	0.7a	-	-	9.0b	-	30c	29c
BARC-SF	E	28 Mar 2007	0.0a	0.0a	0.0a	0.3a	20b	20b	71c	16b
	F	1 April 2008	2.5a	0.0a	-	-	3.8a	-	14b	13b
			Percent weed cover at planting time							
BARC-NF	A	30 April 2007	4.8a	9.0b	5.3ab	5.3ab	96d	98d	85d	47c
	B	3 May 2008	30b	15a	-	-	33b	-	72c	80c
BARC-SF	E	25 April 2007	3.8a	4.8a	4.8a	4.0a	69b	55b	89b	53b
	F	3 May 2008	58a	62ab	-	-	78ab	-	81b	62b

[†]FR = forage radish, NO = no cover crop
[±]S_0 = shoots removed, S_1 = shoots remain or added to no cover, S_2 = shoots doubled
[§]R_0 = roots removed or absent from no cover, R_1 = roots remain or added to no cover, R_2 = roots doubled
[¶]NO-weedy = plots never weeded, NO-fall weeded = plots hand weeded in October and November
[#]Means followed by different letters indicate significant difference (α=0.05) within a site-year and rating period.

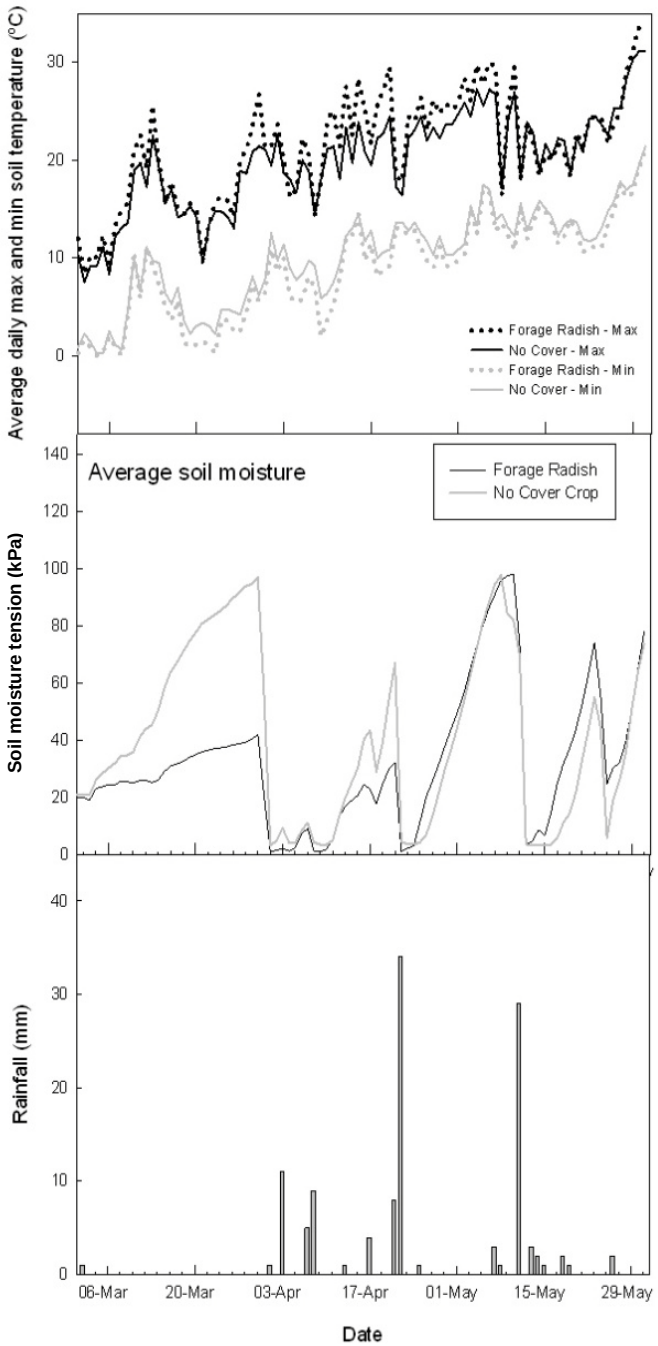

Figure 4.8: Effect of forage radish cover crop on average daily maximum (max) and minimum (min) soil temperature and average daily soil moisture relative to no cover crop the following spring (March to May 2006) in field Field-B at the USDA Beltsville Agricultural Research Center North Farm.

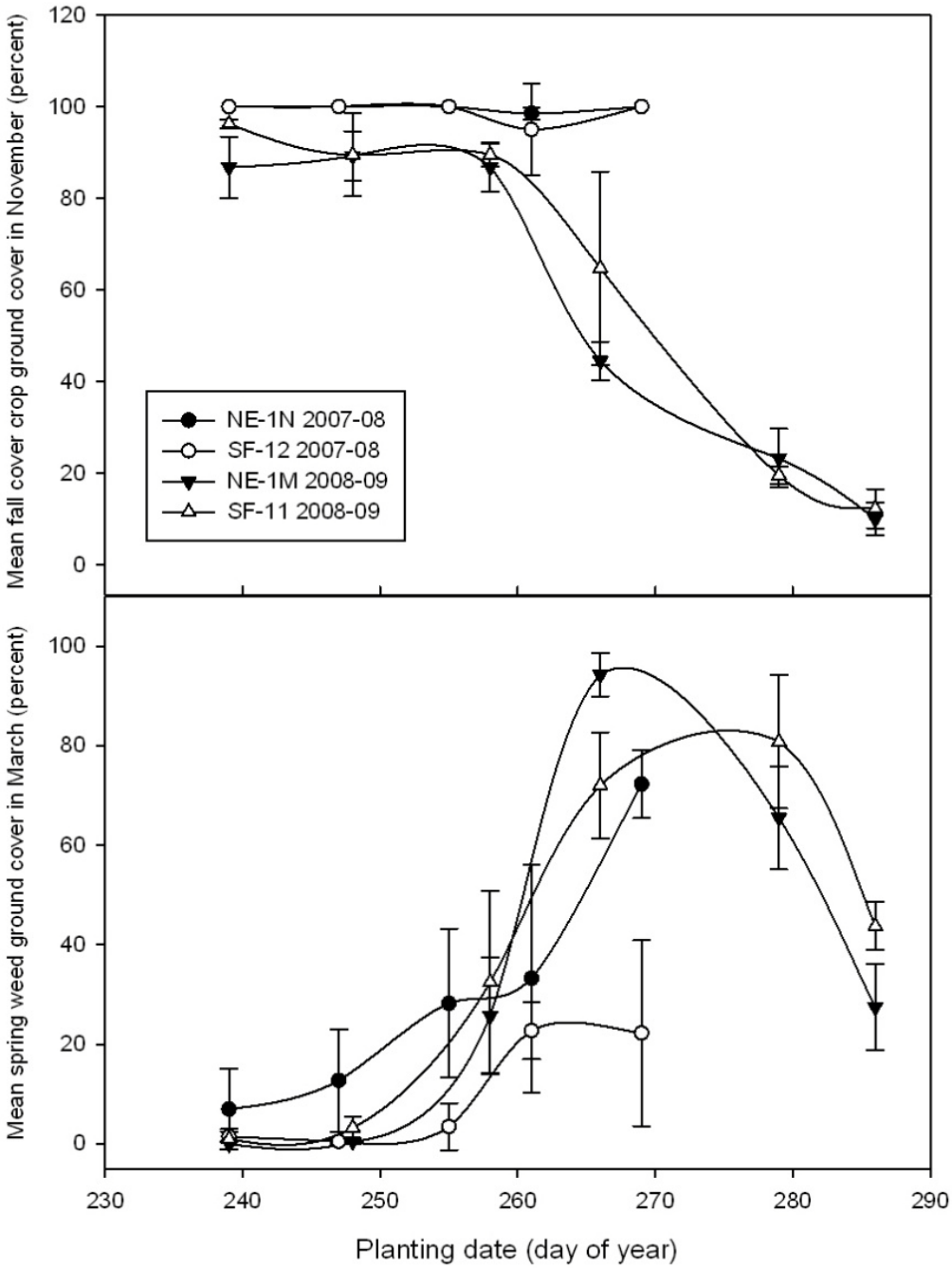

Figure 4.9: Influence of cover crop planting date on fall cover crop canopy and weed suppression the following March in 2007 and 2008 at the USDA Beltsville Agricultural Research Center North Farm (Field-A and Field-B) and South Farm (Field-F and Field-E). Error bars represent stand deviation.

Chapter 5: Conclusions

Objective 1: Characterization of weed suppression following forage radish winter cover crops

Prior to this study, little was known about the amount and duration of forage radish (*Raphanus sativus* L. var. *longipinnatus*) weed suppression. Forage radish winter cover crops, when planted prior to 1 September in the coastal plain of Maryland, consistently provided nearly complete weed suppression in the fall and early spring. However, the weed suppression did not persist into the subsequent corn growing season. Thus, growers cannot expect any residual weed control from forage radish winter cover crops.

This study also identified that winter annual weeds were most affected by forage radish cover crops. Forage radish provided consistent fall and early spring suppression of common chickweed (*Stellaria media* L. Vill.) and henbit (*Lamium amplexicaule* L.). Although forage radish suppressed the fall growth of common lambsquarters (*Chenopodium album* L.), it also stimulated common lambsquarters emergence the following spring in three site-years. Thus, fields with a significant common lambsquarters population in the weed seedbank will likely need alternative weed control measures following forage radish cover crops.

Horseweed (*Conyza canadensis* L.) was suppressed by forage radish at BARC-NE-1N in spring of 2006. Horseweed behaves both as a winter annual and summer annual in Maryland (Ronald Ritter, personal communication). It is a growing concern

because of the presence of glyphosate resistant biotypes in the state. Future work should evaluate whether cover crops like forage radish could be used to suppress herbicide resistant weeds.

Objective 2: Impact of forage radish cover crops on subsequent corn crop performance

Farmers frequently ask about the impact of forage radish cover crops on subsequent crops. This study demonstrated at multiple sites over multiple years that forage radish did not negatively impact corn yield or plant population relative to rye or no cover crop treatments. When a forage radish cover crop was used in place of a preplant burndown herbicide, some weeds were present at the time of corn emergence but corn yields were not reduced for either early or typical planting dates if weeds were controlled with a postemergence herbicide application. Additional in-crop weed control measures should be anticipated even if a forage radish cover crop is used in place of preplant cultivation or burndown herbicide.

Objective 3: Mechanism of forage radish weed suppression

This study revealed that fall competition was the primary mechanism of forage radish weed suppression. The planting date experiment demonstrated that early planting of forage radish winter cover crops resulted in greater spring weed suppression. The residue moving experiment demonstrated that whether forage radish residues remained or were removed in the late fall there was little impact on spring weed suppression.

At the start of this study, it was hypothesized that allelopathy was responsible for spring weed suppression following forage radish cover crops. This hypothesis was based on early observations of dramatic early spring weed suppression following forage radish cover crops despite the low amount of residue remaining in the spring. It was also based on prior research with other cover crops in the *Brassicacea* family that had demonstrated the inhibitory effects of isothiocyantes and other glucosinolate hydrolysis products on weed seed germination and growth.

Controlled environment bioassays involving cover crop amended soil and aqueous extracts along with field experiments utilizing planted seeds did not provide evidence that allelopathy was the mechanism of forage radish weed suppression. Although not supported by the findings of this study, it is not possible to eliminate allelopathy as a potential mechanism of forage radish weed suppression.

Recommendations

To increase the adoption of cover crops in the Mid-Atlantic and reach targeted water quality improvements in the Chesapeake Bay watershed, farmers need to be advised of the multiple benefits of cover crops. This project demonstrated that forage radish winter cover crops can be used as a tool to manage fall and early spring weeds without compromising the performance of subsequent crops like corn.

Strategies to control weeds with a forage radish cover crop should focus on fall weed suppression and the preplant window of weed control in early spring. Farmers that want to take advantage of this weed suppression need to plant forage radish prior to 1 September in the coastal plain of Maryland. It is challenging to find this window in the

typical corn-winter wheat-soybean grain rotation used in the Mid-Atlantic region. Forage radish may be a better fit in rotations that include corn silage or vegetable crops. Factors such as drought, low soil fertility, or unusually early frosts that limit fall cover crop growth may also impact spring weed suppression. In these cases, farmers should anticipate the need to use alternative preplant weed control the following spring.

Appendix 1: Weather summary

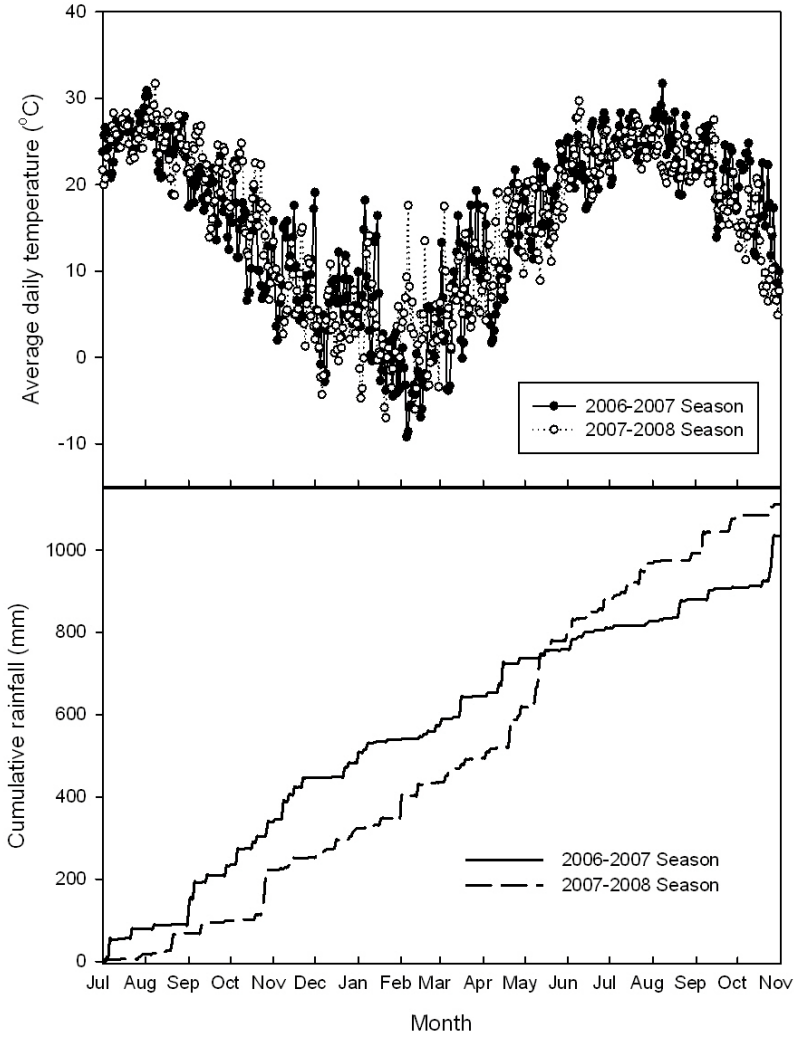

Figure A1.1: Average daily air temperature and cumulative rainfall during the cover crop and corn growing season at the USDA Beltsville Agricultural Research Center during the 2006-07 and 2007-08 seasons.

Appendix 2: Field names and selected soil properties

Table A2.1: Research farm field names and selected soil properties 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.

Research Farm	Field	Research Farm Field Name	Surface soil textural class	Soil organic matter (%)	Previous tillage system
BARC-NF	A	NE-1N	loamy sand	1.3	conventional
	B	NE-1M	loamy sand	2.0	conventional
	C	NE-1F	loamy sand	2.0	conventional
BARC-SF	D	SG-10A	silt loam	1.2	conventional
	E	SF-11	silt loam	1.5	conventional
	F	SF-12A	silt loam	2.2	conventional
	G	SF-12B	silt loam	2.2	conventional
CMREC	H	5-39A	loamy sand	1.9	no-till
	I	5-39D	loamy sand	1.9	no-till
WREC	J	E-2	silt loam	1.4	conventional

Appendix 3: Observation of horseweed (*Conyza canadensis* L.) suppression following forage radish cover crops

Table A3.1: Horseweed (*Conyza canadensis* L.) and total weed suppression following forage radish cover crops in Field-A at the Beltsville Agricultural Research Center during the winter and spring of 2006.

Rating date	Forage radish cover crop[±]	No cover crop[±]
	Total weed (percent ground cover)	
28 January	0[†]	60
18 March	0	84
13 April	11	90
26 April	37	94
21 May	98	76
8 June	85	40
	Horseweed (percent weed ground cover)	
28 January	0	0
18 March	0	0
13 April	0	4
26 April	0	4
21 May	0	24
8 June	0	27

[†]Means represent the average of four replicates.
[±]Both forage radish and no cover crop treatments were not sprayed with herbicides from the time of cover crop planting on August 25, 2005 through to the last sampling date in June. No test crop was planted after the cover crop treatment.

Appendix 4: Impact of forage radish cover crop on spring soil conditions

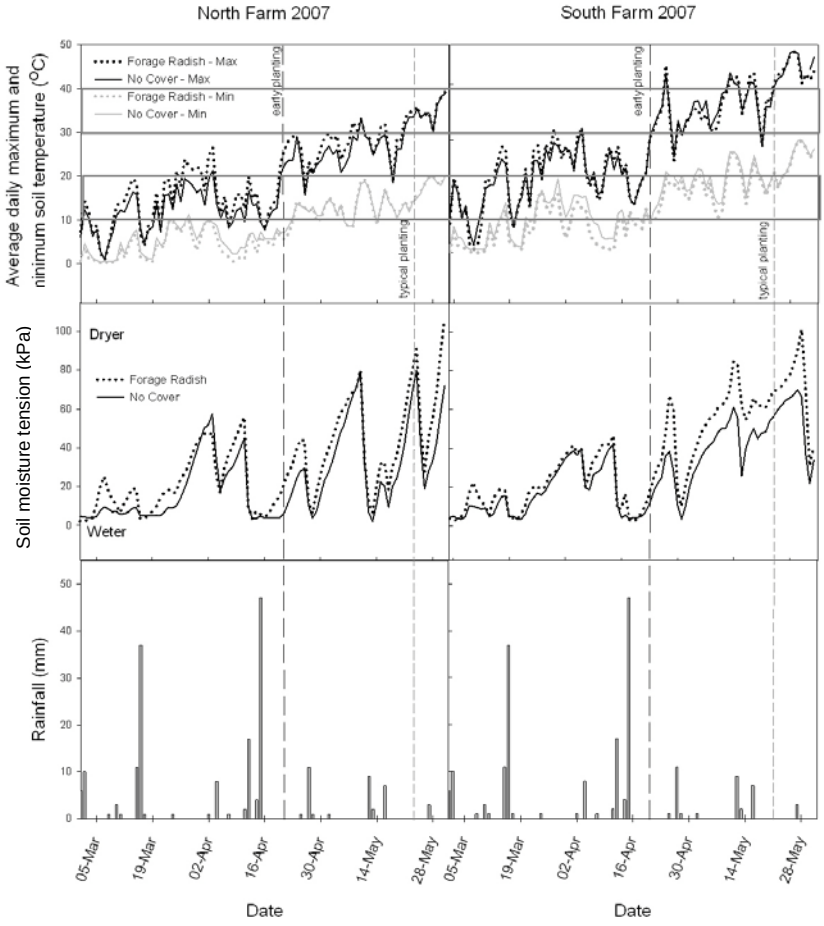

Figure A4.1: Average daily maximum and minimum soil temperature, average daily soil moisture tension, and daily rainfall in forage radish and no cover crop treatments at the USDA Beltsville Agricultural Research Center North Farm (BARC-NF) and South Farm (BARC-SF) in spring 2007.

Appendix 5: Natural weed seed bank study

Objectives

To determine effect of forage radish cover crops on weed seeds in the soil seed bank.

Hypothesis

Forage radish cover crops will reduce the population of weed seed with germination capacity in the natural soil seed bank.

Materials and methods

Site descriptions

Soil samples were collected for the weed seed bank study from existing trials at two locations in 2005 and 2006. In 2005, the locations were field NE-6 at the North Farm of the USDA Beltsville Agricultural Research Center in Beltsville, MD and field 39 at the Lower Eastern Shore Research and Education Center (LESREC) in Salisbury, MD. In 2006 the trials were field NE-1N at the North Farm and field SG-10A at the South Farm of the USDA Beltsville Agricultural Research Center, in Beltsville, MD.

Soil sampling

Soil samples were collected in May of 2005 and in March of 2006. In 2005, samples were collected by removing two 20 cm x 20cm x 5cm squares of soil from plots. In 2006, soil samples were collected using 20 randomly sampled cores that were 5 cm in

diameter and 5 cm deep. Soil samples were homogenized and stored in a refrigerator at $4^{o}C$ until the experiment was initiated.

Tray preparation and management

A 5 cm thick layer of steam sterilized sandy loam was placed into 36 cm wide x 50 cm long x 10 cm deep plastic tray and cover by a 1 cm thick layer of field soil. In 2005, soil from each plot was split into two trays. In 2006, soils were weighed before being placed in trays and only one tray was prepared for each field plot sampled. Trays were incubated in a green house from 29 May to 27 June in 2005 and from 16 March to 15 June in 2006 under seasonally variable temperature conditions. During the longer incubation period of 2006, soil was stirred on 9 May to stimulate a second flush of weed seeds. Trays were watered from above once daily or every second day as needed.

Emergence counts

Emerged weeds were counted weekly. Seedlings were identified, counted, and pulled when they had two true leaves. In 2005, seedlings were identified as either monocots or dicots. In 2006, seedlings were identified to species level.

Statistical analysis

Emergence was calculated on a soil volume basis in 2005 and on a soil weight basis in 2006. Data were analyzed by ANOVA using the Mixed procedure of SAS version 9.1 (SAS Institute, Cary, NC). Data for each soil was analyzed separately. In the model, block was considered a random effect and cover crop treatment was considered a fixed effect. For the 2005 data, square root transformation was applied prior to analysis to improve homogeneity of variances. Back transformed means were reported. When the

ANOVA indicated significant differences between cover crop treatments ($P<0.05$), mean comparisons were made using Fisher's Least Significant Difference test.

Results and discussion

Crop effects on the weed seed bank were compared at the four previously mentioned locations over two years, for a total of four site-years. The natural weed seed banks of the two sites sampled in 2006 had opposing trends in total weed emergence (Table A2.1). Total weed emergence was higher in the forage radish treatment relative to the no cover crop control at NE-6 but was higher in the no cover crop treatment for LESREC-39. In 2006, dicot weeds were the dominant type of weed in the seed bank at both of these sites. Trends in monocot weed emergence mirrored trends in dicot weed emergence for LESREC-39 site with greater emergence in the no cover crop treatment. There were low numbers of monocot weeds and no differences between cover crop treatments for NE-6 site.

More detailed emergence counts were taken for both sites sampled in 2007 to determine the weed species driving trends in weed emergence. Total weed emergence was the same for both sites with higher emergence in no cover crop treatments than in the forage radish treatment at both 2007 sites. Summer annual dicot weeds drove trends in total weed numbers for both locations (Table A2.2). The dominant summer annual weeds at the SG-10 and NE-1N were redroot pigweed and carpet weed, respectively. There were small effects of cover crop type on winter annual weed seed emergence. This may have been due to the timing of soil sampling. Differences in winter annual weed emergence may have been observed if fall soil sampling during the cover crop growing season had

been conducted rather than spring soil sampling following the decomposition of forage radish cover crop residues.

Other researchers have suggested that forage radish cover crops reduce weed seed production during its fall growth and residue decomposition period into the spring. Wang et al. (2008) observed that cover crops, including oilseed radish, planted and incorporated in the fall reduce the number of weed seeds in the soil the following spring relative to a no cover crop control. The no cover crop control in the study of Wang et al. (2008) had weeds that grew during the fall, as was the case in the current study. Unfortunately Wang et al. (2008) do not report which species of weeds had reduced weed seed densities following cover crop treatments. In the current study, fall growth and winter residue decomposition of forage radish delayed emergence of winter annual weeds.

Soil samples were not sieved to retrieve weed seeds following the experiments to count retrieved seeds and test for seed viability. Thus, reductions in weed emergence may have been due to the influence of cover crop treatments on seed rain, seed dormancy, or seed mortality due to allelopathy. Weed seed emergence was lower in all cover crop treatments compared to the no cover crop control in three of four site years. This finding suggests that the presence of the cover crop, regardless of its allelopathic potential, can influence weed seed emergence. One possible mechanism for this finding would be the ability of the growing cover crop canopy to interfere with environmental signals used by weed seeds as dormancy signals. Environmental signals known to influence seed dormancy include light, temperature, soil moisture, or soil nutrients (Baskin and Baskin, 2001). Further research is needed to identify the impact on weed seed emerge, seed viability, and the impact of cover crops on environmental signals of seed dormancy.

Conclusions

This study looked at the impact of cover crop amended soil on the natural weed seed bank and revealed that cover crops decreased the number of weed seeds in the active seed bank in three of the four locations sampled. The conclusions that can be drawn from this study are limited as soil samples were not sieved to retrieve weed seeds following the experiments to count retrieved seeds and test for seed viability. Thus, reductions in weed emergence may have been due to the influence of cover crop treatments on seed rain, seed dormancy, or seed mortality.

Reference

Baskin C.C., J.M. Baskin. 2001. Germination ecology of seeds with nondeep physiological dormancy, in: C. C. Baskin and J. M. Baskin Eds., Seeds: Ecology, biogeography, and evolution of dormancy and germination, Academic Press, San Diego. pp. 49-85.

Wang G., M. Ngouajio, D.D. Warncke. 2008. Nutrient cycling, weed suppression, and onion yield following brassica and sorghum sudangrass cover crops. Horttechnology 18:68-74.

Table A5.1: Natural weed seed bank emergence in soils sampled during May 2006 following forage radish, rye, rapeseed, and no cover crop treatments at the USDA Beltsville Agricultural Research Center North Farm (NE-6) and the Lower Eastern Shore Research and Education Center (LESREC) in Salisbury, MD.

Site	Forage Radish	No Cover Crop	Rye	Rapeseed
	Total weed emergence cm^{-3} soil			
NE-6	0.703a†	0.574b	0.600b	0.509b
LESREC-39	0.548b	0.627a	0.519b	0.544b
	Dicot weed emergence cm^{-3} soil			
NE-6	0.702a*	0.571b	0.597b	0.588b
LESREC-39	0.540b	0.618a	0.555b	0.536b
	Monocot weed emergence cm^{-3} soil			
NE-6	0.190a	0.180a	0.199a	0.222a
LESREC-39	0.253b	0.298a	0.271b	0.261b

† letters represent differences between cover crop treatments within a site for each weed class.

Table A5.2: Natural weed seed bank emergence in soils sampled in March, 2007 following forage radish, oat, and no cover crop treatments at the USDA Beltsville Agricultural Research Center North Farm (NE-1N) and South Farm (SG-10A).

Site	Forage Radish	No Cover Crop	Oat
	Total weed emergence kg^{-1} soil		
NE-1N	91b[†]	187a	109b
SG-10A	35b	335a	97b
	Winter annual weed emergence kg^{-1} soil		
NE-1N	6b	7b	10a
SG-10A	9a	8a	7a
	Summer annual weed emergence kg^{-1} soil		
NE-1N	85b	181a	99b
SG-10A	25b	325a	89b
	Redroot pigweed (*Amaranthus retroflexus*) emergence kg^{-1} soil		
NE-1N	5a	33a	18a
SG-10A	5b	248a	45b
	Carpet weed (*Mollugo verticillata*) emergence kg^{-1} soil		
NE-1N	58a	110a	54a
SG-10A	10a	36a	27a

[†] letters represent differences between cover crop treatments within a site for each weed class.

Appendix 6: Sample SAS code

Codes used to analyze corn yield and plant populations in Table 3.4

```
Title1 'Analysis by siteyear';
Title2 'Corn Yield in kg ha';

Proc mixed data=cornandcover covtest;
by location;
class cover rep;
model yield_kgha= cover;
random rep;
lsmeans cover/pdiff;
run;
```

Codes used to analyze percent ground cover ratings in Tables 3.5, 3.7, 3.8, 3.9,

```
Title1 'November - total weed cover';
Proc mixed data=November;
by location;
class Location cover rep;
model Tweeds=cover;
random rep;
lsmeans cover/pdiff;
run;
```

Codes used to analyze percent ground cover ratings in Table 3.10

```
*/Split-split-split plot design
Main plot: Corn date (Error A = block*corndate)
sub plot: cover crop (Error B = corndate*cover*block)
sub-sub plot: siteyear (Error C, residual error - does not need to be
specified, SAS will calculate)*/;

title1 'effect of corndate (early and typical), cover (NO, FR, and RYE
),  siteyear (NE-1M, NE-1F, SF-11, SF-12)
on corn yield in kg/ha when site year is random';
title2 'Combined analysis over 4 site years';
title3 'weed cover at the time of corn emergence';

Proc mixed data=emergence nobound covtest;
class  corndate cover block siteyear;
model Tweeds= corndate|cover;
random block(siteyear) siteyear corndate*block(siteyear)
corndate*cover*block(siteyear);
lsmeans corndate*cover/pdiff; run;
```

Codes used to analyze percent weed cover, corn grain yield, corn biomass, and corn plant population in table 3.11

```
*/Split-split-split plot design
Main plot: Corn date (Error A = block*corndate)
sub plot: cover crop (Error B = corndate*cover*block)
sub-sub plot: siteyear (Error C, residual error - does not need to be
specified, SAS will calculate)*/;

*Note: Need to use the nobound option in the proc mixed statement as
the covariance parameter estimates (random effects, interaction terms,
Error A and B terms) are negative. SAS default is to call those
negative values zero. This inflates Type 1 error. No bound option
allows the covariance parameter estimates to be negative values rather
than zeros. Negative values occurred because the whole plot sums of
squares (eg. Corn date) were smaller than the sub plot sums of squares
(eg. Cover).*/;

title1 'corn yield in kg/ha - effect of corndate (early and typical),
cover (NO, FR, and RYE ),  siteyear (NE-1M, NE-1F, SF-11, SF-12) when
siteyear is random';

proc mixed data=corndate nobound  covtest;
class CornDate cover siteyear block;
model yield_kgha = corndate|cover;
random block(siteyear) siteyear corndate*block(siteyear)
corndate*cover*block(siteyear);
lsmeans corndate*cover/pdiff;
run;
```

Codes used to analyze corn grain yield in Table 3.12

```
*/Split-split-split plot design
Main plot: Corn date (Error A = block*corndate)
sub plot: cover crop (Error B = corndate*cover*block)
sub-sub plot: year (Error C or residual erro - does not need to be
specified, SAS will calculate)*/;

title1 'corn yield in kg/ha - effect of corndate (early and typical),
cover (NO, FR, and RYE ), year (2007 and 2008) by site';

proc mixed data=corndate nobound covtest;
by site;
class CornDate cover year block;
model yield_kgha = corndate|cover;
random block(year)year corndate*block(year) cover*corndate*block(year);
lsmeans corndate/pdiff;
run;
```

Codes used to analyze corn grain yield and plant population in Table 3.13

```
*/Split-split-split plot design
Main plot: Corn date (Error A = block*corndate)
sub plot: cover crop (Error B = corndate*cover*block)
sub-sub plot: year (Error C - does not need to be specified, SAS will
calculate)*/;

title1 'yield in kg/ha effect of corndate (early and typical), cover
(NO, FR, and RYE ),  year (2007 and 2008)at South Farm - all as fixed
effects';

proc mixed data=corndate nobound;
where site='South';
class CornDate cover year block;
model yield_kgha = corndate|cover|year;
random block(year) corndate*block(year) cover*corndate*block(year);
lsmeans year*cover/pdiff;
run;
```

Codes used to analyze lettuce and tomato germination and biomass in Figure 4.4 as well

as gravimetric soil moisture and soil nitrate in Figure 4.5

```
Title1 'Lettuce germination';
proc mixed data=exp06.alldata;
by date;
class date field cover block;
model  LTGerm_perc = field|cover;
random block(field);
lsmeans field*cover/pdiff;
run;
```

Codes used to analyze percent weed cover in Figure 4.6

```
*/ Natural log (Ln) transforming April data set to improve normal
distribution of data */;
*creating dummy variables so that lowest value in data line is 1*;
data exp04.Dweedcoverallapril;
set exp04.weedcoverallapril;
DTweed=Tweed+1;
run;

*taking the natural log of the dummy variables to use in ANOVA*;
data exp04.LnDweedcoverallapril;
set exp04.Dweedcoverallapril;
lnDTweed=log(DTWeed);
run;


*plotting data to check that transformation improved normal
distribution – not much improvement following transformation*;
```

```
proc univariate data=exp04.LnDweedcoverallapril;
var lnDTWeed;
histogram;
run;
proc mixed data=exp04.LnDweedcoverallapril;
class siteyear trt block;
model LnDTWeed= siteyear|trt/ outp=c;
random block(siteyear);
lsmeans trt*siteyear/pdiff ;
run;

*Plotting residuals of ANOVA to test if transformation improved
homogeneity of variances –improvement visible in plot of residuals*;

proc plot data=c hpercent=60 vpercent=60;
plot resid*pred;
run;
```

Codes used to analyze common lambsquarters emergence in Figure 4.7

```
proc mixed data=exp02.LQ;
class site cover rep;
model LQemerg_row = site|cover/ outp=a;
random rep(site);
lsmeans site*cover/pdiff;
run;
```

Codes used to analyze weed seed bank emergence in Figure A5.1 and A5.2

```
*/ Square root transformation of data (SQ) to improve normal
distribution of data set*/;
data exp03.SQweeds;
set exp03.weeds;
SQtotal=total*(1/2);
SQWA=WA*(1/2);
SQSA=SA*(1/2);
run;

*/ Plot transformed data to verify that it improved the distribution of
the data set*/;
proc univariate data=exp03.SQweeds;
var SQTotal;
histogram;
title2 'Total Weed emergence';
proc mixed data=exp03.SQweeds;
by location;
class location cover rep;
model SQTotal=cover/ outp=a;
random rep(location);
lsmeans cover/pdiff;

run;
```

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