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EVALUATING CONSTRAINTS AND OPPORTUNITIES IN MANAGING WEED
POPULATIONS WITH COVER CROPS

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Agronomy

by

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ABSTRACT

Efficacy of weed management in cropping systems with reduced reliance on herbicidal weed control is relatively lower and more variable than conventional herbicide management programs. Yet lower herbicide-input systems rely more heavily on cultural controls that can differ in their ability to increase soil organic carbon, a goal that is frequently highlighted by organic and reduced pesticide producers. Reduction in tillage and an increase in cover crop use are both highlighted as practices that increase soil carbon. Therefore, a series of studies were conducted to assess the efficacy of low herbicide weed management practices that vary in cover cropping practices and soil disturbance frequency. The approach involved: 1) using soil disturbance and cover crop residue management to rapidly deplete weed seedbanks in high disturbance organic and low herbicide input systems; and 2) using novel cover crop residue management strategies to reduce or eliminate herbicides in no-tillage cropping systems.

Field experiments were initiated to quantify the influence of five cover crop systems on weed seedbank flux across a range of initial weed seedbank densities. The influence of soil disturbance and cover cropping on the germinable weed seedbank of common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* L.), and foxtail spp. (*Setaria* spp.) was assessed. Cover crop systems ranged from a control treatment (summer fallow) that included tillage approximately every 30 days during the summer, to an oat (*Avena sativa* L.)/red clover (*Trifolium pretense* L.) cover crop mowed periodically to prevent weed seed production. Field studies were conducted in both Pennsylvania and Maine. Soil disturbance associated with cover cropping resulted in

weed seed germination and establishment thereby reducing the density of germinable seed in the weed seedbank. Of the five systems studied, the summer fallow (SF) and yellow mustard (*Brassica juncea* (L.) Czern.)/buckwheat (*Fagopyrum sagittatum* Gilib.)/winter canola (*Brassica napus* L.) (B-BW-B) cover crop consistently decreased seedbanks of a diverse weed community. A quality of both systems is late season disturbance that preempts weed seed rain. If weeds are permitted to reach reproductive maturity in cash or cover crops, the “debits” to the seedbank resulting from early season disturbance will likely be overwhelmed. The magnitude of decline in these high disturbance systems reached complete depletion of the germinable seedbank for foxtail spp., 85% depletion of common lambsquarters, and 80% for velvetleaf. Additionally, the effect of initial weed infestation levels on the efficacy of weed management was tested. Seedbank decline was a positively related (linearly) to initial seedbank density. The slope of that relationship was smallest for the SF and B-BW-B, meaning those treatments provided the greatest level of weed suppression.

Nested within the SF and B-BW-B cover crop systems from the cover crop systems experiment, and within a separate component study, the influence of soil disturbance and green manuring frequency on giant foxtail (*Setaria faberi*) and velvetleaf (*Abutilon theophrasti*) seed persistence, cumulative emergence, and mortality (fatal germination and seed death) was determined. In early spring of 2005 and 2006, after-ripened weed seed buried in the previous fall and exhumed, were either: 1) kept in mesh bags and buried in field receiving a high frequency of soil tillage that varied in green manure additions (mesh bag experiment), or 2) removed from the mesh bags and placed into wire

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The second area of research tested the efficacy of mechanical control of cereal rye (*Secale cereale*) cover crop cultivars using a mechanical crimping apparatus (roller/crimper) across a range of planting and termination dates. Biomass accumulation and subsequent weed suppression were quantified. To increase grower adoption of cereal rye covers, a thermal-based phenological model using growing degree days (GDD) to predict cereal rye development was developed. A Julian date-based analysis of cover crop control identified differences between the two cultivars; however, when based on the Zadoks growth stage, they responded similarly to rolling/crimping. Whereas cultivar growth rates differ, the growth stage at which optimal suppression was achieved was remarkably consistent over years and sites. A thermal-based phenological model separating the effects of heat units accumulated in the fall (Fall_{GDD}) from those accumulated in the spring (Spring_{GDD}) best predicted the phenological development of cereal rye growth stage and biomass accumulation. Cover crop biomass increased

approximately 2000 kg ha⁻¹ from earliest to latest summer and fall planting dates (August 25-October 15) and for each 10-day incremental delay in spring termination date (May 1-June 1). Delay in cover crop termination had the greatest reduction in weed density; early and late emerging summer annuals were both suppressed when cover crop termination date was delayed. Yellow nutsedge was not influenced by cover crop type or the timing of cover crop management. Identifying susceptible growth stages for mechanical control coupled with simple thermal-based phenological models that predict cereal rye development provides a useful decision support framework for farmers interested in such practices. We speculate that the degree of synchrony between weed species emergence periodicity and cover crop biomass accumulation played an important role in defining the extent of weed suppression.

The body of this work provides compelling evidence that cover crops can be used effectively to suppress weedy plant populations in no-till cash crops. Adoption of such practices will be aided by information provided here on the timeliness of establishment and termination of cover crops. This research underscores that species composition changes will result from such management selecting against small seeded weeds, while leaving larger seeded broadleaves and perennial weeds less affected. Such changes in population dynamics can be offset by changes in the sequence of crops to crop phases with increasing frequency of tillage and cover cropping. Another benefit of coupling rotational tillage practices with cover crop-based management is that negative effects of tillage may be offset by incorporation of 3000 kg ha⁻¹ of cover crop biomass in the crop phases with soil disturbance.

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PROLOGUE

The 1930's through 1960's were a defining period in world agriculture and largely shaped the perceptions and goals of modern sustainable agriculture. While the term sustainable agriculture defies definition (Gold 1999), central to the goals of sustainable agriculture are environmental stewardship and economic profitability. Environmental stewardship has focused primarily on soil conservation over the past 70 years and nontarget pollution from fertilizers and pesticides for over the past 40 years. The devastating impact of multi-season drought and poor soil management led to unprecedented losses of soil and farm income during the Dust Bowl of the 1930's; this period raised global awareness of the importance of soil conservation. The U.S. government responded when Franklin Roosevelt formed the Soil Conservation Service, now the Natural Resources Conservation Service. Since this historical event in 1935, a massive campaign to develop innovative soil conservation practices has taken place with both the methodology and the goals continuing to evolve. Shortly after the Dust Bowl era came a very important period in the history of agriculture often referred to as the green revolution. The dramatic increase in availability of synthetic fertilizers, plant breeding that selected for high yielding cultivars, more advanced irrigation techniques, and synthetic pesticides ushered in an industrial model of agriculture that largely de-coupled crop rotations and other cultural practices from soil quality and pest management. Fritz Haber's accomplishments in synthesizing ammonia from inorganic nitrogen and Carl Bosch's ability to expand on these breakthroughs made large amounts of inexpensive nitrogen fertilizer widely available. After WWII, industrial plants shifted from exporting material and equipment to support the war effort to fertilizing the Corn Belt, turning the

United States into one of the world's chief exporters of grain. Between 1940 and 2000, U.S. corn yield increased from less than 2 T/ha to more than 8 T/ha (Kucharik et al. 2005) while the number of total acres declined by about 26%.

This technological marvel did not come without costs. Our monoculture cropping now only covers the soil for half the year, leaving soil open to erosion and large amounts of leachable nitrogen and phosphorous available for off-site movement through leaching and surface runoff. Manure from livestock, once central to providing essential nutrients for crop growth, has become a waste product to be disposed of in an agriculture where animal and plant production have become increasingly de-coupled. Excess nitrogen and phosphorous are now common externalities of agricultural production causing eutrophication of our fresh and saltwater ecosystems. Other nontarget effects of pollutants raised concern. Rachel Carson's *Silent Spring* detailed the nontarget effects of pesticide use in agriculture precipitating a reevaluation of our reliance on such practices. Her book and the movement it started resulted in the formation of the Environmental Protection Agency in 1970. To this day, greater scrutiny on over-reliance on pesticides has been urged by many within the pest management disciplines (Zimdahl 1991; 2006). Increasingly, as our research capacity has increased we are able to quantify the external effects of over-reliance on pesticides. For example, atrazine, the predominate herbicide used in US corn production has been linked to population declines in amphibians (Hayes et al. 2002; Rohr et al. 2006).

These concerns are warranted, as the degradation of surface waters from nonpoint source and ground water from point source contaminants have become increasingly apparent. The United States Geological Survey under the National Water-Quality

Assessment Program conducted surveys of approximately 120 agricultural watersheds throughout the United States throughout the past decade. Approximately 95% of streams and 60% of shallow wells sampled were contaminated with pesticides (Gilliom et al. 2007). Two-thirds of the streams contained five or more pesticide active ingredients, and 20% contained 10 or more. The frequency in which both excess nutrients and pesticides are detected in our nation's water supply is alarming and demands a proactive approach by the agricultural community to reduce and prevent further contamination.

These environmental concerns led to increasing interest in developing agroecosystems that provide ecosystem services beyond food and fiber production. Management of our farmland resource could place a greater emphasis on sustainable management of natural resources, preservation of biodiversity, and conservation of arable land (Boody et al. 2005). Agricultural systems redesigned to provide such nonmarket services could have long-term impacts on crop productivity as well as environmental stewardship. Promoting these multifunctional agricultural services would improve soil conservation and reduce nontarget pollutants. The restructuring of US farm policy is necessary to realize these nonmarket services, and it is encouraging that such policies are beginning to surface (Boody et al. 2005; Boody and DeVore 2006). At present, a number of federal and state departments of agriculture and environment are offering incentives to adopt field buffer plantings (Environmental Quality Improvement Program) while others encourage use of winter cover crops to reduce soil erosion and improve water quality (REAP 2007). Integration of cover crops into cropping systems is a promising tactic that could contribute greatly to a sustainable multifunctional agriculture.

Cover crops can provide ecosystem services while also maximizing crop productivity. Cover crops have been integrated into crop rotations as a cultural practice to conserve soil, improve soil fertility (Decker et al. 1994) or as a replacement to mineral fertilizers (Teasdale et al. 2004). In contrast to synthetic nitrogen fertilizers, cover crops are a renewable resource, which can also serve to maintain or increase the sequestration of soil carbon (Teasdale et al. 1996). Living covers and their dead residues serve to reduce soil erosion (Langdale et al. 1991), increase soil water infiltration and storage (Munawar et al. 1990), and suppress weeds (Teasdale and Daughtry 1993). Therefore, cover crops can serve to help return the balance to agricultural systems by tightening nutrient cycles through reducing the movement of nonsource pollutants. This is accomplished directly by cover crop nutrient uptake and indirectly by increasing soil cation exchange capacity. Increased carbon inputs together with reductions in tillage (e.g., perennial forages or no-till/cover crops) increase soil organic carbon, a principal indicator of soil quality (Roberson et al. 1991; Wright et al. 1999). A number of recent studies (Pimentel et al. 2005; Ryan et al. 2007) have found that practices such as the use of cover crops that increase soil carbon content results in crops that are better buffered against the effects of drought and weed competition stress. It is also clear that reduced pesticide loading can be realized with cropping systems that incorporate cover crops to explicitly provide weed pest suppression (Morse 2001).

To reduce reliance on herbicides, organic producers and agricultural scientists have utilized cover crops to physically suppress weeds. Cover crops can impact weeds in several ways; they provide a competitive environment that can reduce or delay weed seed set (Gallandt 2006; Teasdale and Mohler 1993) and once the cover crop is suppressed, it

can reduce weed establishment (Mohler and Teasdale 1993). When incorporated into the soil, some cover crops release allelopathic compounds that can reduce weed emergence and early growth (Reberg-Horton et al. 2005). Additionally, cover crop residues can increase the biological activity of soil by serving as a substrate for soil microbial communities; such communities can reduce weed germination and establishment.

The growing interest in cover crops among agroecologists is reflected in increased research and publications in the field (Figure 1). Basic agronomic and systems level research is needed to better optimize the integration and benefits of this cultural production practice. The aforementioned concerns about soil conservation and nonpoint source pollutants have resulted in a national effort to conserve soil resources and better regulate agricultural pollutants (i.e., fertilizers, waste, and pesticides). Two important agricultural approaches have surfaced as a means for addressing these environmental concerns: no tillage farming for conserving soil resources and ecologically based weed management to reduce nontarget agricultural pollutants; both of which are addressed in the research outlined in this dissertation.

No-till field crop production has a long, well documented record (30+ years) of effectively managing and improving soil quality and resilience (Duiker and Myers 2005). The successful adoption of no-tillage agriculture is due in part to the adoption of herbicide resistant crops and the ability to use highly effective herbicides to control weeds (Curran et al. 1996; Duiker and Myers 2005; Raimbault et al. 1990). No-till agriculture often requires additional herbicide applications for adequate crop/weed management compared to conventional tillage systems (Young 2006). When pesticide use is reduced or eliminated, growers rely more on cultural and mechanical control

options, sometimes making pest management more challenging. At least two recent national surveys of organic and reduced-input growers consistently identified ecologically-based weed management research as a high priority (Northeast IPM Needs Assessment 2002; O.F.R.F 1998), with particular emphasis placed on developing new methods for reducing weed seed production. Successful weed management in these alternative systems is often largely dependent on practices that result in high levels of soil disturbance (i.e., tillage). A greater frequency of tillage and cultivation in organic and reduced-input cropping systems can result in an overall decrease in soil quality, particularly lower soil organic matter (SOM) concentrations (Gerhardt 1997).

These challenges have largely created a dichotomy in the agricultural community, those that focus on enhancing soil quality and those that focus on eliminating synthetic pesticide use (no-till vs. organic). However, efforts have been made to integrate cover crops in no tillage systems with the explicit aim of reducing herbicide use (Gallagher et al. 2003) and to use cover crops in organic systems to manage weeds and integrate conservation tillage practices. The overarching goal of this dissertation research is to provide insights into how cover crops can be incorporated into cropping systems that rely more on cultural weed management practices and less on herbicides. As with every cropping system there are multiple approaches for managing weeds without herbicides and developing cropping systems that improve soil quality. This dissertation examines how cover crops influence weed populations using innovative approaches to managing weeds under low and high soil disturbance.

Cropping systems that rely less on herbicides place a greater emphasis on cultural (crop rotation diversification and cover cropping) and mechanical weed control practices

(e.g., cultivation). The efficacy of these ecologically based weed management (EBWM) practices is more variable than herbicide dominated weed management (Ryan et al. 2007) and can result in weed seedbank increases that threaten the viability of such practices (Forcella and Lindstrom 1988). Weed infestations are driven by propagule density. Weed management outcomes are linked to infestation size, as higher resident weed seedbanks often require more weed control to adequately manage the population (Dieleman et al. 1999; Hartzler and Roth 1993).

Since infestations of annual weeds are dependent on the weed seedbank, effective implementation or transition to reduced-herbicide or organic weed management practices must work to rapidly reduce weed seedbank densities (Dieleman et al. 1999; Forcella et al. 1993). Using weed expressive tactics that increase germination of weed seeds that are subsequently controlled could prove to be a successful EBWM strategy for managing weed seedbanks. Germination of many species is stimulated by soil disturbance (Cavers and Benoit 1989); in this way the expressed germinable fraction can be increased. Integration of cover crops with soil tillage practices may provide added weed suppressive benefits while reducing the negative effects of frequent tillage on soil quality.

To reduce or eliminate herbicide use for weed management in no-till systems, some producers and agricultural scientists have focused on cover crops to physically suppress weeds. However, this surface mulch approach has seen limited adoption because of inconsistencies in weed suppression (Teasdale and Rosencrance 2003). Surface mulches physically suppress weeds by altering light quantity and quality and temperature at the soil surface. They also act as a barrier to reduce successful seedling emergence. Previous research has demonstrated that weed control increases with increasing cover

crop biomass; however, levels that are typically achieved in northeastern U.S. cropping systems (e.g., 3300 kg ha⁻¹) are generally insufficient to provide adequate levels of weed suppression (Mohler and Teasdale 1993). In addition, uniform distribution of cover crop residues is needed for consistent suppression of weed emergence (Creamer et al. 1996; Teasdale and Mohler 1993). Third, the impact of cover crop residues on weed control is species-specific with some species being quite susceptible to cover crop surface mulches, while others are not (Liebman and Davis 2000; Mohler and Teasdale 1993). Finally, weed control with cover crop surface residues alone has generally been incomplete requiring integration of cover crops into a weed management program that relies on additional management tactics (Williams et al. 1998).

This research evaluated the opportunities and constraints to managing weed populations with cover crops in low and high disturbance cropping systems using a two-fold approach: 1) using soil disturbance and cover crop residue management as a means to rapidly deplete the weed seedbank in high disturbance organic and low external input systems and 2) using novel cover crop residue management strategies to reduce or eliminate herbicides in no-tillage cropping systems. This research makes important contributions to sustainable agriculture by providing information on the interplay between the timing of cover crop and tillage practices and weed germination and growth as well as the factors affecting mechanical control of cover crops, biomass accumulation, and resulting weed suppression.

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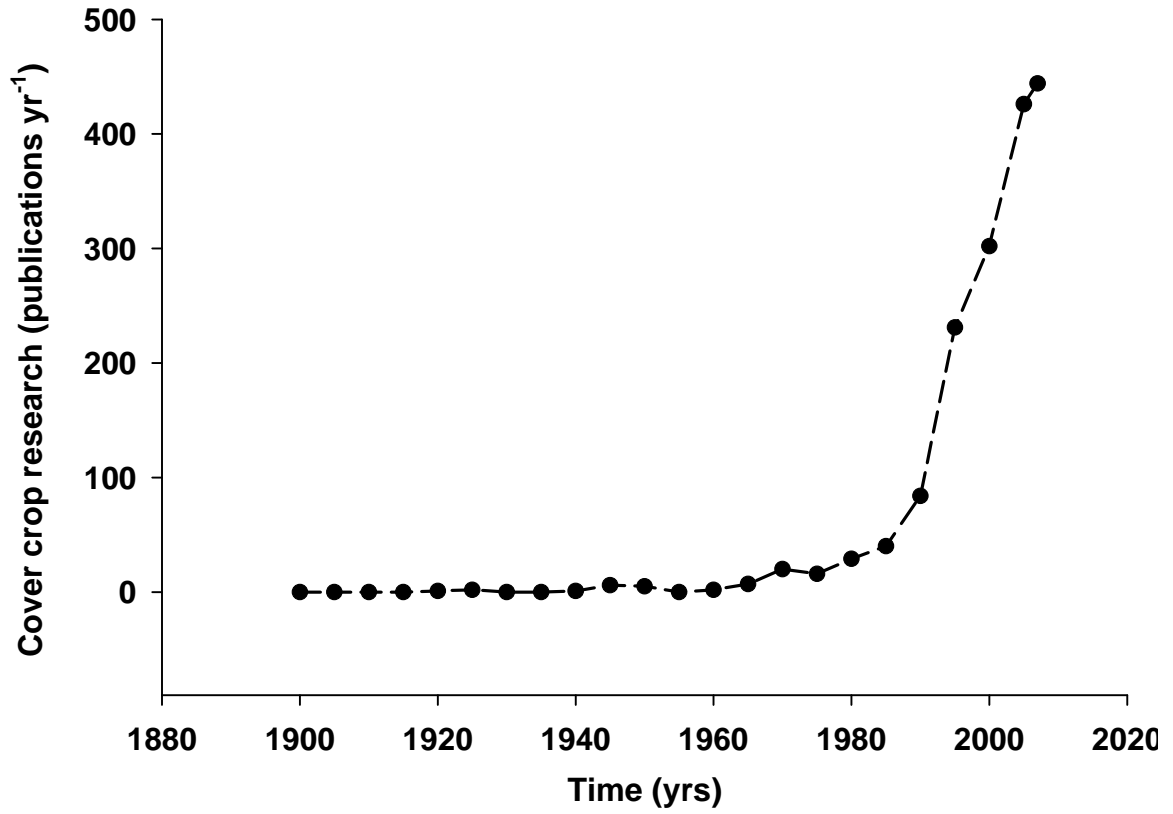
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Figure 1. Cumulative annual peer-reviewed papers published containing the key words cover crop, cover crops, green manure, green manures, mulch and mulches from 1900 through 2007 using web of science.



Chapter 1

Reducing the germinable weed seedbank with soil disturbance and cover crops

ABSTRACT

Reduced reliance on herbicides for weed control can result in weed escapes, potentially allowing the addition of weed seed to the soil seedbank. At the same time, previous research suggests, low weed seedbank densities result in a higher likelihood of successful weed control in reduced herbicide systems. Therefore, developing techniques that quickly reduce the weed seedbank would enable the use of practices that require fewer weed management inputs, especially herbicide use. In this study, we assessed the influence of frequency of soil disturbance and cover cropping on the germinable seedbank of common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* L.), and foxtail spp. (*Setaria* spp.) across a range of initial weed seedbank densities. Cover crop systems investigated ranged from a control treatment (summer fallow) that included tillage about every 30 d during the summer, to an oat (*Avena sativa* L.)/red clover (*Trifolium pretense* L.) cover crop mowed periodically to prevent weed seed production. Generally, soil disturbance associated with cover cropping encouraged germination and seedling establishment thereby reducing the density of germinable seed in the weed seedbank. Of the five cover crop systems studied, the summer fallow and the cover crop sequence that included yellow mustard (*Brassica juncea* (L.) Czern.)/buckwheat (*Fagopyrum sagittatum* Gilib.)/winter canola (*Brassica napus* L.) consistently decreased weed seedbank density. The magnitude of decline in these high disturbance systems reached complete depletion of the germinable seedbank for foxtail

spp., 85% for common lambsquarters, and 80% for velvetleaf. Both systems included tilling the soil three to four times throughout the growing season, with the last tillage event occurring late enough to prevent weed seed production. In contrast, treatments including oat/red clover, oat/pea-rye/hairy vetch, and oat or green bean (*Phaseolus vulgaris*)-rye/hairy vetch allowed weed seed rain in one or more site years. It is clear that the frequent and evenly distributed soil disturbance events can rapidly reduce weed infestations and that combining this with cover cropping can potentially improve or maintain soil quality, while reducing weed seedbank density.

INTRODUCTION

Weed infestations are driven by propagule density. Weed management outcomes are linked to infestation size as larger resident weed seedbanks often require more weed control to adequately manage the population (Dieleman et al. 1999; Hartzler and Roth 1993). Ecologically based weed management (EBWM) relies on an integrated suite of control tactics that achieve an acceptable level of weed suppression (Liebman and Gallandt 1997). EBWM strategies are often adopted by growers moving to lower herbicide use and organic methods of crop production. Systems that rely less on herbicides place a greater emphasis on cultural (crop rotation diversification, and cover cropping) and mechanical weed control practices (e.g., cultivation). However, the efficacy of these practices is more variable than herbicide-dominated weed management (Ryan et al. 2007). For example, cultivation performed at the right time results in a high level of control, comparable to using herbicides (Mohler et al. 1997; Schweizer et al. 1994; VanGessel et al. 1995). Still, EBWM that relies on timely tillage operations can be

compromised when field working days are limited by rainfall (Gunsolus and Buhler 1999; Ryan et al. 2007) with a resulting increase in the weed seedbank (Forcella and Lindstrom 1988). It is therefore critical to design and assess new tactics and their integration that reduce this variation in performance.

The size of the weed seedbank strongly influences the success of any weed management practice, and is critical to the success of EBWM (Dieleman et al. 1999; Forcella et al. 1993). Jordan (1996) suggests that EBWM “must be buttressed by efforts to reduce weed seedbanks and maintain them at low levels.” EBWM can manipulate weed population and community dynamics in a number of ways by: 1) reducing the seedbank pool size by stimulating seed death; 2) stimulating germination; 3) limiting weed seed production of emerged plants; or 4) completely removing above-ground weed biomass (Swanton and Booth 2004). Numerous studies have examined both biotic and abiotic mechanisms that regulate weed seedbanks, including weed seed predation (Westerman et al. 2005), physiological death (Copeland and McDonald 1995), severe temperature swings (Lonsdale 1993), and seed deterioration from microbial activity and pathogenic processes (Kremer 1993). The dormant fraction of the seedbank has been identified as one of the critical life stages for weed population persistence (Jordan et al. 1995) and it is less influenced by management than the readily germinable fraction (Gallandt et al. 2004). In contrast, the germinable fraction of the seedbank has the most substantial impact on weed seedbank flux, with the potential to account for more than half of seedbank losses annually (Gallandt et al. 2004). Therefore, EBWM methods that target the germinable weed seedbank and prevent weed seed production will likely have

the greatest impact on weed seedbank size. Gallandt (2006) suggests an effective way to achieve these reductions is through tillage-induced germination and subsequent control.

Germination of many species is stimulated by soil disturbance (Cavers and Benoit 1989); in this way the expressed germinable fraction can be increased. Potential mechanisms for this germination response include: exposure to light for light-sensitive species (Gallagher and Cardina 1998a); temperature fluctuations (Thompson and Grime 1983), and movement of seed to favorable germination sites (Egley and Chandler 1978; Milberg et al. 1996). Tillage also increases microbial biomass through soil aeration and by exposing occluded labile soil organic matter fractions (Plante and McGill 2002). The increase in microbial activity can also increase biosynthesis of ethylene (Hilhorst and Karssen 2000) which is a known germination stimulant (Egley 1980). Thus, tillage stimulates germination and can be considered a weed expressive tactic (Nordell and Nordell 2006).

Roberts and Feast (1973) observed higher losses (42-56%) of weed seeds through emergence in disturbed soils compared to undisturbed soils (31-34%). Annual losses of seeds to germination range from 6-82% depending on species and depth in soil (Cook 1980; Egley and Williams 1990; Roberts and Feast 1972). These losses vary by location (Burnside et al. 1977; Donald and Zimdahl 1987; Robocker et al. 1969) and sources of seed within an individual species (Donald 1993). Further, Schweizer and Zimdahl (1984) emphasize the importance of consistency in management as poor management in one year can result in dramatic increases in the seedbank that more than offset losses from germination.

Organic farmers and growers using EBWM have relied on weed expressive tactics such as the stale seedbed approach before planting (Johnson and Mullinix 1998; Lonsbary et al. 2003; Nordell and Nordell 2006). Germination periodicity, or loss of seeds to germination, is primarily cued by soil temperature and light (Gallagher and Cardina 1998b). Synchrony of management tactics and germination periodicity can be an effective way of “expressing” then controlling emerged plants. However, because the germination period is species-specific, the timing of EBWM can result in weed community changes (Booth and Swanton 2002). Identifying weed management practices that consistently reduce weed seedbanks across a range of weed life history strategies (i.e., broadleaf vs. grasses; annuals vs. perennials; early vs. late emerging weeds) will further the adoption of EBWM.

Achieving weed suppression through greater soil disturbance could have adverse effects on the soil carbon content and soil structure (chapters 3 and 4), especially in light of the significant transition in U.S. agriculture to reduced- and no-till agriculture. High levels of soil disturbance can dramatically reduce soil quality (Gerhardt, 1997). However, two long-term cropping system experiments demonstrated higher soil C sequestration in conventionally tilled soils receiving higher levels and/or frequencies of manure and cover crops than continuous no-tillage or diversified perennial/annual cash crop systems receiving less or no organic amendments (Mirsky et al. 2008; Teasdale et al. 2007). Therefore, integrating cover crops into higher soil disturbance systems should help offset potential declines in soil C.

In many reduced-herbicide and organic crop production systems, cover crops play an important role and could compliment a stale-seedbed weed management approach.

Cover crops offer multi-tactic weed management by: providing a competitive environment that can reduce or delay the reproductive potential of surviving weeds (Gallandt 2006; Teasdale and Mohler 1993); once suppressed, the cover crop residue can reduce weed establishment (Mohler and Teasdale 1993); or if incorporated into the soil, they can release allelopathic compounds that reduce weed emergence and early growth (Mohler 2001; Reberg-Horton et al. 2005). Additionally, cover crops residues provide an energy source which increases biological activity that can affect weed germination and establishment.

Whereas complementary research efforts are evaluating how the soil surface environment can be manipulated to decrease rates of weed seed persistence (Chapter 2), this study quantified the influence of five diverse cover crop systems on weed seedbank flux. The objective of this study was to quantify the magnitude of weed seedbank depletion resulting from a range of EBWM systems that varied in type and frequency of disturbance and cover crop practices. The effect of initial seedbank density on EBWM is reported. We hypothesized that: 1) the magnitude of decline in the germinable weed seedbank will increase with increasing frequency of soil disturbance and cover cropping; 2) the frequency of soil disturbance and cover cropping must increase as the density of the weed seedbank increases in order to preserve a constant level of weed management efficacy and 3) consistency in weed decline across geographic regions and weed life history traits will increase with increasing soil disturbance and cover crop system intensity.

METHODS

Field experiments were conducted from 2003 to 2006 at the Rogers Farm in Old Town, Maine (44°55' N, 68°41' W) and the Russell E. Larson Agricultural Research Center in Rock Springs, Pennsylvania (40°44' N, 77°57' W) to evaluate the influence of soil disturbance frequency and cover cropping practices on the germinable weed seedbank for three summer annual weeds. The experiment was initiated in the fall of 2003, and repeated in 2004, in adjacent fields in Maine and Pennsylvania. Field site years will be referenced throughout the paper by the year that the cover cropping systems were implemented (2004 and 2005). The study was conducted on a Hagerstown silt loam soil (Fine, mixed, mesic, Typic Hapludalfs) in Pennsylvania and a Buxton silt loam soil (Fine, illitic, frigid Aquic Dystric Eutrudepts) in Maine.

The experiment was arranged as a split-plot randomized complete block with four replicates. Main plot treatments were five cover crop systems representing different crops, levels of soil disturbance, duration of cover, and quantity and quality of biomass production (Table 1.1). The resident weed seedbank was supplemented by adding seed to establish a range of weed seedbank densities. An experimental replicate consisted of five main plots (12.2 by 12.2 m), and 20 weed seedbank density sub-plots (2.7 by 1.5 m); four in each main plot.

Supplemented weed seedbank. Weed seedbanks were supplemented in the late fall (Pennsylvania) or early spring (Maine) prior to planting the cover crops. The supplemented seedbanks were comprised of giant foxtail (*Setaria faberi* L.) in Pennsylvania and yellow foxtail (*Setaria glauca* (L.) Beauv.) in Maine, along with common lambsquarters (*Chenopodium album* L.), and velvetleaf (*Abutilon theophrasti*

Medik.) at both sites. Target weeds were seeded at three densities along with a control subplot that was not amended (0, 60, 450, and 2100 seeds m⁻²). Therefore, the combined subplot densities for the three target species are 0, 180, 1350, 6,300 seeds m⁻². Weed density sub-plots will be referred to as the control, low, medium, and high densities, respectively. The three species were selected because of their economic importance in Northeastern crop production (Curran, personal communication) as well as representing three important life history traits; annual grass (foxtail spp.), small seeded annual broadleaf (common lambsquarters), and larger seeded annual broadleaf (velvetleaf); all of which are known to vary in response to soil disturbance and cover cropping practices (Buhler 1995; Moonen and Berberi 2004).

The mixture of weed seeds for each density plot was combined with 473 cm³ of sand and thoroughly mixed prior to spreading to ensure even spatial distribution of the supplemental seeds when applied to the soil surface. High density plots were also “seeded” with 2100 ceramic beads m⁻² which served as weed seed surrogates (Macrolite 0.06 to 0.02 sphere diameter, No. ML1430; Freeman Manufacturing and Supply Co., 1101 Moore Road, Avon, OH, 44011). The beads were slightly larger than common lambsquarters seeds and served as an internal standard to quantify the efficiency of weed seed recovery (Mohler et al. 2006) in the greenhouse assay and elutriation procedure (below). To enhance visibility, beads were painted with an orange acrylic paint. In Pennsylvania, fields were disked and culti-mulched twice to ensure a smooth seedbed and the seed mixture was spread by hand in each density plot. In Maine, primary tillage consisted of chisel plowing followed by two passes with a soil conditioner (Perfecta Harrow, Unverferth Manufacturing Co, Inc. 18107 U.S. 224 West P.O. Box 357, Kalida,

OH 45853). In Pennsylvania, weed seeds were lightly incorporated after sowing using a leaf rake or tine weeder; in Maine seeds were frost-seeded in early spring.

Cover crop systems. Cover and cash crop treatments were established in the spring of 2004 and repeated in an adjacent field in 2005 (Table 1.2). In Pennsylvania, the previous crops were field corn and soybean and in Maine, fallow and corn silage for 2004 and 2005, respectively. The timing and number of field operations for each cover crop system are provided in Tables 1.1 and 1.2. The five cover crop systems included: 1) summer fallow where no crop was grown (SF); 2) an oat (*Avena sativa* L. ‘Ogle’) cash crop followed by rye (*Secale cereale* L. ‘Aroostook’)/hairy vetch (*Vicia villosa* Roth.) in Pennsylvania (O-R/HV) or a green bean (*Phaseolus vulgaris* L. ‘Provider’) cash crop followed by rye/hairy vetch in Maine (GB-R/HV; this within treatment difference between the two locations reflected regional differences in production practices); 3) oat/pea (*Pisum sativum* L. ‘Maxum’) followed by rye/hairy vetch (O/P-R/HV); 4) oats/red clover (*Trifolium pratense* L. ‘Mammoth’) (O/RC); and 5) yellow mustard (*Brassica juncea* L. ‘Idagold’) followed by buckwheat (*Fagopyrum esculentum* Moench.) followed by winter canola (*Brassica napus* L. ‘Dwarf Essex’) (B-BW-B).

Prior to establishing the cover and cash crop treatments in the spring, primary tillage was completed in Maine with a Perfecta II s-tine cultivator (2x), while in Pennsylvania, fields were tilled twice with a cultimulcher (2x). All legume cover crops were inoculated with appropriate strains of *Rhizobium* spp. prior to planting. Crops were seeded in 19 cm spaced rows with either a Great Plains drill (1006NT) in Pennsylvania or a Massy Harris drill in Maine (1960’s model), or for buckwheat and mustard species with a Brillion (“SS-Solid Stand”; 1.5 m width) seeder (both locations) in 10 cm rows.

The green bean cash crop was planted in 76 cm rows. For treatments with more than one crop grown in a season, the preceding cover crop was flail or rotary mowed and soil incorporated using a rotary cultivator. In Pennsylvania, the plots were additionally cultmulched twice prior to seeding the next crop. The direction of travel during each tillage operation was alternated to minimize the movement of weed seed out of the density plots.

The five cover crop systems spanned a range of cropping and tillage intensity. Cover crop systems were based on practices farmers are currently working with in the Northeast (Clark 2007). Systems were chosen to represent a range of cover cropping intensities which is described by the duration of living plant cover, the biomass production of the cover crop, and the number of unique tillage or mowing passes conducted during the recruitment year (Tables 1.1 and 1.2). The SF and B-BW-B were the highest disturbance cover crop systems, one with no living plant cover (SF) and one with a significant period of the field season with living plant cover (B-BW-B). The SF treatment was selected to maximize depletion of the seedbank through a stale-seedbed approach while the B-BW-B system incorporated cover crops to help suppress weeds and off-set soil C losses associated with high soil disturbance frequency (Table 1.1). The O-R/HV and GB-R/HV cash crop systems also had high disturbance frequency, but in this case a cash crop was harvested and considerably less plant biomass was incorporated in the soil. An additional feature of these cash crop systems was soil disturbance in late spring and not evenly distributed throughout the growing season. The oat cash crop was treated with 0.56 kg ae ha⁻¹ MCPA amine, postemergence about six weeks after seeding for control of annual broadleaf weeds, while the green bean cash crop was managed

organically relying on cultivation for weed control. The oats and green beans were machine harvested for grain or fresh market produce, respectively in early August. The O/P-R/HV and O/RC systems were low disturbance systems that primarily test the capacity of living covers to suppress weeds in combination with multiple mowings for the biennial red clover system, and a single mowing and mid-summer tillage for the O/P-R/HV system. The oats cover crop within the O/RC system was terminated by mowing the oats down to about 15 cm above the soil surface or approximately 1 cm above the red clover stand at the late boot stage with a rotary mower in Pennsylvania and flail mower in Maine. Crops were flail or rotary mowed prior to soil incorporation in the O-R/HV, O/P-R/HV, O/RC, and B-BW-B systems. Above ground cover crop and weed biomass were measured prior to each termination event by clipping all above-ground plant material from two 0.25-m² quadrats in each plot. The biomass was dried at 50°C for one week prior to weighing. Biomass reported in this study only included spring and summer planted cover crops; most of the biomass accumulated from the fall planted covers resulted after the final seedbank census.

Quantifying changes in seedbank populations. The initial and final weed seedbank density was enumerated at both locations in the spring of each field site year prior to management using greenhouse assays and direct extraction (Gross 1990; Gallandt et al. 1998). Greenhouse germination (Gallandt et al. 1998) was used to estimate the readily germinable (non-dormant to partially dormant) fraction of the seedbank from the density subplots. Ten (8.3 cm diameter by 10 cm deep) soil cores were collected from each density subplot in the control, low, and medium plots, and 15 cores were sampled from the high density subplots. Samples were randomly collected from half (2.7 by 0.75 m) of

each density subplot in order to separate the region of the sub-plots sampled for seedbank enumeration from the area used to collect recruitment (seedling emergence) data. Soil cores from each plot were combined and stored at 5 °C prior to conducting seedbank enumeration. A sub-sample equivalent to five soil cores was also taken from the high density 15 soil core samples and stored at -5 °C for later direct extraction.

Soils were prepared for the greenhouse assays immediately after sampling or stored at (5°C) prior to analysis (between 1 and 4 weeks). Soil samples were prepared for the greenhouse assay by crushing large soil aggregates and passing the sample through a 6-mm sieve to remove stones and large organic debris. The soil was spread over a 2.5 cm layer of fine vermiculite in plastic flats (40 x 51 x 6-cm deep), then placed in a greenhouse maintained at a 25/15 °C 12/12 hour thermoperiod. Flats were watered daily and emerged weed seedlings were identified by species, counted, and then removed after four to six weeks in the glasshouse. The soil was then allowed to air dry two to three weeks, separated from vermiculite layer, hand-crushed, mixed, then placed back into the flats on a bed of vermiculate, and seedling census repeated. This sequence was repeated four times.

Direct extraction, in which weed seeds are separated from the soil using elutriation (Gross 1990), was performed on soil taken from the high density subplots to corroborate the greenhouse assays. Direct extraction of weed seeds from soil samples is labor intensive and requires expensive wet sieving equipment. In addition, difficulties in detecting small seeds, variations in seed color, and difficulty distinguishing among species with similar seed morphologies, may underestimate seedbank enumeration and distort estimates of weed community composition (Gross 1990). Common lambsquarters

seed were not targeted in the elutriation procedure because of small seed size and similarity to *Amaranthus* spp. species also present in the field.

Direct extraction was completed for the ceramic beads, velvetleaf and foxtail spp. with a modified hydropneumatic root elutriator (Gillison's Variety Fabrication Inc.,) (Gross 1990; Smucker et al. 1982). A subsample of soil (approximately 900 g) from the five soil core composite sample was submerged in water for 10 minutes in a vertically mounted polyvinyl chloride (PVC) column agitated with forced air and then all organic material and suspended soil particles were rinsed through 600 μm screens. The screens permit passage of the clay, silt, and smaller sand particles while retaining weed seeds, larger sand particles, and related organic matter size fractions. The remaining sample was submerged into a K_2CO_3 solution (125 g L^{-1}) to separate remaining velvetleaf in the sample by flotation (Buhler and Maxwell 1993). Weed seeds were then identified and separated from sieved soils under a dissecting microscope. Viability was estimated by applying pressure to seeds with forceps or a dissecting needle. Firm seeds were assumed to be viable (Ball and Miller 1989; Forcella 1992).

Because germination is a primary mechanism by which weed seeds leave the seedbank (Bekker et al. 2003), recruitment was measured in the field prior to each field disturbance between May and August. Seedling emergence was quantified by placing a 0.5 m^2 quadrat within each density subplot and counting the target weed species including other dominant weed species present in the field. In general, emerged weed seedlings were considered a deficit to the seedbank unless weeds survived to produce seeds. Although fecundity of mature weeds in the different cover crop systems was not quantified, mature weed populations capable of introducing seeds were documented.

Statistical methods. The relationship between the two seedbank enumeration methods was determined using correlation statistics. Correlation analysis between the greenhouse assay and the direct extraction method was tested on the high density plots including both initial and final seedbanks at both locations and field site years. Analysis of variance (ANOVA) was conducted using a PROC MIXED procedure in SAS v. 9.1 (SAS Institute Inc. 2004) to test for cover crop system and density effects on the initial germinable seedbank by field site year and location. Preliminary analyses showed field site year to be significant at both locations; therefore, the change in seedbank, hereafter referred to as Δ seedbank, was evaluated across cover crop systems by location and field site year using analysis of covariance (ANCOVA), with initial seedbank density as a covariate. Annual seedbank change (Δ) represents the difference between final to initial germinable weed seedbank. This relationship can be examined using proportional change (final/initial) or by computing the difference. The latter method was selected for the population dynamics analysis because of zero counts in the weed seedbank data. ANCOVA was performed using Proc Mixed in SAS version 9.1. ANOVA was also used to test the effects of field site year, location, and cover crop system on cumulative weed seedling recruitment. All mean comparisons were performed using the Tukey-Kramer method ($P < 0.05$).

Weed community dynamics were examined using redundancy analysis (RDA) with CANOCO 4.5 (ter Braak and Smilauer 2002). RDA is well-suited for quantifying associations between nominal and continuous explanatory variables and their associations with the weed community (Reberg-Horton et al. 2006). A constrained form of principle component analysis, RDA is similar to principle component analysis in that RDA identifies optimal linear models describing community structure and predicts species

response. Regression coefficients in RDA were constrained by factors in the experimental design as well as environmental gradients which allows for hypothesis testing by partitioning the treatment effects into individual factors (Reberg-Horton et al. 2006). RDA was performed on the proportional change (Final/Initial seedbank) of the three target weed species by constraining the weed community with the following explanatory variables: location, cover crop systems, field site year, and the disturbance gradient (Table 1.1). Weed count data typically have a high frequency of zeros that cannot be corrected by transformation to meet the assumptions of multivariate normality (Reberg-Horton et al. 2006). To avoid this potential difficulty, RDA was conducted only on the weed seedbanks from the high density plots; this is justified because the relationship between Δ seedbanks and initial seedbank density was determined to be linear. This issue was avoided in the previous ANCOVA analysis because we used differences instead of proportions; however, the community analysis did not use initial seedbanks as a covariate and only examined the proportional relationship. A Monte Carlo permutation test was used to test for a significant community gradient using 499 permutations. The significance of the community gradient was determined by calculating the proportion of F-statistics generated from the permuted environmental matrices that were greater than the F-statistic calculated from the empirical species-environmental matrix. The environmental variables that best predict the species response was then determined by using a forward selection procedure on the environmental variables. The RDA performed herein is considered a partial RDA because blocks were treated as covariables to remove the block effect. Biplots, developed in CanoDraw (graphical package bundled with CANOCO 4.5) were then used to visualize the degree of association of the target weed

species and explanatory variables. Close proximity or an acute angle between weed group vectors and explanatory variables is indicative of a high degree of association, while vectors perpendicular to the weed species vectors were not correlated and those at 180° of the weed species vectors were negatively correlated.

Hypothesis testing in structured field experiments is desired for evaluating treatment effects. Therefore, a complimentary permutational multivariate analysis of variance, PERMANOVA (Anderson 2005), was used to account for treatment effects and interactions. PERMANOVA simultaneously tests for responses of multiple variables (i.e., weed species) on multiple treatment factors (i.e., cover crop systems, field site year, and location) based on distance measures, retaining the structure of the experimental design, using permutation methods (Anderson 2001; McArdle and Anderson 2001). A single distance measure is computed from community signatures, distance measures of community composition compared between samples, and then F-statistics are calculated similarly to the Monte Carlo permutation method previously described. The Bray-Curtis distance measure was used in this analysis, and the data were permuted 499 times.

RESULTS AND DISCUSSION

Cover and cash crop biomass. The cover crop treatments (with the exception of SF) had living cover present for much of the experimental period. Cover crop systems typically yielded in excess of 3000 kg ha⁻¹ during the 12 month experimental period. The oats/pea system produced the greatest cover crop biomass, averaging 5200 and 8000 kg ha⁻¹ in Maine and Pennsylvania, respectively. The O/RC and B-BW-B systems yielded approximately 2700 and 3800 kg ha⁻¹ of cover crop biomass in Maine and Pennsylvania,

respectively. It is likely that the cooler, shorter growing season in Maine accounts for the lower biomass yields. Cover crop systems that allowed weeds to reach reproductive maturity tended to have higher weed biomass (data not shown). Yellow foxtail reached reproductive maturity in 2004 in Maine in the O/P-R/HV and O/RC systems, while in Pennsylvania, giant foxtail set seed in both field site years in O/RC and in 2004 in O-R/HV. Some common lambsquarters produced seed in both field site years in Maine's O/P-R/HV system and the 2005 field site in Pennsylvania's O/RC. Velvetleaf did not reach maturity in any of the cover crop systems at either location.

Seedbank quantification. Efforts were made to ensure that tillage traffic patterns were bi-directional, to reduce seed movement out of the weed density sub-plots. Based on ceramic bead recovery (data not presented), recapture efficiency was consistent across cover crop systems, field sites and locations in this study. A significant positive linear relationship was observed for foxtail spp. and velvetleaf seedbanks between the greenhouse germination assay and direct extraction across seedbank densities and cover crop system treatments ($P < 0.001$; $r = 0.692$). Although the two methods represent different proportions of the total weed seedbank, they responded similarly to the diverse range of management practices. These results are consistent with other comparisons of seed enumeration (Ball and Miller 1989; Cardina and Sparrow 1996; Gross 1990). Elutriated soils usually recover a greater portion of the seedbank, including a larger portion of the highly dormant fraction, while the greenhouse method is a better measure of species diversity; both methods perform well when targeting commonly occurring agronomic weeds (Gross 1990). Because the greenhouse assay showed a level of precision similar to direct extraction, and was conducted on the full range of weed

seedbank density treatments it was selected as the primary means for quantifying Δ seedbank and is the basis for the results reported in this paper.

As expected, the springtime weed seedbank sample, made prior to implementing the cover crop treatments indicated weed seedbanks were similar across cover crop systems within a location. Seedbank supplementation, combined with the background populations, resulted in a wide range of seedbank densities ($P < 0.001$) within each cover crop system. Background populations added to this range, resulting in a nearly ten-fold difference observed for common lambsquarters and a 42-fold difference for foxtail spp. (Table 1.3). The wide range in initial weed seedbank densities (the combined effect of seed supplementation and the naturally occurring seedbank) enhanced our ability to resolve the weed suppressive effects of the cover crop treatments (Table 1.3).

Population dynamics. Univariate analysis was conducted on the change in weed seedbank pool sizes over the range of initial seedbank densities (Tables 1.4-1.7; Figures 1.1-1.3). The slope for the relationship between Δ seedbank and initial seedbank was significant for most cover cropping systems. The slopes of the individual systems express the magnitude of change in the weed seedbanks of the individual systems (Tables 1.4 and 1.5). Due to a significant result in the ANCOVA test for equal slopes, comparisons of fitted values of the Δ weed seedbank at three points over the range of initial germinable seedbank was conducted for giant foxtail, common lambsquarters, and velvetleaf (Table 1.6 and 1.7).

The magnitude of weed seedbank change varied significantly across cover crop systems and weed species (Tables 1.4 and 1.5). Less suppressive cover crop systems that allowed weed seed production always resulted in net seedbank increases (Figure 1.1-1.3).

Those systems that included oats or a slow growing legume tended to be less weed suppressive than the high disturbance systems where the highest rates of seedbank decline were observed (Tables 1.4 and 1.5). There was complete depletion of the germinable foxtail spp. seedbank in the B-BW-B and SF systems at both field site years in Maine and the 2004 field site in Pennsylvania. The common lambsquarters seedbank declined by 85% over the same period in the three high disturbance systems (SF, GB-R/HV or O-R/HV, and B-BW-B) across all field site years and locations. The velvetleaf seedbank consistently declined in all systems but the SF and B-BW-B system had the highest rates of decline (approximately 80%). The O/P-R/HV, O/RC (the two low disturbance treatments) and the cash crop systems still resulted in high rates of decline in the germinable seedbank, averaging about a 73% reduction.

These results suggest a greater potential for depleting the weed seedbank than in a typical cropping season with good weed management where rates of seedbank depletion may approach 50%. For example, Smith and Gross (2006) observed rapid change in weed species abundance and composition over the course of a field season where changes were attributed to crop type and management inputs (Smith and Gross 2006). Teasdale et al. (2004) reported greater than 50% reductions in the smooth pigweed (*Amaranthus hybridus* L.) germinable weed seedbank in years of good weed management in a soybean (*Glycine max* (L.) Merr.) cash crop. In another study that included eight locations across the US Corn Belt, common lambsquarters, giant foxtail, and velvetleaf seedbanks declined 40-47%, 78%, and 42%, respectively over a one year period (Davis et al. 2005).

The species-specific responses to the cover crop treatments resulted in a restructuring of the weed community. While we chose to study three summer annual weed species,

they broadly represent different classes (small seeded grass and broadleaf and larger seeded broadleaf) of commonly occurring summer annual weeds. Therefore, we infer that these systems would act in a similar way on a broader spectrum of species; drastic declines in number of species with the possible increase in population size of a select few depending on disturbance frequency and cover cropping practices.

A comparison of cover crop systems at points over the range of initial foxtail spp. seedbank density indicated that foxtail spp. increased in O/RC in the 2004 field site in Maine, in both field site years in Pennsylvania, and also increased in O/P-R/HV in Maine in 2004 (Table 1.6 and 1.7). Common lambsquarters increased in the O/P-R/HV in both field site years in Maine and in O/RC in Pennsylvania (2005). In Maine, increases in common lambsquarters and yellow foxtail weed seedbanks in O/P-R/HV were attributed to inclement weather (heavy rains). The increase in the giant foxtail seedbank in the Pennsylvania cash crop system that included oats was partially due to uneven crop establishment, resulting in stand gaps that allowed giant foxtail establishment and reproductive success (Table 1.7). In addition, there is no effective method for postemergence control for giant foxtail in spring oats and the cash crop was not harvested until mid August, allowing foxtail reproduction.

Proportional decline in foxtail seedbanks was highest in high disturbance systems at the medium and high initial seedbank densities (Tables 1.6 and 1.7). Contrary to the cash crop system in Maine (green beans), the Pennsylvania cash crop system was generally less weed suppressive, resulting in lower rates of giant foxtail seedbank decline or actual increases to the seedbank as was the case in 2004 (Table 1.7). The common lambsquarters seedbank was reduced by all cropping systems except in O/P-R/HV in

Maine (both field site years) (Table 1.6) and O/RC in Pennsylvania (2004) (Table 1.7). In Pennsylvania, SF typically had the greatest seedbank decline (2004). The O/RC system generally reduced the common lambsquarters seedbank population less at the medium to high weed densities compared to the other systems. Velvetleaf Δ seedbank was consistently reduced by all cropping systems at both locations and field sites (Figures 1.3). In Maine in 2005, the decrease in the velvetleaf seedbank was lower at the medium to high initial seedbank densities for the GB-R/HV and O/RC compared to the other systems (Table 1.6). The Δ seedbank for velvetleaf was similar across cropping systems in Pennsylvania; only O/P-R/HV in 2005 resulted in a lower rate of seedbank decline at medium to high population densities (Table 1.7).

Where declines in the weed seedbank were observed, the rate of decline, for a given system, was not influenced by the initial weed seedbank densities (Figures 1.1-1.3). Therefore, while the rate of decline did vary between systems, this rate was constant within a given system (Tables 1.4-1.7); the relationship between seedbank decline as a function of initial seedbank densities, for a given system, was a constant linear relationship (Figures 1.1-1.3). These results lead us to reject the hypothesis that weed control efficacy decreases at higher weed seedbank density. Changes in efficacy may exist in the case of systems where fecundity occurred. However, cover crop systems that allowed weed seed production maintained or increased seedbank populations and did not permit further exploration of this hypothesis. Although limited, other empirical studies have tested the relationship between initial weed seedbank size and weed management efficacy and have shown density to influence efficacy (Dieleman et al. 1999; Neeser et al. 2002; Taylor and Hartzler 2000; Zasada et al. 1997). Zasada et al. (1997) observed no

difference in acceptable weed control 57 days after planting when using a preemergence, postemergence, or no herbicide when measured across a range of low initial common lambsquarters densities (10-42 seedling m⁻²) in no-tillage corn. However, in this same experiment, additional control measures were necessary for adequate suppression when initial weed seedling densities were higher (130-205 seedling m⁻²). Neeser et al. (2002) observed a strong density dependent response, curvilinear relationship between pre- and post-mortality velvetleaf density when reduced post-emergence herbicide rates coupled with cultivation were applied to velvetleaf populations varied with seedbank densities (10 – 22,2000 seeds m⁻²). While efficacy of weed control can be density dependent, the systems that successfully reduced weed populations in this study did not have successful seed production. Without weed seed inputs, the linear rates of decline across varying initial seedbanks observed in this study might be expected.

Cumulative recruitment. Cumulative weed seedling recruitment was used to document losses in the total seedbank from the germinable fraction. System effects were observed when density plots were pooled (data not shown); however, large variations in background weed populations limited our ability to resolve on cover cropping systems effects. Therefore, ANOVA and means separation are reported for the density treatments excluding the SF system (Table 1.8). Although field site year was a significant source of variance for velvetleaf and common lambsquarters in Maine (Table 1.8), field site year was pooled because preliminary analysis showed a similar relationship for both species. Cumulative recruitment differed by cropping system and density, but there were no interactions between these treatments; recruitment did not vary by density for any of the target weeds at either location (Table 1.8).

Summed over systems and treatments, the cumulative emergence for foxtail, common lambsquarters, and velvetleaf was 39, 211, and 69 plants m⁻² in Maine and 68, 77, and 44 plants m⁻² in Pennsylvania. Seedling densities ranged from 0 to 242 and 0 to 448 for foxtail spp.; 37 to 582 and 0 to 388 for common lambsquarters; and 0 to 386 and 0 to 250 plants m⁻² for velvetleaf, in Maine and PA, respectively. Heggenstaller and Liebman (2007) found similar variations in weed seedling recruitment for velvetleaf and foxtail spp. with proportional emergence of initial seedbanks ranging from 0.02 to 0.9 in diversified cropping systems.

Significant differences were not observed for common lambsquarters cumulative recruitment by system at either location (Table 1.9). We attribute this lack of response to high initial background weed populations in both locations and field site year. In Maine, the greatest yellow foxtail recruitment occurred in O/P-R/HV and O/P-R/HV and O/RC for velvetleaf. In Pennsylvania, cumulative recruitment of giant foxtail and velvetleaf was greatest in the B-BW-B and SF systems. In Maine, foxtail spp. and velvetleaf cumulative recruitment was unexpectedly greater in low disturbance systems compared to systems with greater soil disturbance (Table 1.9). This was not the case for the Pennsylvania field site where the systems with higher soil disturbance resulted in the greatest levels of foxtail spp. and velvetleaf seedling recruitment (Table 1.9).

The seedbank density treatment was significant at all three levels (low, medium, and high) for cumulative recruitment of foxtail spp. and velvetleaf in both Maine and Pennsylvania and recruitment was proportional to initial seedbank size (Table 1.10). In contrast, only the high density common lambsquarters treatment in Pennsylvania was significant. In Pennsylvania, systems with high cumulative recruitment also were those

with high seedbank declines; recruitment was greatest in high disturbance systems. This was not the case in Maine, where low disturbance systems tended to have higher cumulative recruitment. While not congruent to recruitment, all of the high disturbance systems in Maine resulted in deficits to the seedbanks for all target weed species (Figure 1.1-1.3).

While cumulative weed emergence strongly corresponded to initial seedbank densities, it is unclear why emergence did not consistently correspond to the disturbance gradient in Maine. This was probably not due to a lack of response by the weeds to disturbance, but rather functional changes in the soil environment brought on by cover crops and tillage resulting in fatal germination. The suppressive effects of allelopathic cover crops are greatest during weed emergence and early growth (Mohler 2001). Most of the cover crops selected in this study are allelopathic including cereal rye (Shilling et al. 1986), hairy vetch (Creamer et al. 1996), *Brassica spp.* (Putnam 1994), red clover (Davis and Liebman 2003), and oat (Putnam and DeFrank 1983). These cover crops can influence weed seedling emergence in a number of ways. The magnitude and pattern of weed seedling emergence is a complex, species-specific process (Egley and Williams 1990; Ogg and Dawson 1984) that is influenced by soil temperature (Baskin and Baskin 1989), moisture (Weaver et al. 1988), light quantity and quality at the soil surface, soil fertility, chemical germination stimulants (Gallagher and Fuerst 2006), and disturbance frequency and timing (Baskin and Baskin 1989; Roberts 1981). Elucidating effects of the cover crop treatments on fatal germination was outside the scope of this project. The stimulating effect of disturbance on weed seedling recruitment in Pennsylvania is consistent with other reports in the literature. Mulugeta and Stoltenberg (1997) observed

up to a 6-fold increase in giant foxtail and common lambsquarters emergence in tilled versus untilled soils. Additionally, these authors reported 16-fold reductions in common lambsquarters, and 6-fold reductions in giant foxtail seedbanks in a single season.

Weed community analysis. Velvetleaf, common lambsquarters and foxtail spp. responded strongly to cover crop treatments and field sites (Figure 1.4). Using RDA, significant primary and secondary community gradients were quantified where the horizontal (1st) and vertical axes (2nd) were significant (1st axis: $F=15.48$, $P=0.002$; 2nd axis: $F=3.30$, $P=0.002$). The primary axis, which accounts for the greatest amount of variation in the weed communities, represented a soil disturbance gradient ($F=11.85$, $P=0.002$) (Figure 1.4). The cover crop systems were strongly associated with the disturbance gradient, the distribution of systems resulted in the SF, B-BW-B, and cash crop-R/HV on one extreme and O/RC and O/P-R/HV on the other. The species vectors were negatively correlated with disturbance, with the population size (species vectors) increasing toward the lower disturbance regimes. Foxtail spp. population was strongly associated with O/RC particularly in Pennsylvania. Common lambsquarters predominately increased in Maine and was strongly positively associated with O/P-R/HV. Velvetleaf displayed little association with either disturbance gradient or field site year. Species vectors tended to associate with locations where the greatest increases in the populations were observed: giant foxtail and common lambsquarters in Pennsylvania in 2004 and common lambsquarters for both years in Maine (Table 1.3). The B-BW-B and SF systems were both negatively correlated with velvetleaf, common lambsquarters and foxtail (Figure 1.4). The cash crops systems were negatively correlated with common lambsquarters and not correlated to velvetleaf. The orthogonal secondary axis represented

a growing condition gradient (field site years) ($F=3.11$, $P=0.002$). Location had a minor influence on the community gradient, as indicated by proximity to the centroid in the biplot, and based on the forward selection analysis not being significant ($P = 0.940$).

PERMANOVA was used to test the main treatment effects of field site year, location, and cover crop systems on the three targeted species. Weed community was significantly influenced by field site year and cover crop systems, and interactions between field site year and location, and field site year and cover crop systems (Figure 1.4). These results confirm the significant community gradient observed in the ordination biplots, where species vectors and several cover crop systems strongly associated with a given field site year (Figure 1.4). Location was not a significant source of variance, but there was an interaction with field site year. Interactions between location and field site year may have resulted from variation in background seedbank populations between locations, causing greater changes in the seedbank; Pennsylvania having a higher velvetleaf population in 2004 and Maine in 2005 (Table 1.3). Since both cover crop systems and the species vectors were distributed along the disturbance gradient, the results indicate the SF and B-BW-B were the only cover crop systems that consistently reduced all weed populations. In this sense, these two treatments provided the most robust weed management. These results confirmed our hypothesis that consistent depletion of the germinable seedbank increases with greater frequency of soil disturbance and cover cropping.

In their framework for long-term management of weed seedbanks, Swanton and Booth (2004) identified four management tactics that target critical life history stages: increase seed mortality, manipulating seed germination and emergence, reduce seed

production, or complete removal of the above-ground biomass. The success of our community-based weed management approach was a result of the cover crop systems with high disturbance and cover cropping frequency directly and indirectly targeting these four life history stages. A distinct feature of the SF and B-BW-B systems is the soil disturbance that is distributed evenly throughout the growing season, thereby stimulating germination and then controlling the germinated plants. In effect, the SF and B-BW-B serve as a full season form of stale seedbed management. The success of this stale-seedbed approach is only realized if resulting weed cohorts are managed and not allowed to reproduce (Bond and Grundy 2001; Gallandt 2006). Given the B-BW-B system has a lower disturbance frequency than the cash crops systems, which varied in its weed suppressive performance, the distribution of the disturbance events are likely to be as important as frequency.

The SF system served as the control system and was expected to give consistent results across locations because it directly targeted weeds before maturity. However, increases in seed/propagule of a perennial weed were highest in the SF system. Yellow nutsedge (*Cyperus esculentus*) emergence increased by 3-fold in the greenhouse assay ($P < 0.001$) in the SF compared with the B-BW-B system in Pennsylvania (data not shown). Most of the yellow nutsedge emergence in the greenhouse assays appeared to arise from vegetative structures rather than from seed, as indicated by the vigorous plant growth observed during the 4 to 6 week evaluation period. Clearly tillage alone (SF) was not enough to manage the nutsedge. In contrast, the B-BW-B system provided significant suppression of nutsedge. A number of factors could have contributed to decline in yellow nutsedge emergence in the cover crop systems including resource competition and direct

phytotoxic effects (allelochemicals) from the cover crops. Johnson et al. (2007) also found that a multi-tactical approach (solarization and summer fallowing) was needed to adequately manage yellow nutsedge populations. The suppression of yellow nutsedge in the B-BW-B system warrants further investigation.

Our results also suggest that the timing of soil disturbance is as important as frequency in reducing weed fitness. For example, a weather related delay in field operations in the O/P-R/HV system in Maine, resulted in large increases in the common lambsquarters weed seedbank. Similarly, poor crop stand establishment and delays in management in the oats cash crop in Pennsylvania resulted in foxtail surviving to reproductive maturity with corresponding increases in the foxtail seedbank. Variations in timing of disturbance can cause species shifts. If the disturbance coincides with the emergence period of a species, that species will be effectively controlled by the disturbance (Crawley 2004).

CONCLUSION

In this study, cover crops provide multiple agroecosystem services, notably linking management to improve soil quality with multiple direct and indirect stresses that may reduce weed populations (Bàrberi 2002; Gallandt 2004). We identified an approach to rapidly deplete the germinable weed seedbank, while at the same time countering the negative effects of tillage on soil organic matter by incorporating cover crop residues. Field experiments, conducted in Pennsylvania and Maine, demonstrated that soil disturbance associated with cover cropping encouraged weed seed germination and establishment thereby reducing the density of germinable seed in the weed seedbank. Of

the five cover cropping systems, one, B-BW-B consistently depleted the weed seedbank through weed expression and subsequent control of emerged plants. That same system also provided the greatest suppression of the troublesome perennial yellow nutsedge. The frequency and even temporal distribution of soil disturbance in the B-BW-B system stimulated germination and preempted weed seed rain. We also found that the ability to reduce weed populations was dependent on the timeliness of practices. For example, the long growth period of perennial cover crops in this study, allowed emergence, flowering and seed set of rapidly growing summer annual grasses like foxtail spp. If weeds are permitted to reach reproductive maturity in cash or cover crops, the “debits” to the seedbank resulting from early season disturbance are easily overwhelmed by the resulting seed rain “credits” (Forcella 2003). The B-BW-B system provided an effective and consistent community-based approach to weed management (Swanton and Booth 2004). The lower disturbance and cash crop systems may still provide a useful population-based approach to managing weeds. However, their weaknesses were revealed during the course of this study.

In farming systems (e.g. transition to organic, market gardens,) that experience years of inconsistent weed control that result in large additions to the weed seedbank, the strategy of taking a field out of cash crop production and integrating a weed recruitment cover cropping phase appears to be justified given the precipitous declines that can be achieved in the weed seedbank. This practice primarily served as a rescue practice when weed management in the previous year is compromised. The highly dormant fraction of the seedbank will still persist in these cropping systems and will require continuous management. Future research should evaluate how to directly manipulate the persistent

fraction of the seedbanks well as considering strategies for integrating the weed expressive tactics evaluated in this study into cash crop-based systems which do not permit setting aside land to manage weeds.

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Table 1.1. Planting details and disturbance events for the five cropping systems.

Crop System	Variety	Seeding rate (kg/ha)	Disturbance Regime			
			Cultivation		Mowing	
			ME	PA	ME	PA
Fallow	-	-	4	4	0	0
Green beans						
Winter rye	Aroostook	79	4	NA	0	NA
Hairy Vetch	Common	34				
Oats	Provider	95				
Winter rye	Aroostook	79	NA	4	NA	1
Hairy Vetch	Common	34				
Yellow mustard	Idagold	11				
Buckwheat	Common	123	3	3	2	2
Winter canola	Dwarf Essex	11				
Oat	Ogle	79				
Field peas	Maxum	112				
Winter rye	Aroostook	79	2	2	1	1
Hairy vetch	Madison	34				
Oat	Ogle	79				
Red clover	Common	17	1	1	1	2/3 ¹

¹mowing events separated by a / indicate mowing frequency in 2004/2005.

Table 1.2. Cover and cash crop management log during 2004 and 2005 weed recruitment period in Stillwater, Maine and Rock Springs, Pennsylvania.

System	Pennsylvania		Maine		Management
	Field 1 - 2004	Field 2 - 2005	Field 1 - 2004	Field 2 - 2005	
SF	May 12-24	May 27	May 14 & 20	June 28	Field cultivation (2x) ¹
	June 15	June 29	July 6	July 20	Field cultivation (2x)
	July 09	July 20	August 5	August 8	Field cultivation (2x)
	August 17	August 15	August 26	September 6	Field cultivation (2x)
GB- R/HV	-	-	May 14	-	Field cultivation (2x)
	-	-	May 20	-	Field cultivation (2x)
	-	-	June 11	June 28	Field cultivation (2x)
	-	-	June 11	June 28	Plant green beans
	-	-	July 6	July 20	In-row cultivation
	-	-	August 9	August 16	Harvest green beans
	-	-	August 9	August 18	Field cultivation (2x)
	-	-	August 27	August 7	Field cultivation (2x)
	-	-	August 27	August 7	Plant R/HV cover crop
O- R/HV	April 28-30	May 05	-	-	Field cultivation (2x)
	April 28-30	May 06	-	-	Plant oats cash crop
	May 12	-	-	-	Reseeded oats
	May 17,23	May 11,18	-	-	Tine Weeding (2X)
	June 15	June 29	-	-	Herbicide application
	August 09	August 15	-	-	Harvest oats crop
	August 18	August 24	-	-	Field cultivation (2x)
	August 18	August 29	-	-	Plant R/HV cover crop
B -BW- B	May 12-24	May 05	May 14	June 28	Field cultivation (2x)
	May 24	May 06	May 20	June 28	Plant cover crop
	July 09	June 29	July 20	August 6	Mow
	July 17	July 07	July 20	August 6	Field cultivation (2x)
	July 17	July 07	July 22	August 6	Plant buckwheat cover crop
	September 05	September 15	September 2	September 7	Mow with flail mower
	September 11	September 17	September 2	September 7	Field cultivation (2x)
September 14	September 18	September 2	September 7	Plant canola cover crop	
O/P- R/HV	April 28-30	May 05	May 14	June 28	Field cultivation (2x)
	April 28-30	May 06	May 20	June 28	Plant O/P cover crop
	July 09	July 07	August 25	September 7	Flail mow
	August 18	August 24	August 25	September 7	Field cultivation (2x)
	August 18	August 29	August 27	September 7	Plant R/HV cover crop
O/RC	April 28-39	May 05	May 14	June 28	Field cultivation (2x)
	April 28-30	May 06	May 20	June 28	Plant O/RC cover crop
	July 09	July 07	July 30	August 16	Mow O at boot stage
	July 22, Aug. 02,16	July 19,29			Mow tops of clover (2-3X)

Table 1.3. Mean, standard deviation and range of initial germinable seedbank for foxtail spp., common lambsquarters, and velvetleaf populations at Pennsylvania and Maine for 2004 and 2005.

Location	Field site year	Foxtail spp.			Common lambsquarters			Velvetleaf		
		Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
ME	2004	41	58	0-301	4270	2152	844-12,357	26	41	0-181
	2005	152	233	0-1266	2938	2107	121-11,212	131	197	0-1236
PA	2004	1734	1229	91-6030	1768	1182	364-6333	166	212	0-939
	2005	309	276	0-1364	447	639	0-4061	113	176	0-788

Table 1.4. Coefficients for the linear regression of foxtail spp., common lambsquarters, and velvetleaf Δ germinable seedbank as a function of initial germinable seedbanks across the cropping systems in Maine.

Weed Species	Cropping System	2004 Field Site			2005 Field Site		
		β_0	β_1	P > T	β_0	β_1	P > T
Foxtail spp.	SF*	2.21(22.90)	-1.02(0.24)	< 0.0001	2.28(4.70)	-0.98(0.02)	< 0.0001
	GB-R/HV	-7.34(22.37)	-0.47(0.29)	0.1092	5.84(4.75)	-1.00(0.02)	< 0.0001
	B/BW/B	7.14(23.97)	-1.02(0.39)	0.0093	-0.03(4.53)	-1.00(0.01)	< 0.0001
	O/P-R/HV	54.14(22.91)	0.01(0.30)	0.9686	6.55(4.59)	-0.96(0.02)	< 0.0001
	O/RC	38.18(22.86)	0.31(0.32)	0.3342	21.06(4.44)	-0.86(0.01)	< 0.0001
Common lambsquarters	SF	1328.75(1404.76)	-0.83(0.31)	0.0080	393.73(751.68)	-0.91(0.16)	< 0.0001
	GB -R/HV	892.45(1051.79)	-0.71(0.23)	0.0024	-55.15(644.55)	-0.80(0.15)	< 0.0001
	B/BW/B	750.43(1068.95)	-0.73(0.22)	0.0012	-174.64(630.29)	-0.78(0.15)	< 0.0001
	O/P-R/HV	-148.64(1275.88)	1.99(0.26)	< 0.0001	5155.80(588.36)	-0.94(0.11)	< 0.0001
	O/RC	1906.96(1250.49)	-0.57(0.19)	0.0025	1411.69(576.19)	-0.91(0.13)	< 0.0001
Velvetleaf	SF	2.05(6.72)	-0.87(0.13)	< 0.0001	16.95(10.46)	-0.95(0.04)	< 0.0001
	GB -R/HV	2.17(6.66)	-0.74(0.15)	< 0.0001	8.15(10.86)	-0.81(0.05)	< 0.0001
	B/BW/B	4.99(6.83)	-0.56(0.17)	0.0015	7.23(9.87)	-0.94(0.03)	< 0.0001
	O/P-R/HV	1.51(6.53)	-0.60(0.14)	< 0.0001	26.88(10.56)	-0.97(0.04)	< 0.0001
	O/RC	13.10(6.59)	-0.71(0.12)	< 0.0001	19.70(10.36)	-0.78(0.03)	< 0.0001

*SF, summer fallow; GB-R/HV, green bean-rye/hairy vetch; B-BW-B, Brassica-Buckwheat-Brassica; O/P-R/HV, oats/pea-rye/hairy vetch; O/RC, oats/red clover

Table 1.5. Coefficients for the linear regression of giant foxtail, common lambsquarters, and velvetleaf Δ germinable seedbank as a function of initial germinable seedbanks across the cropping systems in Pennsylvania.

Weed Species	Cropping System	2004 Field Site			2005 Field Site		
		β_0	β_1	P > T	β_0	β_1	P > T
Giant foxtail	SF*	302.27(198.24)	-1.01(0.09)	< 0.0001	21.82(59.47)	-0.73(0.11)	< 0.0001
	O-R/HV	1122.50(216.23)	0.01(0.09)	0.9680	-10.43(59.47)	-0.37(0.12)	0.0017
	B/BW/B	224.71(186.25)	-1.00 (0.10)	< 0.0001	-9.31(61.23)	-0.61(0.12)	< 0.0001
	O/P-	81.51(175.94)	-0.80(0.07)	< 0.0001	24.75(61.16)	-0.57(0.14)	< 0.0001
	O/RC	296.39(214.76)	0.08(0.11)	0.4663	206.78(64.04)	0.75(0.13)	< 0.0001
Common lambsquarters	SF	359.23(187.58)	-1.05(0.09)	< 0.0001	29.88(219.34)	-0.94(0.30)	0.0019
	O-R/HV	419.37(219.84)	-0.90(0.13)	< 0.0001	107.02(206.73)	-0.93(0.18)	< 0.0001
	B/BW/B	702.50(219.57)	-0.83(0.07)	< 0.0001	43.04(214.48)	-0.88(0.26)	0.0010
	O/P-	444.41(184.52)	-0.85(0.07)	< 0.0001	63.45(204.09)	-0.89(0.25)	0.0004
	O/RC	706.57(187.34)	-0.89(0.05)	< 0.0001	814.68(217.76)	1.35(0.36)	0.0002
Velvetleaf	SF	14.56(14.72)	-0.77(0.05)	< 0.0001	10.69(12.13)	-0.79(0.05)	< 0.0001
	O-R/HV	31.13(14.52)	-0.76(0.05)	< 0.0001	20.11(11.71)	-0.72(0.04)	< 0.0001
	B/BW/B	20.95(15.52)	-0.78(0.07)	< 0.0001	15.82(11.85)	-0.79(0.05)	< 0.0001
	O/P-	31.27(14.59)	-0.72(0.05)	< 0.0001	4.81(12.56)	-0.52(0.06)	< 0.0001
	O/RC	26.745(14.32)	-0.70(0.05)	< 0.0001	15.37(11.91)	-0.71(0.05)	< 0.0001

*SF, summer fallow; O-R/HV, oats green bean- rye/hairy vetch; B-BW-B, Brassica-Buckwheat-Brassica; O/P-R/HV, oats/pea-rye/hairy vetch; O/RC, oats/red clover

Table 1.6. Comparisons for fitted values of Δ germinable weed seedbanks at three points over the range of initial germinable seedbank of the foxtail spp., common lambsquarters, and velvetleaf using ANCOVA with initial germinable weed seedbank as the covariate (Maine). Mean values within a row for a given location and field site year followed by the same letter are not significantly different according to the Tukey-Kramer test for mean separation ($P < 0.05$).

Species	Field Site Year	Initial Seedbank	Δ Germinable Seedbanks in Cover Cropping Systems				
			SF*	GB-R/HV	B/BW/B	O/P-R/HV	O/RC
			seeds m ⁻²				
Foxtail spp.	2004	25	-23 a	-23 a	-18 a	54 b	46 b
		60	-59 a	-59 a	-54 a	55 b	57 b
		120	-121 a	-121 a	-115 a	56 b	76 b
	2005	50	-47 a	-44 a	-50 a	-41 a	-22 b
		400	-390 ab	-395 ab	-398 a	-378 b	-322 c
		750	-734 a	-745 a	-746 a	-714 a	-622 b
Common lambsquarters	2004	2200	-495 a	-666 a	-860 a	4220 b	647 a
		4500	-2402 a	-2296 a	-2544 a	8786 c	-669 b
		6500	-4060 ab	-3713 ab	-4009 a	12757 c	-1815 b
	2005	1200	-701 ab	-1018 a	-1116 a	4030 c	316 b
		3000	-2342 a	-2461 a	-2528 a	2342 b	-1328 a
		4800	-3984 a	-3905 ab	-3939 ab	653 c	-2973 b
Velvetleaf	2004	10	-7 a	-5 a	-1 a	-4 a	6 a
		55	-46 a	-39 ab	-26 b	-31 ab	-26 b
		100	-85 a	-72 a	-51 a	-58 a	-58 a
	2005	50	-30 a	-32 a	-40 a	-22 a	-19 a
		300	-267 ab	-235 bc	-275 a	-265 ab	-213 c
		500	-456 a	-398 b	-463 a	-460 a	-369 b

*SF, summer fallow; GB-R/HV, green bean- rye/hairy vetch; B-BW-B, Brassica-Buckwheat-Brassica; O/P-R/HV, oats/pea-rye/hairy vetch; O/RC, oats/red clover

Table 1.7. Comparisons for fitted values of Δ germinable weed seedbanks at three points over the range of initial germinable seedbank of the giant foxtail, common lambsquarters, and velvetleaf using ANCOVA with initial germinable weed seedbank as the covariate (Pennsylvania). Mean values within a row for a given location and field site year followed by the same letter are not significantly different according to the Tukey-Kramer test for mean separation ($P < 0.05$).

Species	Field Site Year	Initial Seedbank	Δ Germinable Seedbanks in Cover Cropping Systems				
			SF*	O-R/HV	B/BW/B	O/P-R/HV	O/RC
			seeds m ⁻²				
Giant foxtail	2004	1000	-711 a	1126 c	-779 a	-718 a	373 b
		2000	-1723 a	1130 c	-1784 a	-1518 a	450 b
		3000	-2736 a	1134 d	-2788 a	-2317 b	527 c
	2005	50	-15 a	-29 a	-40 a	-4 a	244 b
		400	-270 a	-159 b	-253 ab	-203 ab	507 c
		700	-489 a	-271 b	-435 a	-374 ab	733 c
Common lambsquarters	2004	750	-429 a	-256 ab	-81 b	-194 ab	41 b
		1800	-1532 a	-1202 b	-790 c	-1088 b	-892 bc
		3800	-3633 a	-3003 ab	-2448 b	-2791 b	-2668 b
	2005	100	-65 a	14 a	-45 a	-26 a	950 b
		800	-726 a	-638 a	-663 a	-650 a	1894 b
		1600	-1481 a	-1383 a	-1368 a	-1364 a	2972 b
Velvetleaf	2004	50	-24 a	-6 a	-18 a	-5 a	-8 a
		350	-254 a	-232 a	-251 a	-222 a	-218 a
		550	-408 a	-382 a	-406 a	-367 a	-358 a
	2005	50	-29 a	-16 a	-24 a	-21 a	-20 a
		350	-264 a	-233 a	-260 a	-178 b	-234 a
		500	-382 a	-341 a	-378 a	-256 b	-341 a

*SF, summer fallow; O-R/HV, oats green bean-rye/hairy vetch; B-BW-B, Brassica-Buckwheat-Brassica; O/P-R/HV, oats/pea-rye/hairy vetch; O/RC, oats/red clover

Table 1.8. Analysis of variance table of cumulative seedling recruitment for foxtail spp., common lambsquarters, and velvetleaf populations in Pennsylvania and Maine for the 2004 and 2005 recruitment year.

Location	Cropping System	Foxtail spp.			Common lambsquarters			Velvetleaf		
		DF	F value	P	DF	F value	P	DF	F value	P
ME	System	4	7.10	0.0001	4	0.69	0.6147	4	4.81	0.0107
	Density	2	158.17	0.0001	2	2.74	0.0701	2	273.99	0.0001
	System*Density	8	0.82	0.5901	8	0.90	0.5171	8	0.62	0.7591
	Field Site Year			0.2827			0.0001			0.0001
PA	System	4	4.99	0.0093	4	2.77	0.0767	4	8.47	0.0009
	Density	2	8.88	0.0003	2	20.16	0.0001	2	91.85	0.0001
	System*Density	8	0.33	0.9517	8	0.36	0.9375	8	1.15	0.3370
	Field Site Year			0.2420			0.2404			0.2584

Table 1.9. Cumulative seedling recruitment for foxtail spp., common lambsquarters, and velvetleaf populations across the cropping systems in Pennsylvania and Maine for the 2004 and 2005 recruitment year (density pooled). Mean values within a given location and year followed by the same letter are not significantly different according to Tukey's tests ($p=0.1$).

Location	System	Foxtail	Common	Velvetleaf
		spp.	lambsquarters	
		----- plants m ⁻² -----		
ME	SF	30 b	240 a	54 b
	GB-R/HV	21 b	172 a	46 b
	B/BW/B	34 ab	206 a	56 ab
	O/P-R/HV	65 a	209 a	101 a
	O/RC	41 ab	230 a	90 a
PA	SF	138 a	99 a	68 a
	O-R/HV	38 b	71 a	50 ab
	B/BW/B	90 a	89 a	50 a
	O/P-R/HV	27 b	43 a	22 b
	O/RC	43 b	104 a	33 b

Table 1.10. Cumulative seedling recruitment for foxtail spp., common lambsquarters, and velvetleaf populations in the density plots for the recruitment year of the cover and cash cropping systems in Pennsylvania and Maine for 2004 and 2005. Mean values within a given location and field site year followed by the same letter are not significantly different according to Tukey's tests ($p=0.05$) for the high density plots.

Location	Density	Foxtail	Common	Velvetleaf
		spp.	lambsquarters	
		----- plants m ⁻² -----		
ME	Low	4 c	194 a	6 c
	Medium	28 b	206 a	35 b
	High	83 a	234 a	167 a
PA	Low	54 c	46 b	6 c
	Medium	68 b	55 b	25 b
	High	121 a	101 a	102 a

Figure 1.1. Mean Δ germinable seedbank as a function of initial germinable seedbank across cropping systems for foxtail spp.: \oplus - Oats/Red Clover; \circ - Brassica spp./Buckwheat/Brassica spp.; Δ - Oats/Pea-Rye/Hairy vetch; \diamond - Fallow; \square - Oats for PA or Green beans for ME-Rye/Hairy vetch. Fitted values from ANCOVA with initial germinable weed seedbank as the covariate were superimposed by cropping system across systems: $+$ - Oats/Red Clover; \bullet - Brassica spp./Buckwheat/Brassica spp.; \blacktriangle - Oats/Pea-Rye/Hairy vetch; \blacklozenge - Fallow; \blacksquare - Oats for PA or Green beans for ME-Rye/Hairy vetch. Analysis was performed using SAS Proc Mixed, and bars represent the standard error of the estimate.

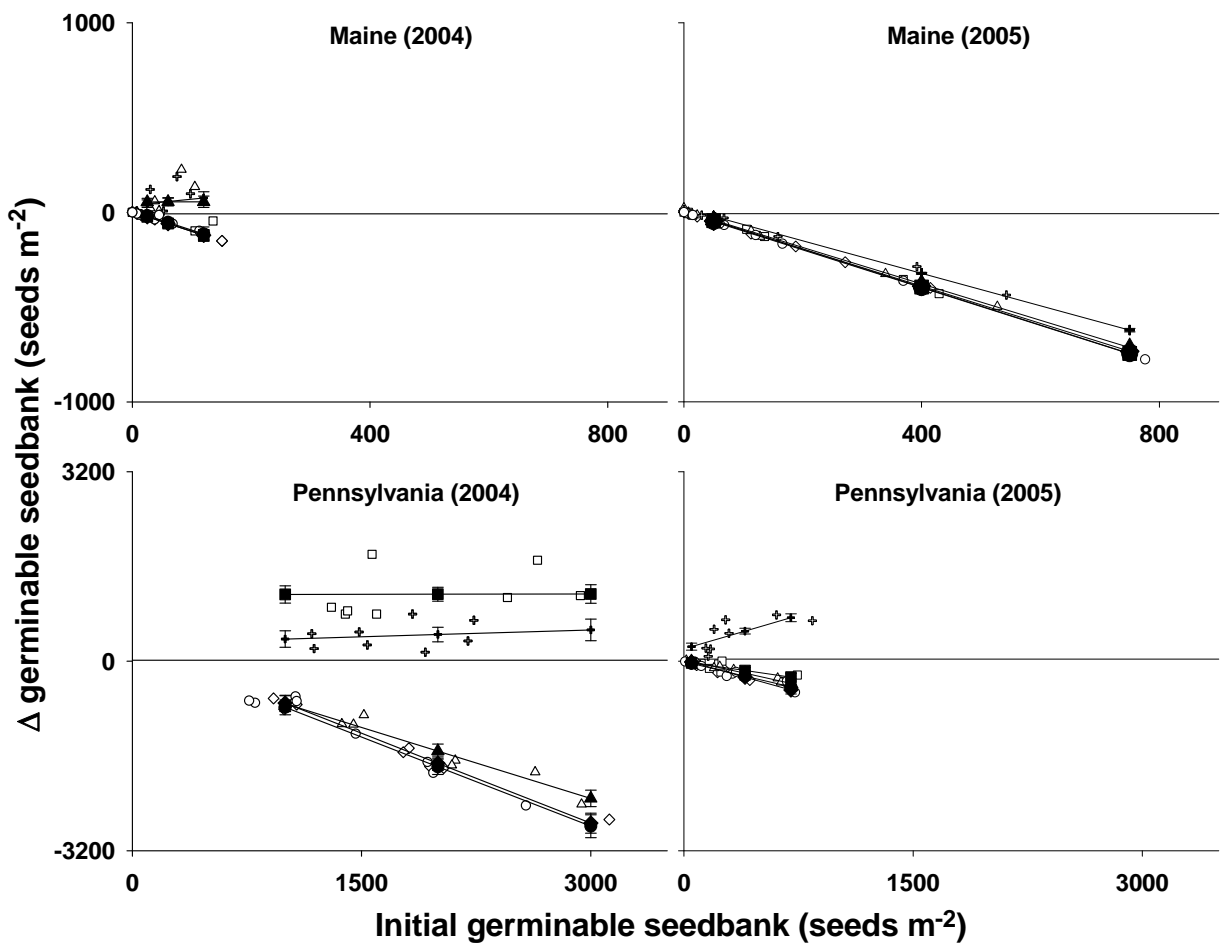


Figure 1.2. Mean Δ germinable seedbank as a function of initial germinable seedbank across cropping systems for common lambsquarters: \oplus - Oats/Red Clover; \circ - Brassica spp./Buckwheat/Brassica spp.; Δ - Oats/Pea-Rye/Hairy vetch; \diamond - Fallow; \square - Oats for PA or Green beans for ME-Rye/Hairy vetch. Fitted values from ANCOVA with initial germinable weed seedbank as the covariate were superimposed by cropping system across systems: $+$ - Oats/Red Clover; \bullet - Brassica spp./Buckwheat/Brassica spp.; \blacktriangle - Oats/Pea-Rye/Hairy vetch; \blacklozenge - Fallow; \blacksquare - Oats for PA or Green beans for ME-Rye/Hairy vetch. Analysis was performed using SAS Proc Mixedd, and bars represent the standard error of the estimate.

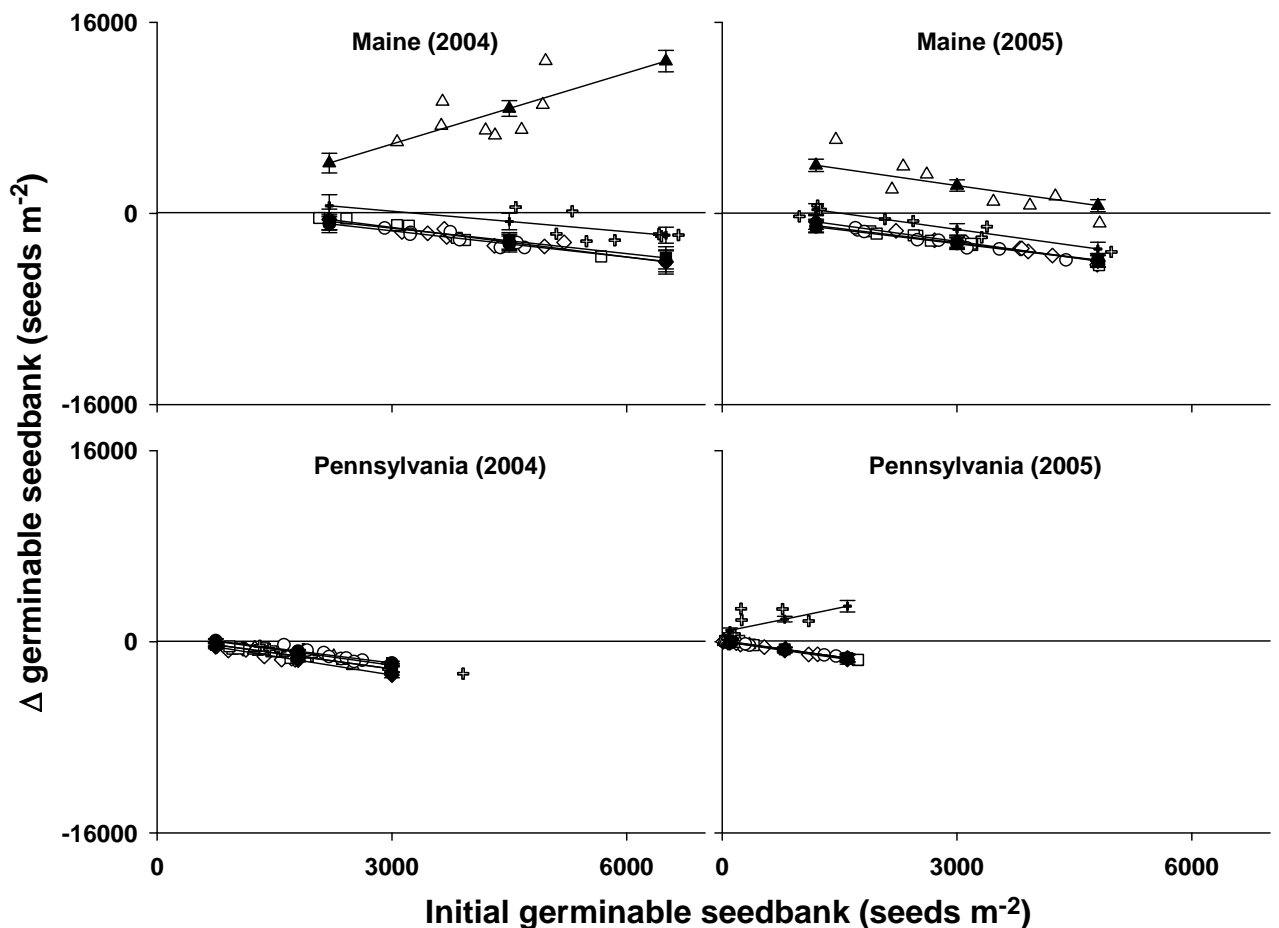


Figure 1.3. Mean Δ germinable seedbank as a function of initial germinable seedbank across cropping systems for velvetleaf: \oplus - Oats/Red Clover; \circ - Brassica spp./Buckwheat/Brassica spp.; Δ - Oats/Pea-Rye/Hairy vetch; \diamond - Fallow; \square - Oats for PA or Green beans for ME-Rye/Hairy vetch. Fitted values from ANCOVA with initial germinable weed seedbank as the covariate were superimposed by cropping system across systems: $+$ - Oats/Red Clover; \bullet - Brassica spp./Buckwheat/Brassica spp.; \blacktriangle - Oats/Pea-Rye/Hairy vetch; \blacklozenge - Fallow; \blacksquare - Oats for PA or Green beans for ME-Rye/Hairy vetch. Analysis was performed using SAS Proc Mixed, and bars represent the standard error of the estimate.

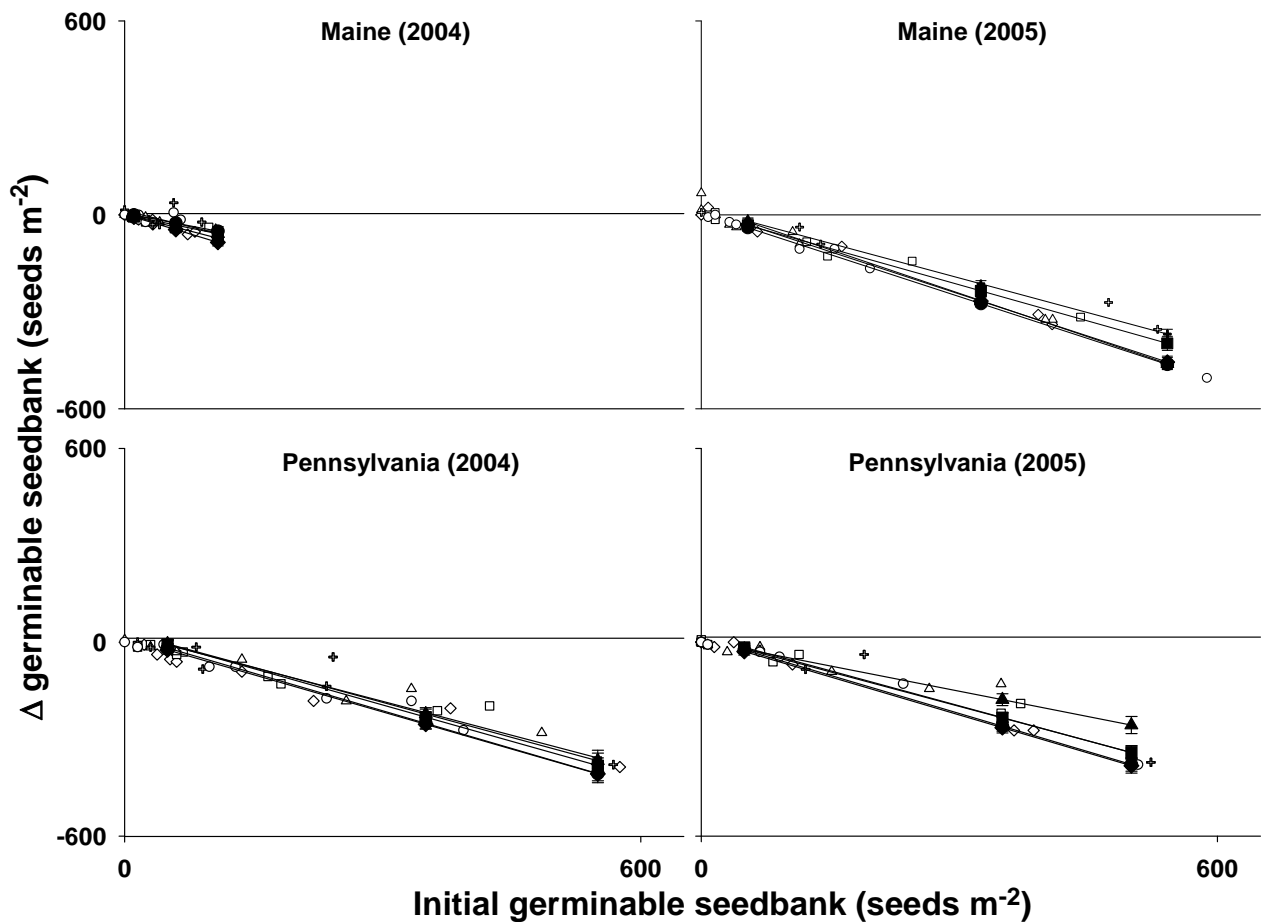
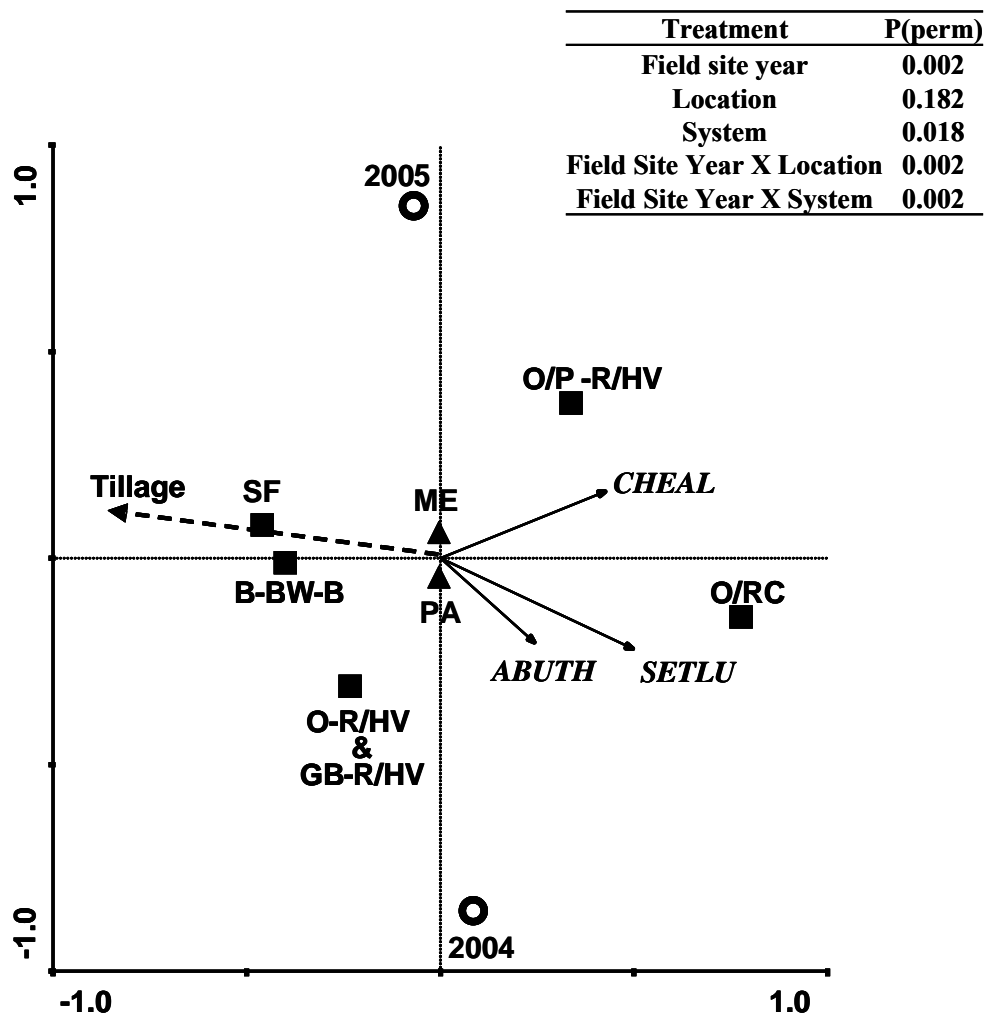


Figure 1.4. Biplot ordinations from a redundancy analysis displaying the associative relationships between the proportional change (final/initial) in the weed community assembled from the three target weed species (CHEAL - common lambsquarters; SETFA - foxtail spp.; ABUTH - velvetleaf) and the explanatory variables: field site years (●) (2004-2005; 2005-2006), location (▲) (Maine; Pennsylvania), cropping system (■) (O - Oats; RC - red clover; HV - hairy vetch; P - pea; GB - green bean; B - brassica spp.; BW - buckwheat), and tillage (---). Multivariate analysis of variance table using permutational multivariate analysis of variance of Field site year, Location, and System treatment factors was superimposed on the biplot.



Chapter 2

Giant foxtail (*Setaria faberi*) and velvetleaf (*Abutilon theophrasti*) seed persistence, and recruitment as influenced by tillage and green manures

ABSTRACT

The weed seedbank is a critical life history stage that regulates summer annual weed population growth rates and represents a source of propagules that continue to challenge weed management. Low initial seedbanks have been identified to be critical to the success of ecologically based weed management tactics. It has been suggested that increased microbial biomass resulting from organic amendments to soils can result in higher rates of seed decay and increased weed expression via recruitment; however, management-induced changes in persistence has been limited. Integrative strategies for directly managing weed seedbanks are needed. The objective of this research was to evaluate the influence of soil disturbance and green manuring frequency on giant foxtail (*Setaria faberi*) and velvetleaf (*Abutilon theophrasti*) seed persistence, cumulative emergence, and mortality (fatal germination and seed death). In early spring of 2005 and 2006, after-ripened weed seed buried in the previous fall in mesh bags were either: 1) kept in the mesh bags and buried in fields receiving a high frequency of soil tillage that varied in green manure additions (mesh bag experiment), or 2) removed from the mesh bags and placed into wire mesh cages that were buried flush with the soil surface (seed cage experiment). The magnitude of decline for velvetleaf and giant foxtail, over a one year period (November through November), was 72 and 80% in 2004, and 47 and 87% in 2005, respectively. Weed seed persistence decreased with tillage for both species. Green manuring did not influence weed seed persistence, however, reductions in giant foxtail

cumulative emergence was observed. However, green manure did not influence weed seed persistence. Giant foxtail mortality was primarily due to fatal germination; whereas other factors appear to influence velvetleaf seed death.

INTRODUCTION

Summer annual weeds form persistent weed seedbanks in farm fields buffering them against fluctuating soil environmental conditions as well as human directed weed control tactics (mechanical and chemical). The need to manage the weed seedbank is recognized by farmers (Nordell and Nordell 2006), and supported by empirical evidence (Dieleman et al. 1999; Taylor and Hartzler 2000) and through simulation studies (Davis et al. 2004; Jordan et al. 1995). In their book “Weed the soil not the crop: A whole farm approach to weed management”, the Nordell’s argue that a seedbank-centric approach to weed management is essential for small-holder organic farmers as mid and late-season weeding is both unmanageable and unaffordable (Nordell and Nordell 2006). Hartzler and Roth (1993) demonstrated that weed control in the current year is dependent on weed control in preceding years; that management has a legacy, and that legacy is manifested in the weed seedbank. Finally, Jordan et al. (1995) demonstrated that weed seed survivorship in the top 10 cm of soils (particularly over-winter survivorship) was the most influential life history stage regulating summer annual weed population growth rates for velvetleaf and green foxtail (*Setaria viridis*).

The weed seedbank presents a great challenge when herbicide use is either constrained or not allowed. The efficacy of weed management in these systems is more variable (Ryan et al. 2007); potentially resulting in increases to the weed seedbank

(Forcella and Lindstrom 1988). Since infestations of annual weeds are dependent on the weed seedbank, effective management must work to reduce weed seedbank densities (Dieleman et al. 1999; Forcella et al. 1993).

Gallagher and Fuerst's (2006) conceptual model of seed longevity identifies three seed quality characteristics which are the mechanisms by which weed seeds persist in the soil: seed dormancy, vigor, and resistance to microbial decay. Seed mortality is due to: weed seed predation (Westerman et al. 2005); fatal germination (Davis and Renner 2007); physiological death (Copeland and McDonald 1995); exposure to severe temperature fluctuations (Lonsdale 1993); and seed deterioration from microbial activity and pathogenicity (Kremer 1993). Annual seedbank loss by these fates varies at organismal (Leishman et al. 2000), generational (Cook 1980; Donald 1993), and spatial scales (Schafer and Kotanen 2003; 2004). The degree to which these fates vary are largely governed by plant genetics, environmental conditions in which seed maturation occurred, and the biotic and abiotic characteristics of the soil (Gallagher and Fuerst 2006).

The effects of management on seed persistence varies across a number of studies. Some researchers have hypothesized that increased microbial biomass resulting from organic amendments can result in higher rates of seed decay (Gallandt et al. 1999; Kremer 1993). Fennimore and Jackson (2003) found smaller seedbanks and higher microbial biomass in soils receiving compost and cover crop amendments. Although Gallandt et al. (2004) did not observe differences in the persistence of weed seeds in a no-till and conventional tillage comparison, they did observe lower seed dormancy for wild oats (*Avena fatua* L.) in the no-till treatment and credited this difference to higher soil C, warmer fall soil temperatures, and the potential for greater biological activity. In

contrast, Davis et al. (2006) observed the highest rates of seed mortality in conventionally managed soils receiving mineral based fertilizers compared to soils managed with compost-based fertilizer amendments.

There is also evidence suggesting that soil C:N ratios can influence weed seed persistence. Shem-Tov et al. (2005) evaluated the persistence of burning nettle (*Urtica urens* L.) across a gradient of C:N ratios and found seed viability was lowest (40-50%) after incubation in 13:1 C:N ratio soils, compared to greater than 90% viability in high (25:1) C:N soils. Davis (2007) suggested high C:N ratios in the soil may slow microbial decay rates when nitrogen is limiting. While Shem-Tov et al. (2005) work focused on a single species, Davis (2007), working with a broad range of summer annual weedy species, found C:N response to be species-specific.

Green manures can increase microbial biomass C, respiration, and N mineralization (Schutter and Dick 2002). Soils frequently managed with cover crops may also exhibit faster decomposition of C substrates. The seed coat is recognized as the main barrier protecting the seed and preventing microbial mediated mortality (Kremer 1993). While the extent to which weed seed survival is influenced by soil processes and the microbial community is limited, several causal mechanisms have been identified including: 1) direct penetration of weed seed coat walls by fungal and bacterial pathogens (Kirkpatrick and Bazzaz 1979; Schafer and Kotanen 2003, 2004); 2) phytotoxic metabolites produced by microbes (Harman 1983); and 3) the microbial production of seed coat damaging enzymes (Gogue and Emino 1978).

Enhancing seed mortality through coordinated management will likely require an integration of tactics that impact protective mechanisms common in weed seeds. For

example, increased fungal pathogenic attack and velvetleaf seed mortality was observed when seeds were partially damaged by insect predation (Kremer and Spencer 1989). Using weed expressive tactics that increase germination of weed seeds that are subsequently controlled through additional integrated practices could prove to be a successful EBWM strategy for managing weed seedbanks. Germination of many species is stimulated by soil disturbance (Cavers and Benoit 1989); in this way the expressed germinable fraction can be increased. Potential mechanisms for this response include: exposure to light for light-sensitive species (Gallagher and Cardina 1998); improved soil aeration which may increase loss of volatile inhibitors from soil; and raise buried seed to more favorable germination sites (Milberg et al. 1996; Egley and Chandler 1978). Thus, tillage can be classified as an expressive weed management tactic by stimulating germination (Nordell and Nordell 2006). Tillage also increases microbial biomass through soil aeration and by exposing occluded labile soil organic matter fractions (Plante and McGill 2002). The increase in microbial activity can also increase biosynthesis of ethylene (Arshad and Frankenberger 2002), a known germination stimulant (Egley 1980). Therefore, coupling green manuring with increased soil disturbance may result in greater decline to the weed seedbank through induced germination, fatal germination, and seed decay.

In Chapter 1 we examined approaches to managing weed seedbanks through rapidly depleting the germinable fraction of the seedbank and reducing or eliminating fecundity. In this Chapter, component studies were conducted in more controlled “pulse-chase” experiments where seed recapture efficiency was improved and where seed persistence was evaluated in high disturbance cover crop systems. The objective of this

work was to assess the influence of soil disturbance frequency and green manuring on seed fates and weed seed persistence. We hypothesized that weed seed mortality would increase with increasing soil disturbance through tillage and the addition of cover crop residues.

METHODS

Field experiments were conducted from 2004 to 2007 at the Russell E. Larson Agricultural Research Center in Rock Springs, Pennsylvania (40°44' N, 77°57' W). The study was conducted on a Hagerstown silt loam soil (Fine, mixed, mesic, Typic Hapludalfs). The study consisted of two separate experiments located within the same farm field: the first was a component study conducted within a subset of treatments in the cover crop systems experiment examined in Chapter 1; the second experiment was conducted immediately adjacent to the cover crop systems study. The two experiments, which contrasted in weed seed burial method, are referred to as the “mesh bag” (conducted in a sub-set of treatments in the systems study) and “seed cage” (located adjacent to the systems study) experiments. Both experiments were simultaneously initiated in the fall of 2004 and completed in the spring of 2006 (2004 replicate year) and repeated in the fall of 2005 to the spring of 2007 (2005 replicate year). The mesh bag method is commonly used because it allows for expedient sampling and full recovery of weed seeds. However this method is limited because it prohibits precise separation of seed fates within the bag (i.e., germination versus mortality). Therefore a modified soil core method (Teo-Sherrell and Mortensen 2000) was employed to quantify weed emergence and seed persistence from seed buried in soil-filled permeable cages within

the soil profile. Climate variations between year replicates were documented with cumulative growing degree days and precipitation (Figure 1).

Velvetleaf (*Abutilon theophrasti* Medicus) and giant foxtail (*Setaria faberi* L.) were used in this study because of their economic importance in northeastern field crop production. Additionally, these species reflect large differences in seed coat anatomy (velvetleaf is hard seeded, foxtail is not) and seed persistence in soil (Buhler and Hartzler 2001). Giant foxtail and velvetleaf seed were collected in the fall just prior to burial from local fields within 5 km of the study site.

Mesh bag experiment. The experiment was nested within two cover crop systems over an 18 month period previously described in Chapter 1. The two systems were: 1) a summer fallow where no crop was grown and emerged weeds were managed with tillage; and 2) a three cover-crop system that included yellow mustard (*Brassica juncea* L. 'Idagold') rotated to buckwheat (*Fagopyrum esculentum* Moench.) followed by winter canola (*Brassica napus* L. 'Dwarf Essex') (B-BW-B) (Table 2.1). These two systems were selected based on the following three qualities: high weed seedling recruitment; no fecundity; and one has a cover crop (B-BW-B) while the other does not. The experimental design for the cover crop systems was a randomized complete block with four replications. Nylon bags (64 bags 6.4 x 6.4 cm) with a mesh size of 1.6-mm² containing 75 seeds each of giant foxtail and velvetleaf (150 seeds total) were buried 5-cm deep on November 18, 2004 and December 2, 2005. The first sub-samples of the mesh bags were collected prior to primary tillage in April. The exhumed mesh bags were immediately placed in cold storage (5°C) and subsequently analyzed for remaining viable seed (within 24 hours). The mesh bags that remained in the soil were removed when a

tillage operation was performed. At such times, the remaining mesh bags that were removed before each primary tillage event, placed in dark plastic covered buckets for between 20 and 90 minutes then reburied at a depth of five cm. Mesh bags were exhumed during the day and were therefore briefly exposed to light. However, velvetleaf and giant foxtail dormancy is primarily regulated by temperature (Leon and Owen 2003). A single mesh bag sample from each of four replicates was removed at one month intervals from April through September, followed by a winter (November) and spring (May) sample in the following year. After field removal, seed viability was estimated by applying pressure to seeds with a forceps and dissecting needle. Firm seeds were assumed to be viable (Ball and Miller 1989; Forcella 1992). Previous research has demonstrated that this test is strongly correlated to a standard tetrazolium assay (Borza et al. 2007).

Seed cage experiment. Foxtail and velvetleaf seed were buried in soil contained within coarse sieve wire mesh cages that allowed for weed emergence. The experiment was arranged as a randomized complete block design with four replicates. The following four treatments were examined: 1) zero tillage and no green manure; 2) two tillage and two green manure events that included yellow mustard followed by buckwheat; 3) three tillage events and no green manure; and 4) three tillage and three green manure events including yellow mustard followed by buckwheat followed by winter canola. The tillage events were simulated by thoroughly mixing the soil and weed seeds with a metal bar (2.5-cm x 21.4-cm) for five seconds. For the green manure treatments, cover crop biomass was harvested from the cover crop systems experiment, dried intact at 50°C for about 72 hours, and then shredded to reduce particle size. Green manuring was simulated by adding dried cover crop residues at rates equivalent (wt/area) to those produced in the

cover crop systems experiment (mesh bag study). Cover crops were sampled and dried intact so as to preserve the allelopathic potential. Cylindrical cages measuring 10 by 17.8 cm were constructed using wire mesh (1.25 x 1.25 cm) open at the top and enclosed at the bottom. The cages were lined with fine mesh screen (1.3 x 1.13 mm), and filled with steam sterilized (90°C for 8 h to kill weed seeds) soil from the cover crop systems experiment. Prior to filling the seed cages, the sterilized soil was inoculated with 14.8-cm³ of fresh (nonsterile) soil collected from the field site. Seed cages were then filled to within 4 cm of the top of the cage. A detailed procedure follows in which weed seed ‘pulses’ are added to the soil cage then disturbance and cover crop treatments imposed. To track weed seeds through these treatments, we located seeds in a small volume of soil (5.0 cm³) in the center of the core. This was accomplished by affixing a polyvinyl chloride (PVC) frame (10.16-cm diameter by 12.6-cm depth) to the top of the cage (approximately 6.3-cm depth) (Figure 2). The frame served as a guide for resampling the seed cage. The top half of the PVC frame was fitted with a cylindrical wooden block intended to guide the placement (hole drilled in wood to diameter of probe) of a 1.6 cm soil core.

Nylon mesh bags containing giant foxtail and velvetleaf seed were buried in the fall (as described previously in the mesh bag experiment) to create a source of after-ripened seed. In May, mesh bags were exhumed from the field (Table 2.2) and immediately placed in the dark (opaque plastic container) until seed cage preparations were complete. Using the PVC frame to guide the coring operation, a soil core (1.6-cm diameter by 2.5-cm in depth) was removed from the center of the seed cage and seeds from a mesh bag were placed into the resulting cavity. Seeds were then covered with

weed seed-free soil from the initial soil core and then cages were buried flush with the soil surface (4-cm of wire cage extended above soil surface). For each subsequent soil disturbance event and addition of cover crop residue, the seed cage was exhumed from the field and the diameter of the central hole was expanded by approximately 1.3-cm in diameter and 0.5 cm in depth to accommodate a larger probe resulting in a soil volume of 22.7, 53.2 and 88.2 cm³ sampled at each subsequent disturbance. The purpose of increasing the volume of soil sampled was to ensure a high seed recapture. At each disturbance event, a core from the center of the seed cage was removed, disturbed, and the soil remaining in the seed cage was also subjected to the same disturbance. Following each disturbance event, the remaining soil, after the core containing the weed seed/soil mixture was removed, was poured back into the seed cage. The same diameter pipe used to extract the weed seed/soil mixture from the cage was used to extract an additional soil core to the equivalent depth. The original core containing the weed seed/soil mixture was placed back into the cavity caused from the previous soil core. Finally, soil from the seedless additional soil core was poured back over the top surface of the cage to ensure coverage of the soil seed mixture. Weed seed in the zero tillage treatment remained at the 2.5-cm depth the duration of the experiment. Variations in soil temperature and moisture were assumed to be similar between this treatment and the remaining tillage/green manure treatments.

Emergence of weed seedlings was recorded prior to each disturbance event or before emerged weeds grew beyond the seedling stage. Seedlings were counted and removed by hand from the seed cage. Care was taken to minimize soil disturbance during seedling removal. At the end of the experiment, soil seedbanks were enumerated using a

direct extraction technique approximately four weeks after the final cover crop residue and/or disturbance treatment. Direct extraction was completed by removing a 685 cm³ volume of soil from the center of the seed cage and weed seed were separated using a modified hydropneumatic root elutriator (Gillison's Variety Fabrication Inc.) (Gross 1990; Smucker et al. 1982). The remaining sample was then passed through a 600-µm screen to separate weed seed from soil residual material. All foxtail seed was removed from the first rinsing procedure. To ensure complete velvetleaf recapture, the remaining sample was deflocculated by adding potassium carbonate (K₂CO₃) during the rinsing step (Buhler and Maxwell 1993). Weed seeds were then identified and separated from sieved soils under a dissecting microscope. Viability was estimated by applying pressure to seeds with forceps or a dissecting needle. Firm seeds were assumed to be viable (Ball and Miller 1989; Forcella 1992).

Data analysis. Seed persistence and emergence data were $\sin^{-1}(x^{0.5})$ transformed prior to analysis to address the lack of homogeneity of variances and meet assumptions of normality. Weed seed persistence (%) was modeled against Julian days following modified negative exponential decay model (Teo-Sherrell and Mortensen 2000):

$$S = a \exp^{-b(DSB)} \quad [1]$$

where S is the proportion of seed still viable; a and b are shape parameters; and DSB is the number of days the seeds were buried in the cover crop systems experiment.

Response S is hereafter referred to as weed seed persistence. Weed seed persistence and proportional emergence (E) were both calculated as a proportion of the total initial viable seed. Percentage of weed mortality was determined by Equation 2:

$$1-(E+S) \quad [2]$$

Weed seed mortality did not distinguish between direct seed death and fatal germination. Negative exponential decay models were fitted to the $\sin^{-1}(x^{0.5})$ seed persistence as a function of Julian days using the non-linear least squares (nls) package in R 2.4 (R Development Core Team, 2006). F-tests were used to test for differences in cover crop systems treatments by year and species (Zar 1999). ANOVA was conducted using a PROC MIXED procedure in SAS v. 9.1 (SAS Institute Inc. 2004) to test for disturbance and green manuring effects on emergence and persistence of weed seedbanks in the seed cage experiment.

RESULTS

Mesh bags. Coefficients for this nonlinear regression, the coefficient of determination (R^2), and the F-test for significance between cover crop system treatments are presented in Table 2.3. The negative exponential model fit the observed data well. Year was a significant factor for the persistence of both weed species, so nonlinear regression was conducted separately by year and individual species. In contrast to year and species, weed seed persistence did not vary between cover crop systems for either year or species. This allowed pooling across cropping systems for both velvetleaf and giant foxtail and the nonlinear regression for seed persistence as a function of Julian date was reanalyzed separately for each year (Table 2.3). Based on the selected exponential decay models, the magnitude of decline for velvetleaf and giant foxtail, over a one year period from the initiation of this experiment (November to following November), was 72 and 80% in 2004, and 47 and 87% in 2005. Although the mesh bag study was conducted over an 18

month period, magnitude of decline was reported at a one year interval for comparative purposes with other values reported in the literature.

Seed cages. Year effects were observed between the fitted models for the mesh bags, but not for the ANOVA in the seed cage experiments. The year effect observed within the mesh bag experiment was due to differences in seed persistence over the duration of burial. The seed cage experiment, which tested for treatment differences at end of an 18 month interval of time, compared means of the tillage and green manure treatments, not rates of persistence. Within the seed cage study, treating year as a random effect only suggests a lack of difference in variance, not in means by year. Therefore, differences in replicate years existed in the mesh bag experiment, but could be pooled for the interpretation of the seed cage experiment.

The tillage/green manure treatment was a significant source of variation for velvetleaf and foxtail seed persistence, seedling emergence, and seed mortality in the seed cage experiment (Table 2.4). Year, analyzed as a random effect, was not a significant source of variance for any dependent variable. Therefore data was pooled across prior to each analysis. Velvetleaf seed persistence was influenced by the tillage gradient over the 18 month period. Greater than 50% viable seed remained in the zero tillage plus no green manure treatment (0-0) compared to 26% viable seed remaining following the three tillage and green manure treatment (3-3) The means for the two tillage, two green manure treatments fell in between the no disturbance and high disturbance treatments (Table 2.5). No differences were observed between the 3-3 treatment and three tillage plus no green manure (3-0) treatment leading us to conclude that tillage was driving seedbank turnover. Giant foxtail persistence was 20 -30% less

than velvetleaf seed persistence when tillage/green manure treatments were compared (Table 2.5). Giant foxtail seed persistence was at least 3 times higher in the 0-0 treatment compared to treatments in which seed cages received tillage or tillage plus green manure. However, no differences in giant foxtail seed persistence were observed between the seed cages receiving varying frequency of tillage or tillage plus green manure (Table 2.5).

Tillage and green manure treatments had minimal influence on cumulative weed seedling emergence; only the 0-0 and the 3-0 were different from one another and only by about 7% (24 vs. 31% emergence, respectively). In general, a greater proportion of giant foxtail emerged with emergence rates as high as 62% in treatments with more soil disturbance. In contrast, the greatest rate of velvetleaf emergence in any of the treatment was 31%. For giant foxtail, tillage increased weed emergence, however no differences were observed between the two and three tillage treatments that received green manure. The 3-0 treatment had the highest levels of emergence (62%) and was 18% higher than the treatment with the same tillage frequency plus green manuring.

Velvetleaf seed mortality increased with increasing tillage frequency, almost doubling (24 vs. 44%) from the 0-0 treatment to the 3-0 treatment (Table 2.5). However, the addition of a green manure did not influence velvetleaf seed mortality, as evidenced by similar rates of decline in the treatments with three tillage events that differed only in addition of green manure (Table 2.5). Giant foxtail seed mortality did not vary between the 0-0, 2-2, and 3-3 treatments. The three tillage without green manure treatment levels had 20% less giant foxtail mortality than the three tillage plus green manure treatment.

DISCUSSION

It's difficult to fully explain the interannual variation in velvetleaf seed persistence. Interannual differences in rainfall and temperature were small (Figure 1) and therefore were unlikely to drive the response. While locally collected, the source of the velvetleaf seed could account in part for the differences observed. First, seed were collected from two populations and may have carried with them heritable differences in seed dormancy (which would have affected the proportion of seeds lost to germination). Second, maternal effects may have played a role as seed for the 2004 experiment originated from plants growing in corn and soybean fields while seed for the 2005 experiment originated from plants grown in a fallowed field. Nurse and DiTommaso (2005) observed up to a 30% reduction in proportional dormancy from velvetleaf grown in competition with corn compared to those grown in a velvetleaf monoculture.

The mesh bag experiment and the high disturbance systems in the seed cage experiment were very similar in the resulting weed seed persistence. Both experiments averaged about 70-75% decline for velvetleaf and a striking 90 % decline for giant foxtail after the 18 month period. The magnitude of decline observed in this study was comparable or greater than other reports of velvetleaf and foxtail decline. When inputs to the seedbank were eliminated, Buhler (1999) observed greater than a 70% decline in velvetleaf and 90% decline in giant foxtail populations. However, this Iowa study did not use mesh bags. In that study, seed decline estimates were derived from excavating soils from plots that were supplemented with weed seeds. The authors reported that 40 and 60% of the giant foxtail and velvetleaf seed, respectively, were not accounted for and suggested predation, fatal germination, and decomposition as fates of these seeds.

Predation may have inflated the losses in the seedbanks they reported. In another study that examined buried mesh bags at eight locations across the US Corn Belt, seedbank decline for giant foxtail and velvetleaf in a one year period was between 80-84 and 36-54%, respectively in a conventional tillage system (Davis et al. 2005).

The SF and B-BW-B systems, selected from the cover crop systems experiment in chapter 1, demonstrated high rates of total seedbank decline in a one year period (Figure 2.3), corresponding to what was observed with the germinable seedbank (Ch.1; Tables 1.4 and 1.5). However, the addition of green manure did not influence the persistence of either weed in the mesh bag or seed cage experiment; differences in persistence were only observed across year replicates (velvetleaf only) or between the disturbance gradients established in the seed cage experiment. Tillage appears to be more important in regulating seedbank decline than the addition of cover crop green manures. Since both tillage, by releasing occluded organic matter fractions, and cover crop residues through additions of green manures, are factors known to increase soil microbial activity and the presence of germination stimulants (Arshad and Frankenberger 2002; Gallagher and Fuerst 2006; Plante and McGill 2002), the results of the seed cage experiment suggests that the frequency of these events that is more important than microbial substrate availability. While speculative, further evidence for this hypothesis is that even low levels of seed germination stimulants such as ethylene and nitrate have been observed to influence weed germination (Egley 1980).

Velvetleaf was more responsive to the increasing tillage gradient than giant foxtail, where greater than a 90% decline occurred for all treatments except the zero tillage treatment (Table 2.5). Therefore, cropping systems that are comprised of more

ephemeral weeds such as giant foxtail can better buffer inconsistent weed control with weed expressive tactics as described in this study. However, when managing weeds with highly persistent weed seedbanks such as velvetleaf, tillage is an important factor for depleting the seedbank, but a weed expressive approach will not be sufficient in buffering populations against years of inconsistent weed control. A 17-year study evaluating velvetleaf seed longevity in soil, tested persistence across a range of cropping systems that used tillage, perennial crops, and herbicides to prevent velvetleaf reproduction (Lueschen et al. 1993). Tillage practices had the greatest effect at reducing the velvetleaf seedbank; after four years, the intensive tillage systems reduced seedbanks to 10% of the original size compared to 56% in a continuous alfalfa crop, or 37% in a chemical fallow treatment (Lueschen and Andersen 1980). The differences observed in the persistence of the two velvetleaf seed lots examined in our study, suggests that integrated approaches to long-term management of weeds could include exploiting weed/crop competition relationships to select for weed seed quality characteristics that confer higher susceptibility to seed mortality or expressive fates.

Cumulative velvetleaf weed emergence generally increased with soil disturbance, however when a green manure was incorporated, differences across the disturbance gradient were not observed. When a green manure was included in the frequent tillage treatments, velvetleaf cumulative emergence was largely unaffected by the presence of a green manure. This is in contrast to the cumulative emergence observed for giant foxtail where incorporation of a green manure reduced cumulative emergence (Table 2.5). Certainly, higher germination may have occurred in the 3-0 treatment and higher seed mortality in the green manure systems (2-2 and 3-3), but this is unlikely since differences

in mortality between these treatments are equivalent to the differences in weed emergence. Therefore, the large differences in cumulative emergence of giant foxtail are attributed to fatal germination. Causes of fatal germination include phytotoxicity of green manures, allelopathy (Davis and Liebman 2003), and pathogens (Davis and Renner 2007). Burial depth, commonly considered a factor in fatal germination was not considered in this study because all seed were less than 5-cm in depth.

The relationship between velvetleaf and giant foxtail cumulative emergence observed in the green manure treatments corresponds to previous reported values. Davis and Liebman (2003) observed a 30% decrease in giant foxtail emergence following a spring incorporated red clover green manure. Small seeded weed species appear to be most sensitive to allelochemicals (Bhowmik 2003; Putnam and DeFrank 1983). The effect of a red clover bioassay on the seed of 28 crop and 13 weed species (seed mass ranging from 20 – 26,250 mg) found a strong linear relationship between seed weight and radical inhibition (Liebman and Davis 2000). Potential mechanisms for lower phytotoxicity on larger seeds may include lower absorptive surface area, stored reserves, and avoidance through ability to emerge from greater soil depths. Previous evaluations of velvetleaf to allelochemicals from *Brassica* spp. showed no effect of winter canola or yellow mustard (same species used in this study), with exposure to only a white mustard (*Brassica hirta* Moench.) species showing a small decline in emergence (30%) (Krishnan et al. 1998).

The recent demonstration of synergism on weed seedling mortality between very low concentrations of a herbicide (metolachlor) and hairy vetch surface residues (Teasdale et al. 2005) has implications for fatal germination from phytotoxic

allelochemicals, germination stimulants, and soil pathogens. Teasdale et al. (2005) hypothesized that the synergistic relationship was due to light stress imposed on the germinated weed from the hairy vetch mulch. The authors further speculated that allocation of carbohydrates to hypocotyl elongation resulted in a seedling with less ability to detoxify the metolachlor. Therefore, stimulants that induce germination of weed seeds during less optimal times may perhaps increase the potential phytotoxicity from allelochemicals, pathogens, or other mechanisms of mortality.

Causes of differences observed in velvetleaf mortality cannot be determined from the metrics collected in this study. However, while fatal germination and seed death cannot be separated, the small differences in velvetleaf cumulative emergence observed in this study suggests that there is the potential to influence velvetleaf seed death with increasing soil tillage and/or green manures. Davis (2007) showed a 40% decline in velvetleaf mortality in soils amended with high C:N organic amendments, compared to soils receiving N fertilizer and no organic amendments. Using path analysis, the author demonstrated that greater mortality in the nonamended treatments was due to the effect of soil N levels on velvetleaf decay from microbial activity. In contrast, soil N increased mortality for other weed species through stimulation of germination. This species-specific response parallels observations in this study; giant foxtail mortality was primarily due to fatal germination, whereas other factors appear to influence velvetleaf seed death. Therefore, while tillage appears to play a larger role than green manures on influencing weed seed persistence in the soil, the incorporation of the residues and the timing in which this occurs may play an important role in the long-term management of weed populations.

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Table 2.1. Cover crop management log and seed bank sampling in the mesh bag study in the 2004-2006 and 2005-2007 replicates.

Cover Crop System	Field Operation	Time of field operations	
		2004	2005
Summer fallow	Seed burial	November 22 2004	November 27 2005
	Cultivation (2x) ¹	May 24 2005	May 27 2006
	Cultivation (2x)	June 15 2005	June 29 2006
	Cultivation (2x)	July 09 2005	July 20 2006
	Cultivation (2x)	August 17 2005	August 15 2006
<i>Brassica</i> spp.	Seed burial	November 22 2004	November 27 2005
	Cultivation (2x)	May 05 2005	May 08 2006
-	Plant cover crop	May 06 2005	May 08 2006
Buckwheat	Mow	June 29 2005	June 25 2006
-	Cultivation (2x)	July 07 2005	July 06 2006
<i>Brassica</i> spp.	Plant cover crop	July 07 2005	July 06 2006
	Mow	September 15 2005	September 12 2006
	Cultivation (2x)	September 17 2005	September 13 2006
	Plant cover crop	September 18 2005	September 15 2006
	Mow	May 4 2006	May 6 2007
	Cultivation (2x)	May 4 2006	May 6 2007

Table 2.2. Seed cage management log for 2004 and 2005 replicate years.

		Seed Burial	Seed Exhumed	Burial In Cages	Disturbance 1	Disturbance 2	Disturbance 3
2004	0-0	November 22 2004	May 04 2005	May 05 2005			
	2-2	November 22 2004	May 04 2005	May 05 2005	July 08 2005	September 16 2005	
	3-0	November 22 2004	May 04 2005	May 05 2005	July 08 2005	September 16 2005	May 03 2006
	3-3	November 22 2004	May 04 2005	May 05 2005	July 08 2005	September 16 2005	May 03 2006
2005	0-0	November 27 2005	May 09 2006	May 09 2006			
	2-2	November 27 2005	May 09 2006	May 09 2006	July 06	September 16	
	3-0	November 27 2005	May 09 2006	May 09 2006	July 06	September 16	May 08 2006
	3-3	November 27 2005	May 09 2006	May 09 2006	July 06	September 16	May 08 2006

Table 2.3. Parameters of exponential decay models and goodness-of-fit statistics of weed seed persistence as a function of Julian days ($Y=a*\exp^{-k(DSB)}$) where Y is percentage seed persistence (%) at time DSB; a is initial condition (i.e., seed persistence at DSB = 0); and k is the relative decomposition rate. Nonlinear regression and F-test was conducted by year and weed species on $\sin^{-1}(x^{0.5})$ -transformed data. Untransformed data was presented.

Crop	Year	Cover Crop System	<i>a</i> persistence (%)	<i>k</i> DSB ⁻¹	R ²	P > F
Velvetleaf	2004	Combined	1.04(5.25E-02)	3.56E-03(2.97E-04)	0.76	<0.0001
		2005	Combined	0.99(3.19E-02)	1.69E-03(1.42E-04)	
	2004	Fallow	1.03(8.23E-02)	3.46E-03(4.62E-04)	0.71	0.812
		B-BW-B	1.05(6.72E-02)	3.67E-03(3.83E-04)	0.81	
	2005	Fallow	0.98(4.55E-02)	1.76E-03(2.05E-04)	0.73	0.777
		B-BW-B	0.99(4.56E-02)	1.64E-03(2.01E-04)	0.69	
Giant foxtail	2004	Combined	1.06(5.97E-02)	4.62E-03(3.8E-04)	0.79	0.028
		2005	Combined	1.04(6.15E-02)	5.71E-03(4.77E-04)	
	2004	Fallow	1.07(8.22E-02)	4.36E-03(5.07E-04)	0.82	0.562
		B-BW-B	1.06(8.76E-02)	4.92E-03(5.887E-04)	0.73	
	2005	Fallow	1.03(8.37E-02)	5.60E-03(6.41E-04)	0.80	0.969
		B-BW-B	1.04(9.25E-02)	5.81E-03(7.26E-04)	0.77	

Table 2.4. Analysis of variance for velvetleaf and giant foxtail as influenced by soil disturbance and green manuring.

		Persistence	Emergence	Mortality
		----- P > F -----		
Velvetleaf	Year	0.2414	0.2481	0.2450
	Treatment	<0.0001	0.0291	<0.0001
Giant foxtail	Year	0.2742	0.2924	0.2604
	Treatment	<0.0001	<0.0001	0.0137

Table 2.5. Mean percentage of weed seed persistence, emergence, and mortality as influenced by soil disturbance and green manuring, pooled across years for the seed cage experiment. Mean comparison was performed by weed species and seed fate independently, with different lower case letters indicating significant differences ($P < 0.05$) using the Tukey-Kramer method.

	ID	Tillage	Cover crop*	Persistence	Emergence	Mortality
				----- (%) -----		
Velvetleaf	0-0	0x	none	52a	24b	24c
	2-2	2x	B-BW	40b	25ab	35b
	3-0	3x	none	25c	31a	44ba
	3-3	3x	B-BW-B	26c	27ab	47a
Giant Foxtail	0-0	0x	none	29a	28c	43ab
	2-2	2x	B-BW	10b	40b	51a
	3-0	3x	none	7b	62a	31b
	3-3	3x	B-BW-B	6b	44b	50a

* B-before BW, yellow mustard (*Brassica juncea* L. 'Idagold'); BW, buckwheat (*Fagopyrum esculentum* Moench.); B-after BW, winter canola (*Brassica napus* L. 'Dwarf Essex')

Figure 2.1. Cumulative precipitation and growing degree days across year replicates;
(Nov 2004 through May 2006 (—); November 2005 through May 2007 (·····)).

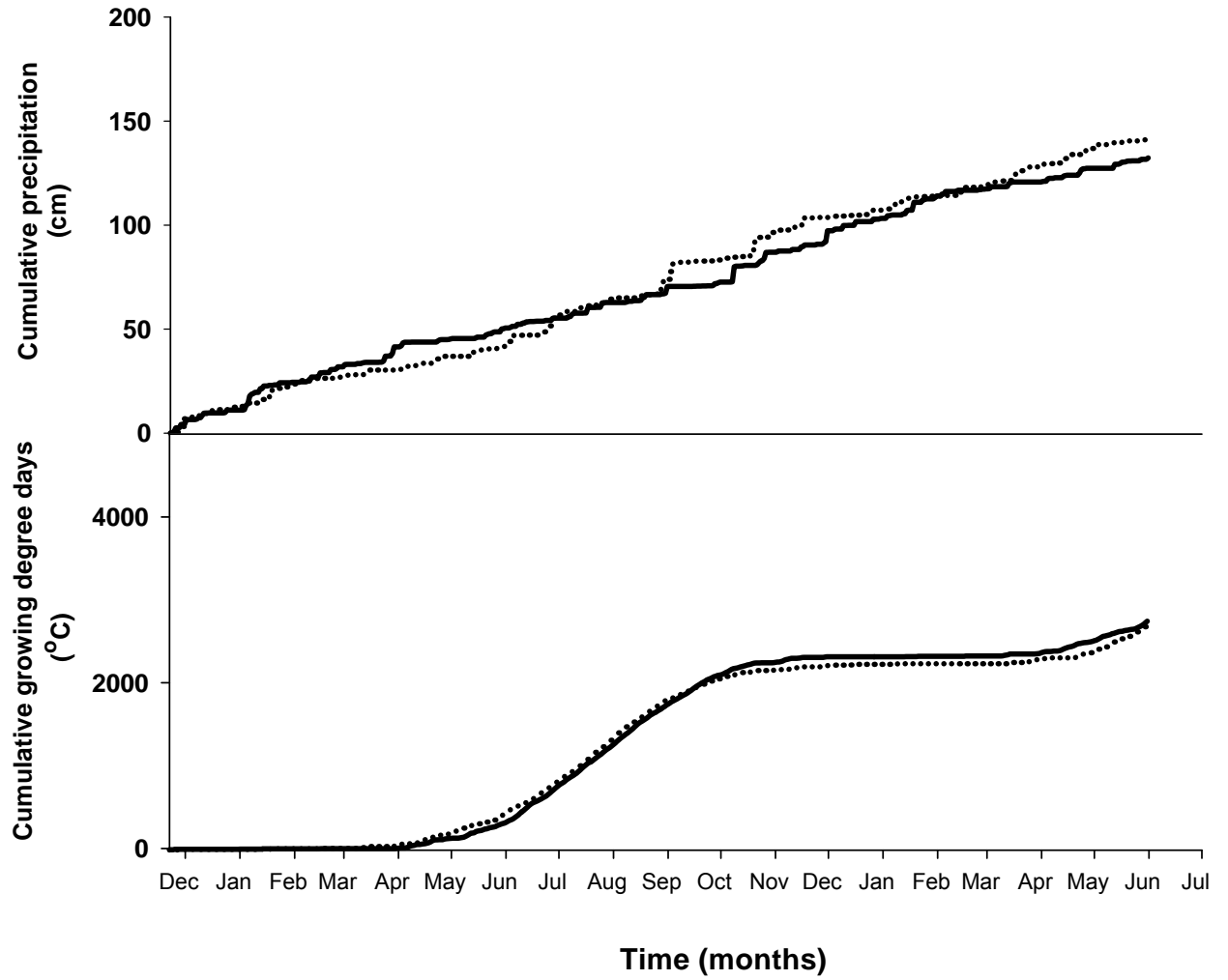


Figure 2.2. A schematic of the soil profile within the seed cages depicting the soil core and seed burial and photographs of the seed cages buried in the field and seed cages with coupling used for extracting soil cores.

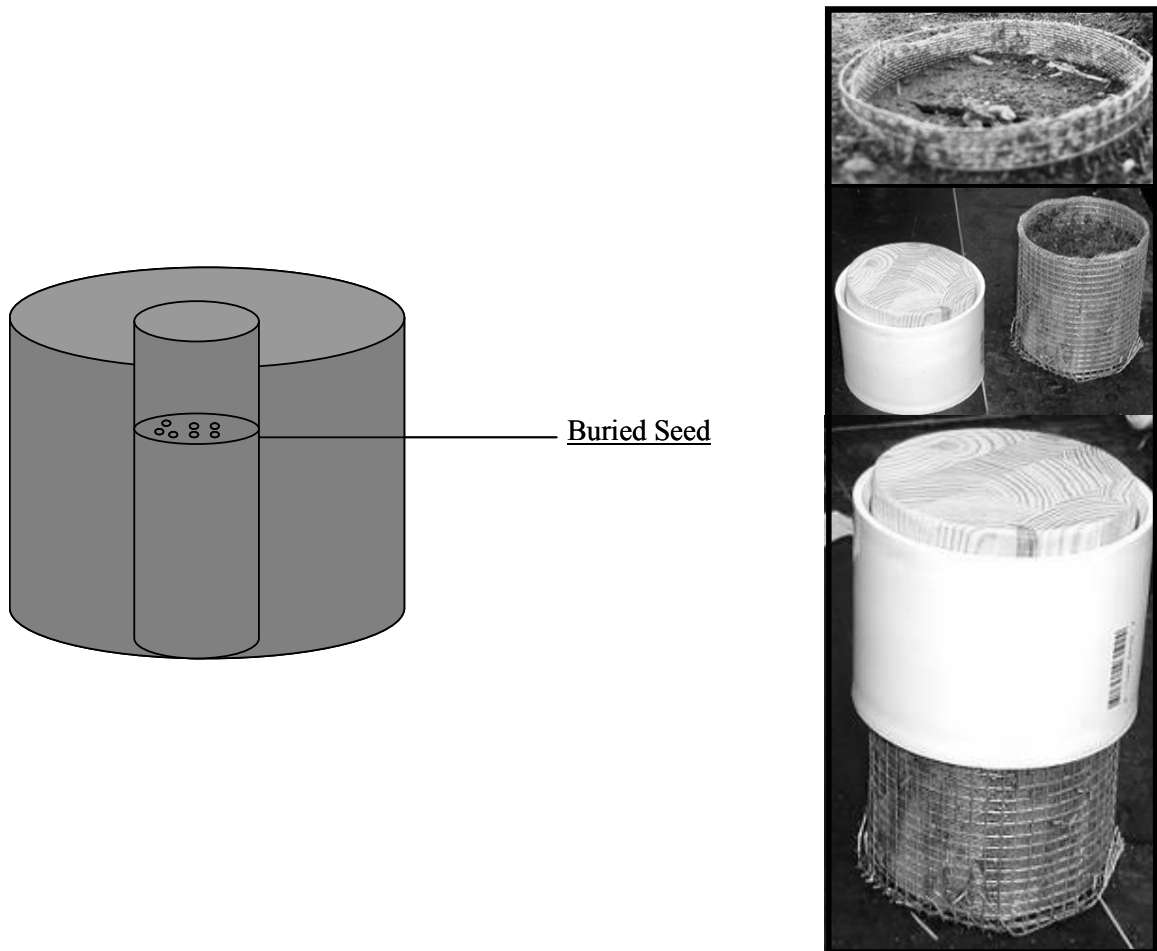
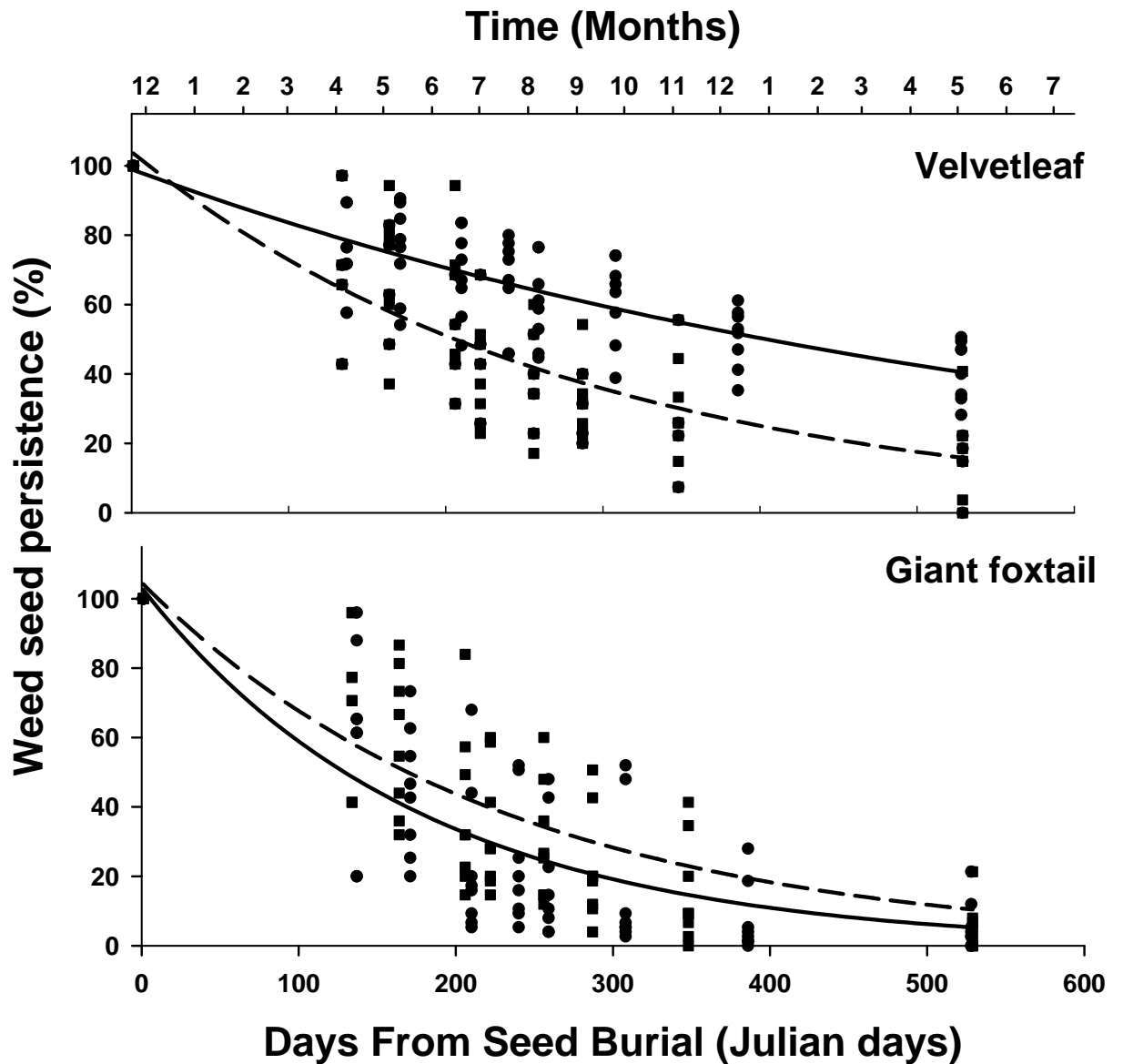


Figure 2.3. Percentage giant foxtail (*Setaria faberi*) and velvetleaf (*Abutilon theophrasti*) seed persistence for 2004 replicate year (—■) and for 2005 replicate year (—●) over time (Julian days). The nonlinear regression lines represent the $\text{back sin}^{-1}(x^{0.5})$ -transformed fitted negative exponential decay regression.



Chapter 3

No-tillage Mechanical Control of Cereal Rye as Influenced by Planting and Termination Date

ABSTRACT

Adoption of conservation tillage (e.g., no-till) production has been driven by the need to enhance soil quality, minimize field labor time, and scale up farm size. However, environmental concerns about pesticide use, development of herbicide resistant weeds, and a rapidly growing organic crop production sector requires research that focuses on conservation tillage approaches that reduce herbicide use while maintaining soil quality. Our research addresses this need by assessing the influence of planting and termination date on successful mechanical cover crop control using a roller/crimper. Two cereal rye (*Secale cereale* L.) cultivars were included and a thermal-based phenological model (growing degree days – GDD) was developed to predict cereal rye growth stage. Percent mechanical control of cereal rye was improved as rye matured. A Julian date-based analysis of cover crop control identified differences between the two cultivars; however they responded similarly to rolling when the analysis was based on cereal rye growth stages with consistent control at a Zadoks growth stage of 61 (rye anthesis). A thermal-based phenological model separating the effects of heat units accumulated in the fall (Fall_{GDD}) from those accumulated in the spring ($\text{Spring}_{\text{GDD}}$) best predicted the phenological development of cereal rye growth stage. This finding presents significant opportunities for integrating cereal rye into crop rotations where fall harvest and spring planting times are constrained by the cash crop. The thermal-based phenological model coupled with local weather summaries enables more strategic decisions regarding cereal

rye planting and termination date, information that may facilitate wider adoption of cover crops.

INTRODUCTION

Decreases in soil quality following the onset of tillage-intensive row crop production have led to efforts to conserve soil resources and the productivity of arable lands (Doran and Parkin 1994). Conservation tillage (e.g., no-till) has a long, well-documented record (30+ years) of effectively managing and improving physical, chemical, and biological indicators of soil quality (Uri 2000). Increased adoption of no-till has been facilitated in part by the introduction of herbicide resistant crops and the accompanying use of effective and affordable broad spectrum herbicides (Curran et al. 1996; Raimbault et al. 1990; Young 2006). Indeed, the widespread adoption of herbicide resistant crops and no-till methods has resulted in an increase in glyphosate use (USDA-National Agricultural Statistics Service 2004; Young 2006), and a subsequent increase in herbicide resistant weeds (e.g., *Conyza canadensis*) (Dauer et al. 2007; Preston 2004). At the same time, herbicides continue to be the most commonly detected pesticide group in both surface and groundwater (Gilliom et al. 2007). These herbicide-related concerns, coupled with the demands of a rapidly growing organic crop production sector (Wyse, 1994; Liebman and Gallandt 1997; Organic Farming Research Foundation 1998; NEIPM Needs Assessment 2002), requires a focus on maintaining crop protection in minimum tillage systems while identifying tactics that reduce or eliminate herbicide use.

Cover crops have frequently been integrated into crop rotations as a cultural practice that can improve soil fertility (Decker et al. 1994), reduce soil erosion (Langdale et al. 1991), sequester soil carbon (Teasdale et al. 1996), increase soil water infiltration

and storage (Munawar et al. 1990) and suppress weeds (Teasdale and Daughtry 1993). Increased carbon inputs together with reductions in tillage (e.g., perennial forages or no-till/cover crops) are needed to maximize increases in soil organic carbon, a principal indicator of soil quality (Roberson et al. 1991; Wright et al. 1999). At present, a number of federal and state departments of agriculture and environment are offering incentives to adopt winter cover crops to help reduce soil loss, and improve water quality (REAP 2007). Cover crops suppress weeds through physical (light and temperature) and chemical (allelopathy) inhibition (Teasdale 1996). However, weed suppression has been inconsistent when using cover crops, particularly for full season weed control (Creamer et al. 1996; Mohler and Teasdale 1993; Yenish et al. 1995; Zasada et al. 1997). Incomplete weed suppression has been attributed to short-lived persistence of phytotoxic allelochemicals, rapid decay of surface mulches, or inadequate biomass levels (Teasdale 1996). Therefore, research aimed at improving soil quality and reducing negative impacts of herbicide use should focus on innovative ways to manage cover crop surface residues in reduced and no-till environments to optimize weed and soil management benefits.

Cereal rye (*Secale cereale* L.) is a winter annual widely used as a cover crop throughout the United States because of its winter hardiness, high biomass production, and persistence due to higher C:N ratios relative to non-grass cover crops (Hoffman et al. 1993; Wilkins and Belinder 1996). Among the common cereal grains managed on temperate arable land, cereal rye is the most cold tolerant and easiest to establish in the fall because it readily germinates under a broad range of conditions (Stoskopf 1985). Additionally, compared to other cereal grain crops, cereal rye produces the greatest levels of biomass and is more compatible for integration into crop rotations because it matures

more rapidly, allowing earlier spring establishment of a cash crop (Stoskopf 1985). Cereal rye suppresses weeds through direct competition before it is killed, and as a mulch barrier that physically and chemically suppresses weeds after it is mechanically or chemically controlled in no-till systems (Teasdale and Mohler 1993). In the Northeast, its use is also driven by tightly coupled crop and livestock production interests, as manure can be applied to winter rye from fall to spring and the cover crop helps sequester nutrients for the subsequent cash crop.

In the absence of herbicides, a cover crop of cereal rye is typically terminated with tillage or with mowing (e.g., sickle bar, flail, or rotary mowing) when no-tillage is desired. In conservation tillage systems, mowing has several drawbacks including the risk of regrowth, reduced residue persistence, and nonuniformity of the cover mulch on the soil surface (Creamer and Dabney 2002; Wilkins and Bellinder 1996). Uniformity in the distribution of rye surface residues is critical for optimizing weed suppression (Teasdale and Mohler 2000). A roller/crimper represents a relatively new mechanical cover crop control implement (Figure 3.1) compatible with conservation tillage systems. This implement lays the cover crop down and crimps plant stems damaging vascular tissue and depositing residues in a more uniform, unidirectional pattern. In contrast to mowing, rolled rye results in a more persistent residue, enhanced weed suppression, moisture retention, and reduced soil erosion (Creamer and Dabney 2002; Morse 2001).

Cereal rye growth stage influences the ability to terminate plant growth mechanically in conservation tillage systems (Creamer and Dabney 2002). However, little research has centered on evaluating control of cereal rye with a roller/crimper. Generally, control of cereal cover crops including rye with a roller/crimper improves with

increasing plant maturity (Ashford and Reeves 2003). However, past experiments in which fall planting date is held constant and termination date in the spring is varied provide only a limited number of growth stages to test for efficacy of mechanical control of cereal rye. Experiments in which fall planting and spring termination dates are varied would allow for testing mechanical control of cereal rye with a roller/crimper across a continuum of growth stages. Additional research is needed to address the temporal dynamic of varied fall and spring planting and termination dates as growers in the region are already experimenting with such manipulations and need additional information to improve their decision-making (Curran et al. 2007). That needed information includes: testing the relationship between growth stage and mechanical control of cereal rye across a continuum of growth stages using descriptive models; defining cultivar specific responses; evaluating interactions between planting date and termination date on cereal rye control; and developing phenology-based predictive models.

Practical decision support tools are needed that use phenological models to accurately predict cover crop developmental stage. Such forecasting tools could be used to estimate timing of spring cover crop termination and also aid in crop rotation planning. Environmentally driven (i.e., temperature, photoperiod, and soil moisture) phenological models have been developed to aid growers in crop cultivar and field selection, insect and plant disease forecasting (Wang 1960), and more recently for weed emergence prediction (Forcella et al. 2000; Myers et al. 2004). Extending phenological models to include cover crop decision making is a logical next step.

Phenology is a biological surrogate for local climate (Hu et al. 2005). The physiological processes that govern phenological development are strongly influenced by

the environment and numerous descriptive and mechanistic models have related environmental factors to crop management (Ritchie 1991; Robertson 1983; Summerfield et al. 1991; Weir et al. 1984), as well as disease (Gleason et al. 1994) and insect control (Nowatzki et al. 2002). Cereal grain crop phenology depends on temperature and length of the photoperiod (Mirschel et al. 2005; Travis et al. 1988); however, moisture and nitrogen limitations can accelerate crop growth and development (Davidson and Campbell 1983; Mirschel et al. 1995). Historical use of these models in cereals has centered on yield prediction and therefore on crop maturation; these models were also parameterized to be used over a wide geographic range (Porter and Gawith 1999; Streck et al. 2003; Yan and Wallace 1998). As a result, mechanistic models were employed to incorporate plant physiological processes and extend the inference domain of the models. However, descriptive models are also used to predict germination, growth, and development; with soil (Myers et al. 2004) or ambient (Teasdale et al. 2004) temperatures being the most popular predictor used. Therefore, regionally specific, thermal-based phenological models that assume typical growing conditions in regions that do not experience spring soil water deficits may provide a practical alternative for predicting cereal rye cover crop development. Making this model relational with growth stage specific mechanical control would provide a useful decision framework for growers interested in greater spring forecasting capabilities. Therefore, the goals of this study were to 1) determine the susceptibility of cereal rye to rolling/crimping over a wide range of cereal rye growth stages; 2) determine if the relationship between cereal rye phenological development and control using roller/crimpers is cultivar specific; 3) determine if control is influenced by fall planting date; and 4) evaluate the relationship

between cereal rye phenological development and thermal time with thermal-based predictive models.

METHODS

Field experiments were conducted from 2004 to 2006 at the Russell E. Larson Agricultural Research Center near Rock Springs, Pennsylvania (40°44' N, 77°57' W) to test mechanical control of 'Aroostook' and 'Wheeler' cereal rye with a roller/crimper. The experimental design was a modified split-plot arranged with cover crop cultivar (two cultivars) and termination date (four termination dates) as main plots and date of fall establishment (six planting dates) as sub-plots. Planting date treatments were nested within cultivar treatments and the experiment was replicated four times. Individual sub-plots measured 1.53 m wide and 2.3 m in length. The experiment was initiated in the fall of 2004 and repeated again in 2005 in an adjacent field. The study was conducted on a Hagerstown silt loam soil (Fine, mixed, mesic, Typic Hapludalfs) with a soil pH of 6.5 and organic carbon content of 20 g kg⁻¹. 'Aroostook' rye was selected because of its winter hardiness and common use in the region and 'Wheeler' rye was selected because it retains more allelochemicals with maturation than other rye cultivars and may have greater utility for suppressing weeds (Reberg-Horton et al. 2005). Cereal rye was seeded on 10-day intervals from August 25 to October 15 (+/- 2 days). The following spring, cover crops were rolled/crimped on 10-day intervals from May 1 to May 30 (four termination dates). In both years, the previous crop was spring-planted oats (*Avena sativa* L.) and seedbed preparation for the cereal rye included disking and cultimulching to eliminate emerged weeds. This work centered on cover crop growth and control and was

not intended to represent a strictly no-tillage regime. As such, the results should be relevant to no-till farmers and those practicing rotational tillage (Peigne et al. 2007; Venterea et al. 2006; Wilson 2007). Rye was drill-seeded in 19-cm rows at 126 kg ha⁻¹ using a 1.8 m wide Great Plains (3P605NT) small plot drill. Ammonium sulfate was broadcast-applied at a rate of 71 kg N ha⁻¹ in March of each year to stimulate rye growth and represent typical fertility conditions for Mid-Atlantic growers who commonly spread dairy manure over growing cereal rye covers.

The roller/crimper used in this experiment was manufactured from cylindrical steel well casing material (3.2-m length x 51-cm diameter x 3.2-mm thickness) with metal slats spaced 10.2 cm apart and welded onto the cylinder in a chevron pattern (after Ashford and Reeves 2003, see Figure 3.1). The roller/crimper, which weighed 1520 kg, was front mounted to a tractor, driven at 7.2 km h⁻¹, and the rye was rolled/crimped in a direction perpendicular to the direction of sowing; thereby laying the cover crop down in a unidirectional pattern. Soybean (Chemgro 3340) was no-till drilled (432,400 seeds ha⁻¹) into the cereal rye residue in 19 cm rows 10 days after the cover crop was rolled/crimped. Soybean was planted with a Great Plains (1006NT) no-till drill in the same direction as the roller/crimper.

Air temperature and precipitation (Figures 3.2 and 3.3) were recorded at a weather station located within 0.25 km of the experiment. Supplemental irrigation (2 cm in May 2005 and 2.5 in May and June 2006) was provided to ensure soybean establishment. Cover crop growth stage was assessed within sub-sub-plots at each termination date using the Zadoks decimal plant development scale (Zadoks et al. 1974). Cereal rye control (% rye mortality) was determined six weeks after each termination date using a visual rating

where a score of 0% represented no control and 100% is complete control. Control was based on visual assessment of survivorship and regrowth of the cereal rye (density and ground cover of any remaining unlodged green vegetation) relative to the control plots. To evaluate the success of the treatments, 85% or greater control of the cereal rye was considered acceptable; this value is often used as commercially acceptable when evaluating common weed control practices in agronomic crops (Curran, personal communication).

Cereal rye phenology and percentage control. Cereal rye control (%) over a range of cereal rye growth stages was modeled with the following three parameter logistic model (dose response curve) (Ritz and Streibig 2005):

$$Y = \frac{d}{1 + \exp\{b(\log(x) - \log(e))\}} \quad [1]$$

where Y is cereal rye control (%); d is the % control at the upper growth stage limit; e , is the growth stage producing a response half-way between d and the lower limit; b is the relative slope around e (% control/growth stage); and x is the growth stage. In the three-parameter logistic function, the lower limit is equal to zero. The effective cereal rye control threshold (85%) is hereafter referred to as the effective growth stage 85 (EGS85); specifically when the lower range of the standard error interval is greater than the 85% control threshold. This is analogous to the term *effective dose* commonly used when evaluating herbicide efficacy with dose response models (Ritz and Streibig 2005).

Thermal time, using growing degree days, was used to predict growth stage using regression models. Growing degree days (GDD) were calculated using the following equation:

$$GDD = \frac{T_{\max} + T_{\min}}{2} - T_{base} \quad [2]$$

where T_{\max} is the maximum daily temperature, T_{\min} the minimum daily temperature, and T_{base} the base temperature set at 4.4 °C (base value below which physiological activity is assumed inhibited) (Nuttonson 1958). Cumulative GDD is the summation of daily GDD's between a planting date and termination date combination. For mean temperatures less than T_{base} GDD's were assumed to be zero.

In this paper we investigated three thermal-based phenological models to predict cereal rye growth stage using cumulative daily heat units; one driven solely by spring temperature (Spring_{GDD}); one based on cumulative heat units from the Fall and Spring (Total_{GDD}); and one based on the separate effects of Spring and Fall heat units (Fall_{GDD} and Spring_{GDD}). The Spring_{GDD} and Total_{GDD} models are commonly used to evaluate crop growth and development (Nuttonson 1958; Teasdale et al. 2004). The Fall_{GDD} and Spring_{GDD} model was included because timing of fall cereal rye planting can influence the development of cereal rye (Fowler 1982; 1983). Spring GDD estimates were initiated on March 1 (Nuttonson 1958). Data collected in the sub-plots from the field experiment described herein were fitted with linear regression using the following thermal-based phenological models:

$$\text{Growth Stage} = \beta_0 + \beta_1(\text{Spring}_{GDD}) \quad [3]$$

$$\text{Growth Stage} = \beta_0 + \beta_1(\text{Total}_{GDD}) \quad [4]$$

$$\text{Growth Stage} = \beta_0 + \beta_1(\text{Fall}_{GDD}) + \beta_2(\text{Spring}_{GDD}) \quad [5]$$

where growth stage is the Zadoks developmental stage, β_0 is the intercept, β_i are parameter coefficients defining the slope of the equation and the proportional relationship between Fall_{GDD} and Spring_{GDD}.

Data analysis. Analysis of variance was conducted using mixed models PROC MIXED SAS/STAT (SAS Institute Inc. 2004) to test the effects of year, cultivar, and planting and termination dates on control of cereal rye using a modified split-plot design. An arcsine transformation was completed on percent control data to address the lack of homogeneity of variances. Dose-response curves were used to examine the relationship between cover crop growth stage and mechanical control using the dose response curve package (drc) in R 2.4 (R Development Core Team 2006). T-tests were used to test for differences at the EGS85 by year and cultivar; all estimates of parameter coefficients were included in this analysis. Linear regression, used to determine the relationship between growth stage and GDD, was completed with the linear mixed models package (lm) in R 2.4. Preliminary analyses indicated significant cultivar effects for most phenology models; consequently all analyses were conducted separately for each cultivar. The adjusted coefficient of determination (R^2) was used as indication of goodness of fit. The Akaike information criterion (AIC) was used for model selection (Johnson and Omland 2004). The R^2 and the AIC were used because both penalize for increasing number of parameters. Mean comparisons were performed using the Tukey-Kramer method ($P < 0.05$) in SAS version 9.1 (SAS Institute Inc. 2004).

RESULTS AND DISCUSSION

Cereal rye control by Julian date. Cultivar, planting date, termination date and the interaction between cultivar and planting date significantly influenced cover crop control (Table 3.1). The roller/crimper was most effective on cereal rye planted early in the fall (Table 3.2) and terminated later in the spring (Table 3.3). Aroostook was more effectively

controlled at earlier termination dates than Wheeler, and both responded similarly at the later two termination dates (Table 3.3). The control of cereal rye cultivars was examined in relation to the control threshold across the planting date and termination date factorial (Figure 3.4). These results illustrate the combination of planting date and termination dates where acceptable control of cereal rye was achieved. Control of Aroostook at the first termination date ranged from 5 to 80%, and Wheeler from 5 to 45%; neither cultivar reached the EGS85 at the first termination date. The large standard errors in percent cereal rye control for Aroostook at the May 1 termination date (Figure 3.4) was due to differences in control between years (2005 and 2006), although year was not a statistically significant source of variability (Table 3.1); these large standard errors were not present for Wheeler (Figure 3.4). While year was not a significant source of variability (Table 3.1), there were larger differences in the standard errors for Aroostook than Wheeler at the May 1 termination date. This suggests a cultivar-specific difference in response to early spring environmental conditions that will be addressed in greater detail in the *phenological growth stage* section. The variation in control between cultivars diminished with delay in cover crop termination date (Figure 3.4). By the May 10 termination date, Aroostook rye was effectively controlled if planted on August 25. Rolling/crimping rye on May 20 resulted in effective cereal rye control for all planting dates except October 5 and 15 for Aroostook and September 25 through October 15 for Wheeler. By May 30, control of both cultivars was similar, ranging from 82 to 98%.

As expected, earlier planting and later termination dates resulted in increased rye maturity (Table 3.4). Fowler (1983) reported a similar influence of fall planting time on cereal rye development. The study conducted in Saskatchewan, Canada found that a one

month difference in fall cereal rye planting resulted in a one week delay in cereal rye heading. The relationship between improved control at the later termination dates and increasing cereal rye growth stage observed in this study (Table 3.4) is consistent with several other winter cereal cover crop studies including those conducted with black oat (*Avena strigosa* Schreb.), wheat (*Triticum aestivum* L.), and cereal rye (Ashford and Reeves 2003; Creamer and Dabney 2002). Ashford and Reeves (2003) demonstrated that rolling and crimping black oat, wheat, and cereal rye averaged 16 to 19%, 81 to 85%, and 95% control at the flag leaf, anthesis, and soft dough stages, respectively. Similarly, Wilkins and Belinder (1996) found over a 10-fold decrease in cereal rye and wheat regrowth with each two week delay in mowing beginning at the first node growth stage (Zadoks 31).

Cereal rye control by phenological growth stage. Percent cereal rye control was fitted with a three parameter logistic model (dose response curve) where rye control was dependent on rye growth stage (Figure 3.5). Coefficients of this nonlinear regression are presented in Table 3.5, which includes the analysis conducted by year (cultivars pooled) and by cultivar in 2005. The analysis could not be performed by cultivar in 2006 due to lack of observations at earlier growth stages in Aroostook in 2006; however, there was a similar trend between cultivars within the range of data observed (growth stage 50 to 85). Cultivars responded similarly and were therefore pooled within a given year (Table 3.5) for the parameter estimates and for the inverse growth stage prediction at the EGS85. Thus, while a Julian date-based analysis of cover crop control using the roller/crimper identified differences between the two cultivars (Table 3.1), they responded similarly to rolling when the analysis was based on cereal rye growth stages (Table 3.5).

In contrast to the percent control analysis by Julian dates, year significantly influenced percent control as a function of cereal rye growth stage (Table 3.5). Although the parameter estimates for d , the percent control at the upper GS limit, and b , the relative slope around the inflection point e , did not differ by year, parameter estimates for e and the inverse prediction of rye growth stage at the EGS85 were significantly different across years (Table 3.5). The parameter e and EGS85 represent the biologically important range for the relationship between growth stage and cereal rye control. There was a strong sigmoidal relationship between growth stage and percent control in both years (R^2 of 0.83 and 0.96 in 2005 and 2006, respectively) (Figure 3.5). Using inverse prediction, at the EGS85, the dose response curve predicted a Zadoks growth stage of 55 in 2005 (confidence interval = +/- 2.74) or 50% emergence of the inflorescence from the boot, and 61 in 2006 (confidence interval = +/- 0.65), corresponding to initiation of anthesis. In 2005, effective control was achieved earlier than previous estimates would suggest, while percent control in 2006 was more consistent with previously reported results (Creamer and Dabney 2002; Ashford and Reeves 2003). The observed convergence of the upper limit parameter on 100% control for a mature cereal rye cover crop was expected. Ashford and Reeves (2003) consistently observed greater than 95% control when rolling cereal grain cover crops at the soft dough growth stage (Zadoks 68).

Although we cannot determine why percent control varied across years with our experimental design; it appears that differences in precipitation may account for the divergent e parameter and EGS85 between years. Field conditions in 2005 were atypically dry for the period following rolling compared to the more characteristic early summer precipitation received in 2006 (Figure 3.2). We speculate that drier conditions

during June 2005 may have enhanced control with the roller/crimper compared to the wetter 2006 field season. While the growth stage for acceptable control ranged from 55 to 61, cereal rye was consistently controlled at a Zadoks growth stage of 61 or greater.

Based on the absence of interactions between planting date and termination date for percent control by Julian dates, and the strong fit of the dose response model, we conclude that percent control was the result of plants being susceptible to rolling at later growth stages rather than at particular planting and termination dates. In other words, cereal rye response to mechanical injury is driven by growth stage directly and calendar date indirectly. Therefore, regardless of cultural practices that may influence timing of cereal rye developmental stage, tying timing of cover crop control to growth stage will result in the greatest consistency in rye control with the roller/crimper.

Growth stage predictive model. The three thermal-based phenological models used to simulate cereal rye development were fitted separately for each cultivar and pooled over years (Table 3.1). The Spring_{GDD} and Fall_{GDD} model accounted for the greatest variation in growth stage estimation, and had the lowest AIC values; therefore, this model was selected as the best predictor of cereal rye phenological development (Table 3.6).

Historically thermal-based phenological models used to predict rye development have focused on yield potential and have therefore considered a narrow fall-time planting window (Nuttonson 1958). For example, a 15-day time interval in Saskatchewan, Canada was considered optimal for cereal rye and wheat planting (Fowler 1983). As a result, thermal-based phenological models have not considered fall heat units and have generally used March 1 (base temperature - 4.4 °C) for model initiation (Nuttonson 1958). This date was identified as an acceptable starting point in an inter-continental evaluation

(Northern US, Canada, Soviet Union, Finland, Poland, and Czechoslovakia) of cereal rye growth, development and climate relations (Nuttonson 1958). However, rye is most commonly used as a cover crop in the northeastern U.S. where a wide range of sowing dates (mid-August to late-November) is typical. Therefore, whereas historical approaches for estimating cereal rye development with GDD only account for spring heat units, our results coincide with previous reports (Fowler 1983) that the wider range of planting dates from late summer through fall influenced phenological development and should be incorporated into predictive models. Incorporating the separate effects of fall and spring heat units in the model improved our ability to predict cereal rye stage of development.

While both cultivars were more strongly influenced by SpringGDD, ‘Aroostook’ development was greater per spring heat unit (Table 3.6). The significant difference in effects of Spring_{GDD} on cereal rye cultivars may explain Julian date differences in maturation (Table 3.3) since heat units in the spring of 2006 were greater than in 2005 (Figure 3.3). The differences may be explained by a greater response of ‘Aroostook’ to heat units in early spring. Vernalization may, in part, also be responsible for the differences in cultivar response to early spring heat units since timing of fall planting can influence the cold-tolerance of cereal rye and therefore, its vernalization requirements (Fowler and Gusta 1977; Nuttonson 1958;). Additionally, these requirements can vary by species and cultivar ranging from 1.1 to 3.9 °C and from 20 to 55 days (Nuttonson 1958). ‘Aroostook’ matured earlier than ‘Wheeler’; the cultivar-specific growth and control responses observed in this study underscore the need for cultivar level data when defining cover-crop performance in local growing regions. Given the accelerated springtime growth, ‘Aroostook’ may be a better suited cover crop for the Mid-Atlantic region

because it would allow for earlier planting of the cash crop, despite the greater allelopathic properties of Wheeler.

Regionally specific thermal-models may prove to be a practical alternative to mechanistic models in guiding farmer decision making. However, these models may be limited in years of extreme climate and soil nutrient availability. Acceleration in phenology attributed to drought stress and nitrogen deficiency was observed for winter cereals in an irrigation and nitrogen fertility experiment on sandy soils (Mirschel et al. 2005). However, the greatest acceleration in phenological development has been observed post-anthesis, with variations still in an acceptable range for cover crop management (5-6 days for moisture and 1-2 days for nitrogen deficiency). Therefore, separation of $Fall_{GDD}$ and $Spring_{GDD}$ is an important component in effectively predicting cereal rye development. While the results of this research further develop the foundational understanding of cover crop growth and control, additional work is needed to rigorously test the thermal-based model across the Mid-Atlantic growing region.

CONCLUSION

In summary, cereal rye control increased with cover crop developmental stage. While cultivar growth rates differed, cereal rye control using the roller/crimper was consistent across cultivars at a given growth stage. In our study, cereal rye at the Zadoks stage of 61 or greater was consistently controlled. Typically, larger more mature plants will provide a greater amount of surface residue resulting in greater water infiltration, reduced soil surface evaporation and greater weed suppression (Decker et al. 1994; Langdale et al. 1991; Munawar et al. 1990; Teasdale et al. 1996). Therefore, producers

interested in using mechanical means for cover crop control in a no-tillage or rotational tillage system can use a roller/crimper for cereal rye termination. While the practice outlined in this paper can reduce the need for tillage or chemical control, careful monitoring and rotation planning is required to properly time control of the cover crop, and align the growing periods of the cash and cover crops to effectively manage the cash crop in the cover crop residue. Growers must also consider how high amounts of cover crop residue can influence cash crop establishment and the potential need for supplemental irrigation.

The identification of susceptible growth stages for mechanical control coupled with simple thermal-based phenological models that predict cereal rye development provides useful information to help guide adoption of cereal rye as a cover crop. Extending the findings outlined herein is time sensitive. Farmer interest in cover crop adoption has never been higher. Spurred by state and federal incentives and an increasing understanding of the impact of surface water runoff into environmentally sensitive catchments like the Chesapeake Bay, interest in adopting cover crops is higher than ever (REAP 2007). Future work should concentrate on developing databases of regional mean fall and spring GDD accumulation as well as determining how different cover crop species might fit into this decision framework. From such spatially explicit weather summaries, regional maps based on fall planting dates could be developed that would help farmers anticipate and time cover crop control based on our ability to predict the Julian date at which the EGS85 is reached. The ability to fit a cover crop into a crop rotation will require farmers to anticipate or forecast the growing period of the cover and cash crop within and over several years. Knowledge of these temporally defined windows

could help guide the choice of when and what type of cover crop is compatible with a particular farming practice and better plan for strategic management activities.

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Table 3.1. Analysis of variance for percent control of cereal rye as influenced by year, cultivar, termination date, and planting date.

Effect	% Control P > F
Cover crop (CC)	< 0.0036
Termination date (TD)	< 0.0001
CC X TD	< 0.0001
Planting date (PD)	< 0.0001
CC X PD	0.4005
TD X PD	0.1982
CC X TD X PD	0.9886
Year	0.2407

Table 3.2. Mean cereal rye control as influenced by planting date (year, cultivar, and termination date pooled). Different lower case letters indicate significant differences ($P < 0.05$) using the Tukey-Kramer method.

Planting Date	% Control
August 25	79a
September 5	77ab
September 15	73bc
September 25	70cd
October 5	67de
October 15	63e

Table 3.3. Mean cereal rye control as influenced by cultivar*termination date (year and planting date pooled). Different lower case letters indicate significant differences ($P < 0.05$) using the Tukey-Kramer method.

Termination Date	Aroostook	Wheeler
	% control	
May 1	41b	21a
May 10	79d	71c
May 20	88ef	86e
May 30	94f	93f

Table 3.4. Cereal rye growth stage (Zadoks) as influenced by cultivar, planting date, and termination date for 2005 and 2006. Table values represent means of the four replications.

Variability among replications was not estimable due to the fact that there was no variability among the replications.

Cultivar	Planting Date	2005				2006			
		May 01	May 10	May 20	May 30	May 01	May 10	May 20	May 30
----- Growth Stage (Zadoks) -----									
Aroostook	August 25	45	55	60	73	58	63	73	85
	September 05	41	53	59	71	58	61	73	85
	September 15	41	50	57	71	57	60	71	83
	September 25	40	49	55	70	55	60	71	83
	October 05	38	41	53	69	53	59	69	80
	October 15	34	41	53	68	52	57	65	71
Wheeler	August 25	45	55	59	71	48	59	70	80
	September 05	39	53	57	71	48	59	67	75
	September 15	39	50	55	70	47	57	66	75
	September 25	37	45	53	67	45	57	64	71
	October 05	34	40	53	67	41	55	62	69
	October 15	32	39	50	63	37	48	58	68

Table 3.5. Coefficients for the nonlinear regression using a dose response model of cereal rye percent control as a function of phenological development where Y is % cereal rye control (%); d is the % control at the upper growth stage limit; e , the effective growth stage 50 is the growth stage producing a response half-way between d and the lower limit; and b is the relative slope around e (% control/growth stage) (Ritz and Streibig 2005). Analysis was conducted by year with cultivars pooled and by cultivar within years to test for significance of parameter estimates. Due to lack of data at the lower range of growth stages for Aroostook rye in 2006, differences in cultivars in 2006 could not be tested. The null hypothesis in this case is formulated as a ratio of estimates, and therefore the t-test is comparing the observed ratio with a value of 1. P-values are probability of getting a t statistic greater than the calculated t –value. Values in parentheses are the standard error.

Model Parameters and Control Threshold	Year			Cultivar		
	2005		p-value	2005		p-value
	2005	2006		Aroostook	Wheeler	
b	-7.99(0.48)	-8.90(0.62)	0.247	-8.71(1.00)	-7.52(0.86)	0.365
d	95.37(1.73)	99.39(1.60)	0.089	94.41((3.01)	95.81(3.56)	0.766
e	43.91(0.39)	50.22(0.39)	0.001	44.42(0.70)	43.23(0.83)	0.271
EGS85	55(1.41)	61(0.65)	0.001	54(2.13)	54(1.78)	0.931

Table 3.6. Thermal-based phenological models predicting cultivars of cereal rye phenological development (years pooled). The parameter estimates characterize the effects of growing degree days (GDD) on growth stage of two cereal rye cultivars. Included are adjusted R^2 values and Akaike Information criteria (AIC) for goodness of fit and model selection, respectively.

	Thermal models	β_0	Total β_1	Fall β_1	Spring β_2	Adj. R^2	AIC
Aroostook	Total _{GDD}	35.96	0.017	-	-	0.343	1451.56
	Spring _{GDD}	21.08	-	-	0.067	0.877	1129.89
	Fall _{GDD} vs. Spring _{GDD}	15.19	-	0.007	0.068	0.927	1030.85
Wheeler	Total _{GDD}	29.83	0.018	-	-	0.434	1402
	Spring _{GDD}	18.74	-	-	0.064	0.869	1121.42
	Fall _{GDD} vs. Spring _{GDD}	11.11	-	0.009	0.064	0.963	882.23

Figure 3.1. Photograph of a front-mounted roller/crimper constructed by Penn State University. The roller/crimper is 3.2-m in length by 51-cm diameter by 3.2-mm thickness and weighs 1520 kg.



Figure 3.2. Cumulative daily precipitation \circ = 2006 and \bullet = 2005 in Rock Springs, Pennsylvania, USA for the 2005 and 2006 cropping seasons.

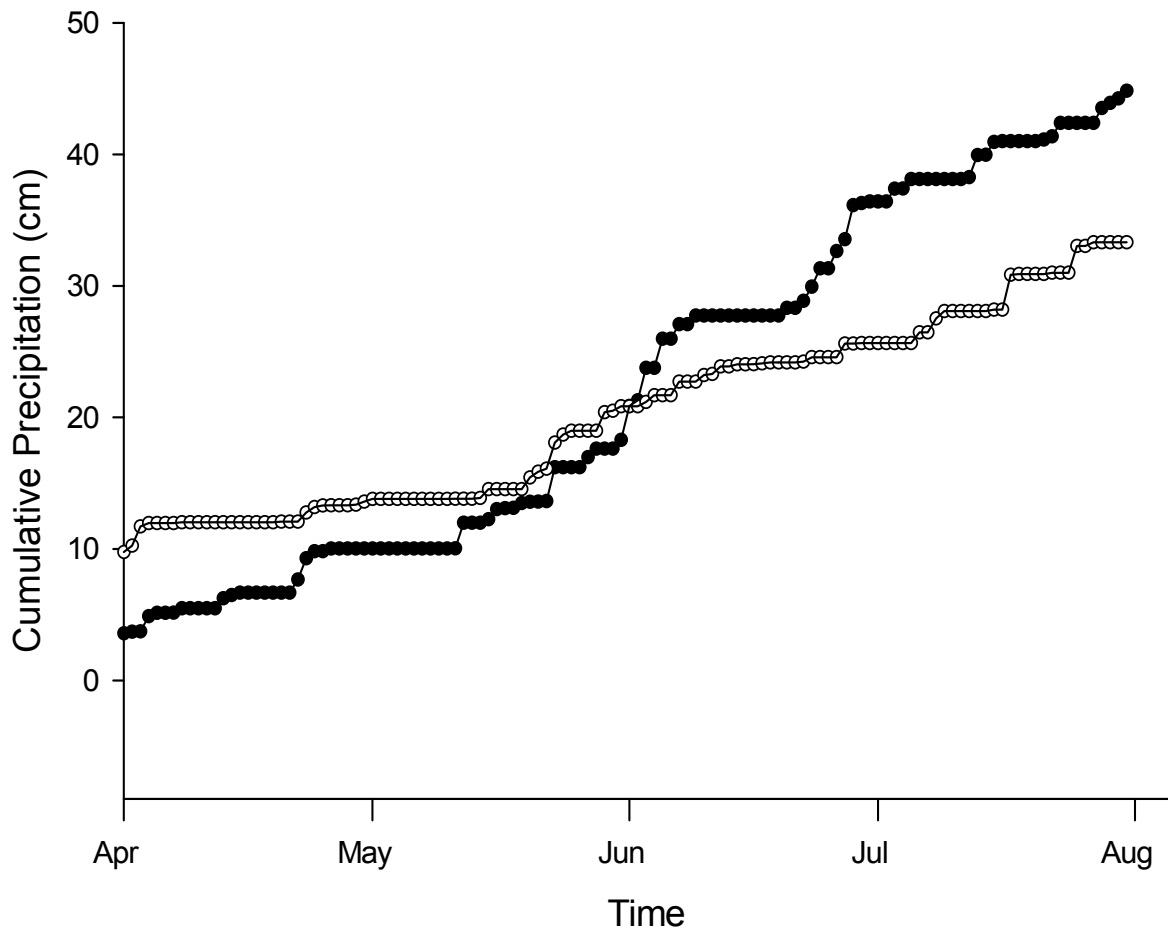


Figure 3.3. Cumulative daily growing degree days (GDD) ○ = 2005 and ● = 2006 in Rock Springs, Pennsylvania, USA for the 2005 and 2006 cropping seasons. Growing degree days were calculated by the following equation: $GDD = ((T_{max} + T_{min})/2) - T_{base}$ where T_{max} is the maximum daily temperature, T_{min} the minimum daily temperature, and T_{base} is the base temperature (4.4 °C) (Nuttonson 1958).

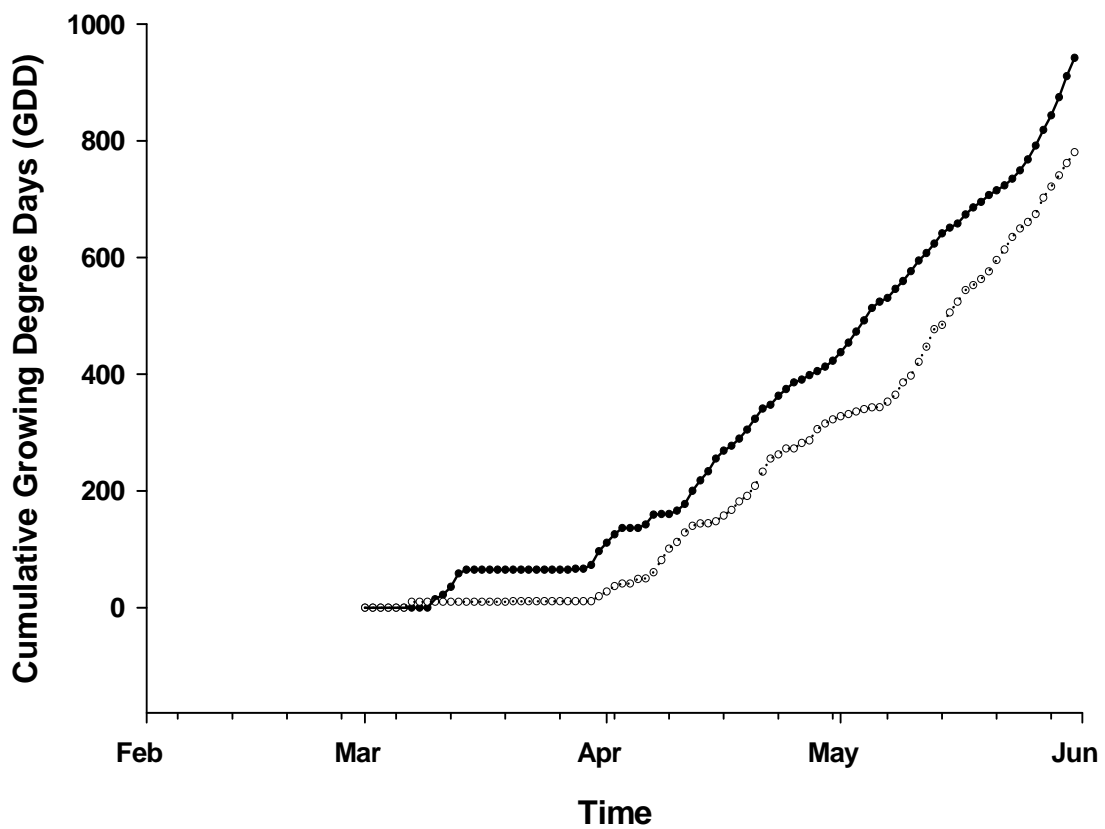


Figure 3.4. Percent control of cereal rye cultivars six weeks after rolling/crimping by cultivar, planting date and termination date (years pooled). Acceptable control of cereal rye cover for planting date and termination date combinations was achieved at the 85% control threshold. Bars represent standard error of the means.

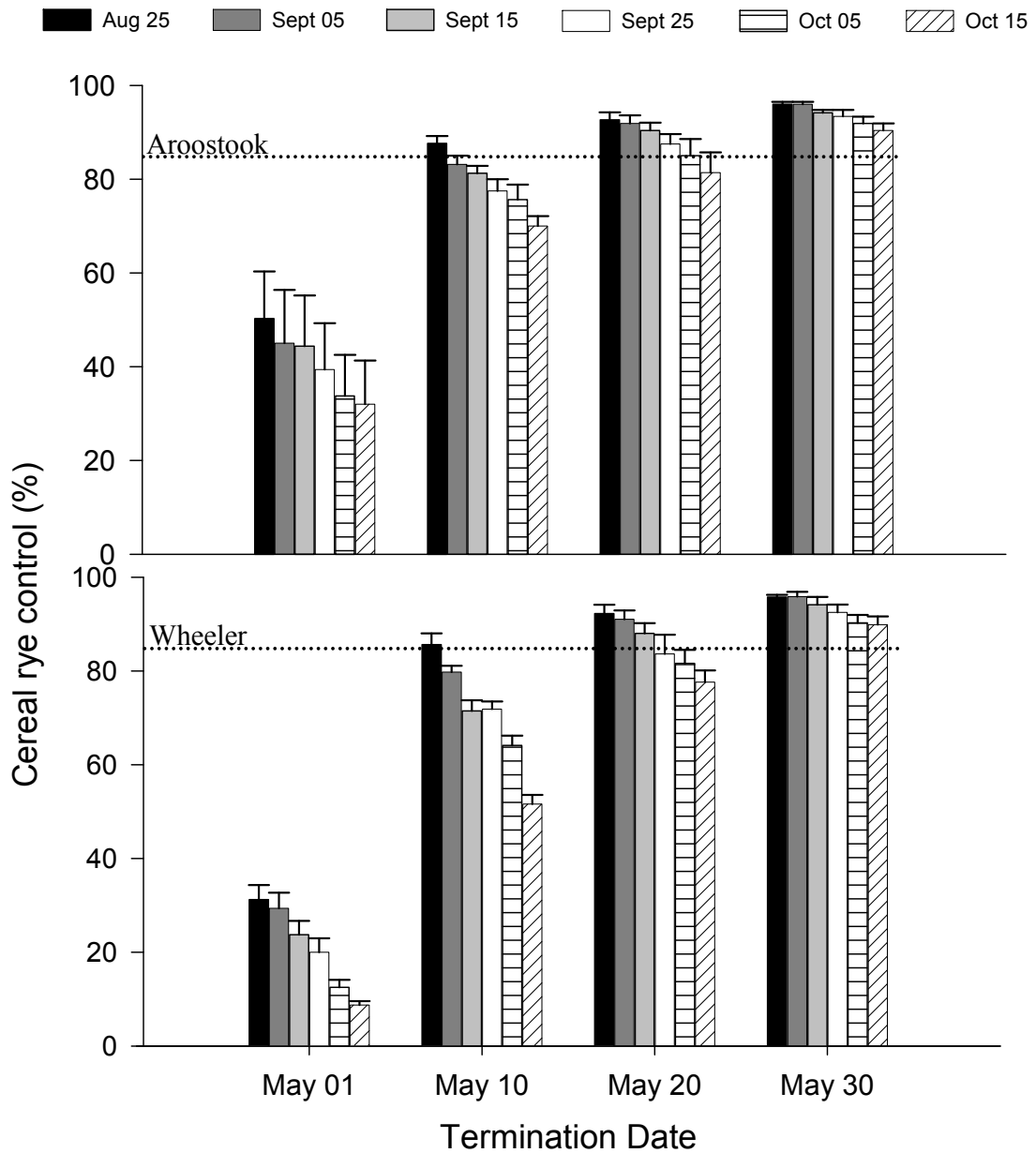
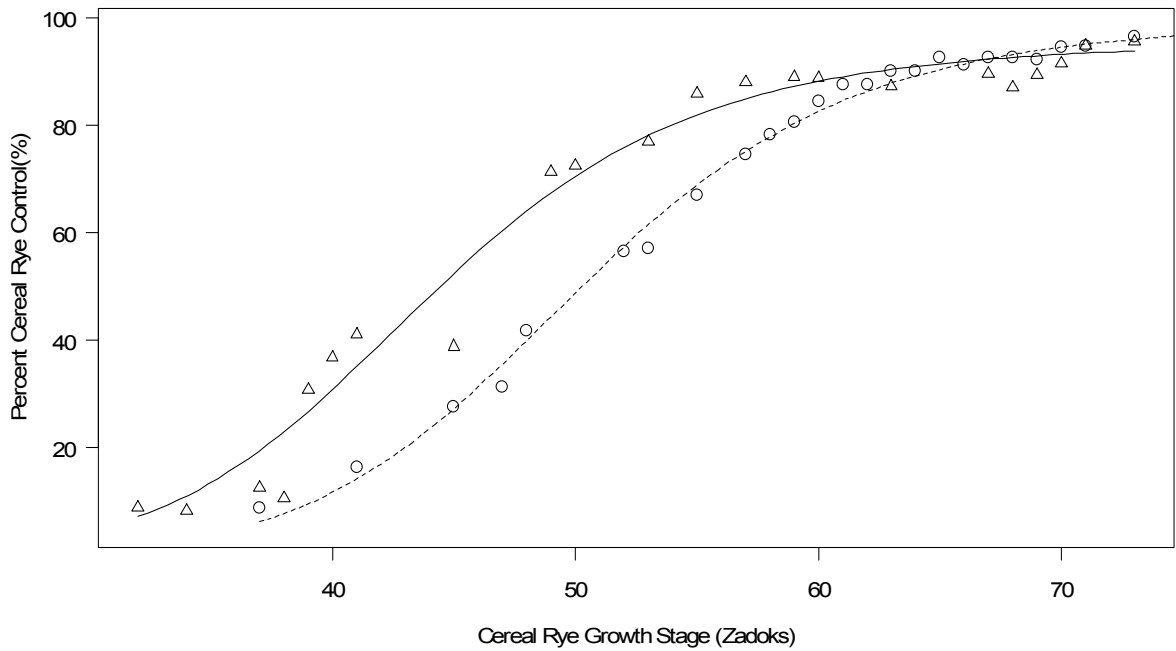


Figure 3.5. Percent cereal rye control in Δ / solid line = 2005 and \circ / dashed line = 2006 as related to phenological development. The line represents the fitted 3 parameter sigmoidal dose response curve regression. Data are pooled over cultivar due to no significant cultivar effects.



Chapter 4

Timing of Cover Crop Management on Weed Suppression in Reduced-till Soybean

ABSTRACT

Integrated weed management tactics are necessary to develop cropping systems that enhance soil quality using conservation tillage and reduced herbicide or organic weed management. In this study, we determined how the growth of two cereal rye cultivars and a rye/hairy vetch mixture created by varying planting and termination dates influenced cover crop biomass accumulation. Through this work, we developed a model to predict cereal rye biomass accumulation as influenced by thermal time. In addition, we evaluated how timing of cover crop management with a roller/crimper affects weed emergence and how this can influence the composition and abundance of the weed community across the biomass gradient. Cover crop biomass increased approximately 2000 kg ha⁻¹ from earliest to latest planting dates (August 25-October 15) and for each 10-day incremental delay in spring termination date (May 1-June 1). Biomass accumulation based on Julian date identified differences between the two rye cultivars; however their rates of growth were similar for the range observed. Biomass accumulation for cereal rye was predicted better with a thermal-based model that separated the effects of fall and spring heat units compared to models that used cumulative (fall+spring) or spring thermal time alone. Differences between cover crops in total weed suppression were observed for the two rye cultivars, while weed suppression with the rye/hairy vetch mixture was intermediate between the two. However, weed suppression of three life history classes (i.e., summer annual broadleaf and grasses, and perennials) and for individual species, was similar across cover crop treatments. Delay in cover crop

termination had the greatest reduction in weed density; early and late emerging summer annuals were both suppressed when cover crop termination date was delayed. Yellow nutsedge was not influenced by cover crop type or the timing of cover crop management. We speculate that the degree of synchrony between weed species emergence periodicity and cover crop biomass accumulation played an important role in defining the extent of weed suppression or success.

INTRODUCTION

Surface mulches physically suppress weeds by altering light quantity and quality, temperature at the soil surface, and by acting as a barrier to reduce seedling emergence. Weed control increases with increasing cover crop biomass; however, levels that are typically achieved in northeastern U.S. cropping systems (e.g., 3300 kg ha⁻¹) are generally insufficient to provide adequate levels of weed suppression (Mohler and Teasdale 1993). In addition, uniform distribution of the cover crop residue is needed for consistent suppression of weed emergence (Creamer et al. 1996; Teasdale and Mohler 1993). The effect of cover crop residues on weed control is species-specific, with some species being quite susceptible to cover crop surface mulches, whereas others are not (Mohler and Teasdale 1993; Liebman and Davis 2000). In general, weed control with cover crop surface residues alone has generally been incomplete, requiring integration of cover crops into a weed management program that includes additional management tactics (Williams et al. 1998).

Cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) are cover crops commonly grown throughout the U.S. and have been evaluated for their weed

suppressive potential in no-till agriculture (Wilkins and Bellinder 1996; Hoffman et al. 1993; Teasdale et al. 2004b). Both are selected for their winter hardiness and high biomass potential. Cereal rye has been selected for its residue persistence and flexible establishment date (Ruffo and Bollero 2003), and hairy vetch for its capacity to fix large amounts of nitrogen (Abdul-Baki et al. 1997). Cereal rye and hairy vetch surface residue levels are often insufficient alone for adequate weed suppression (Mohler and Teasdale 1993). However, by manipulating planting date in the fall or termination date in the spring, greater biomass accumulation for both cover crops can be achieved (Duiker and Curran 2005; Teasdale et al. 2004a). The rate of cover accumulation in the spring is also influenced by the timing of fall planting. Teasdale et al. (2004a) showed that later fall establishment of hairy vetch reduced spring biomass by 43% when terminated in the vegetative stage compared to only 20% at the flowering stage. In a Pennsylvania study, Duiker and Curran (2005) showed that average above-ground cereal rye biomass was three times greater when terminated at the late-boot stage (4200 kg ha^{-1}) compared to the early-boot stage (1400 kg ha^{-1}).

Fall planting and spring termination dates for cereal rye and hairy vetch cover crops are primarily determined by previous and future crops in the rotation sequence. Depending on the cropping system (e.g., field, vegetable, or forage crops), and method of termination, timing of cover crop establishment and termination will vary considerably. In the northeastern U.S., cereal rye is typically sown over a wide range of planting dates from mid-summer to late-fall. Hairy vetch is planted from mid-August to no later than mid-September in the Mid-Atlantic Region to increase the likelihood of over-winter survival. The growing season length is determined by the fall planting and spring

termination dates. Previous work quantifying the relationship between cereal rye growth stage and mechanical control revealed that fall and spring heat units do not equally influence development of cereal rye (Chapter 3). While much work has been conducted to quantify the effect of growing season length on hairy vetch biomass accumulation (Teasdale et al. 2004a), less is known about the combined effects of planting and termination date on cereal rye and rye/hairy vetch mixtures.

Research assessing the weed-suppression of surface killed cereal rye and cereal rye/hairy vetch covers has focused on herbicide-killed cover crops or control accomplished mechanically by mowing (e.g., rotary or flail mowing) or stalk chopping (e.g., Buffalo rolling stalk chopper) (Moore et al. 1994; Yenish et al. 1995; Teasdale and Rosencrance 2003). In general, these control methods result in a suppressed cereal grain or grain-legume mix that is not uniformly distributed on the soil surface, but instead is left partially standing in the case of the herbicide killed covers, or is unevenly distributed following mowing or stalk chopping. (Facelli and Pickett 1991; Teasdale and Mohler 1993). Teasdale and Mohler (2000) modeled the functional relationship between the uniformity of ground cover provided by cover crop residues and weed emergence and suggested that residue management methods that increase uniformity of soil coverage will result in greater physical weed suppression.

The roller/crimper, a new residue management tool adapted from equipment used in southern Brazil and Paraguay, lays cover crops down while crimping and damaging the vascular tissue (Figure 4.1) (Ashford and Reeves 2003). In contrast to mowing, cover crops managed with a roller/crimper are more uniformly distributed on the soil surface. Because the plant material is mostly left intact, residues can persist for longer periods of

time (Morse 2001; Creamer and Dabney 2002). Although not fully investigated, one would expect that greater uniformity coupled with a more persistent cover should result in greater weed suppression (Ashford and Reeves 2003).

The suppressive potential of cover crop surface residues is weed species-specific (Mohler and Teasdale 1993). Differences in weed suppression are likely the result of variation in temporal synchrony between weed germination and the presence of a sufficient quantity of cover crop biomass to influence that process. Environmental factors regulating germination and successful emergence include soil temperature (Vleeshouwers 1997), status of weed seed dormancy (Baskin and Baskin 2006), ambient light and temperature fluctuations (Benech-Arnold et al. 2000), depth of seed burial (Chauhan et al. 2006), soil water potential (Forcella et al. 2000) and seed size (Mohler and Teasdale 1993; Teasdale and Mohler 2000). These factors define the onset of germination, duration, and subsequent emergence. The expressed species-specific period of emergence is termed weed emergence periodicity (Forcella et al. 2000).

The timing and synchrony of crop and weed management practices with weed seed germination and emergence can influence the composition and abundance of a weed community (Booth and Swanton 2002; Facelli and Pickett 1991; Shea et al. 2004). The frequency and timing of soil tillage (Bullied et al. 2003; Roman et al. 2000) and herbicide application (Hilgenfeld et al. 2004) influence the extent to which many management practices serve as effective filters that can suppress and shape the weed community (Smith 2006). Delaying timing of management can alter the weed community structure (Milberg et al. 2001); leading in some cases to decreased density and less competitive weed species. For example, delaying spring tillage and crop planting have been suggested

as ways to reduce crop/weed competition due to increased crop growth rates as temperatures warm in late spring (Nielsen et al. 2002) as well as a tactic to ensure control of early and mid-spring emerging weed species (Nordell and Nordell 2006).

An effective weed management program that utilizes cover crops for weed suppression, and relies less on tillage and herbicides, must focus on integrating multiple tactics. Varying the timing of cover crop management both in the fall and spring to increase biomass accumulation can increase weed suppression from the cover crop mulch. Also, understanding the weed emergence periodicity within a field can help identify which weed species are expressed and when they could be a problem. The relationship between the amount of cereal rye and hairy vetch surface residues and weed suppression has been examined at a single termination date in the spring (Mohler and Teasdale 1993; Moore et al. 1994). The range of cover crop biomass was achieved by clipping and adding residues from adjacent plots (Mohler and Teasdale 1993). While this work carefully quantified the effect on weed emergence from a range of cover crop biomass levels, it was an artificial study system in that the residue was added by hand to represent an array of biomass levels at a single point in time during the spring growing season. *In situ*, winter annual cover crop biomass accumulates during the course of the spring, with low accumulation early in the spring, and with greater amounts being produced as the spring progresses. Therefore, the timing of cover crop management influences the levels of mulch in the field, which, in turn alters soil physical and chemical properties known to directly influence weed seed germination requirements. We hypothesize that efficacy of weed suppression is dependent on cover crop biomass, timing of termination, the

emergence patterns of the resident weed community and the sensitivity of those species to the cover crop residue.

Previously, we reported on the efficacy of mechanical control of cover crops at a range of growth stages with a roller/crimper (Chapter 3). Here we report on the influence of timing of planting and termination of two cereal rye cultivars and a cereal rye/hairy vetch mixture on spring cover crop biomass accumulation. Accumulated growing degree days were used to quantify the relationship between cover crop biomass accumulation and thermal time. We also examined the influence of the timing of cover crop management and the resulting biomass gradient on weed suppression.

METHODS

Field experiments were conducted from 2004 to 2006 at the Russell E. Larson Agricultural Research Center near Rock Springs, Pennsylvania (40°44' N, 77°57'W). The experimental design was a modified split-plot arranged with cover crop type (three treatment levels) and termination date (four termination dates) as main plots and fall establishment (six planting dates) as sub-plots. Planting date was nested within cultivar treatments and the experiment was replicated four times. Individual sub-plots measured 1.53 m wide and 2.3 m in length. The experiment was initiated in the fall of 2004 and repeated again in 2005 in an adjacent field. The study was conducted on a Hagerstown silt loam soil (Fine, mixed, mesic, Typic Hapludalfs) with a surface soil pH of 6.5 and organic carbon content of 20 g kg⁻¹. Cover crops included two cereal rye cultivars and a cereal rye/hairy vetch mixture. 'Aroostook' rye was selected because of its winter hardiness and common use in the region. 'Wheeler' rye was included for comparison

because of its reported high allelochemical content (Reberg-Horton et al. 2005), which is useful for suppressing weeds. The cereal rye/hairy vetch combination is a common mixture used in the region for its soil quality contributions including N fixation (Teasdale 1996). Aroostook rye was used in the seeding of the cover crop mixture; the hairy vetch variety was not stated.

In both years, the previous crop was spring-planted oats (*Avena sativa* L.) harvested for grain. Seedbed preparation for the cereal rye included disking and cultimulching the oat residue prior to sowing to kill weeds and volunteer oats plants and to produce a uniform seedbed. The weed infestation at the site was light to moderate and typical of a well managed conservation-tillage corn, soybean, and small grain rotation for the area. This work focused on cover crop biomass accumulation over time and subsequent suppression of weeds by a cover crop terminated without tillage; it was not intended to represent a continuous no-tillage regime. As such, the results from this research should be relevant to both farmers utilizing some tillage as well as dedicated no-till farmers (Venterea et al. 2006; Peigne et al. 2007; Wilson 2007).

Cereal rye and the rye/hairy vetch mixture were seeded on 10-day intervals from August 25 to October 15 (six equally spaced planting dates in total). Cover crops were drill-seeded in 19-cm rows using a 1.8 m wide 'Great Plains (3P605NT)' small plot drill, at 135 kg ha⁻¹ for cereal rye alone and 90 plus 45 kg ha⁻¹, respectively for the rye and hairy vetch mixture. Ammonium sulfate was broadcast-applied at a rate of 71 kg N ha⁻¹ in March of each year to stimulate rye growth and ensure adequate biomass production. To terminate the cover crop in the following spring, 0.84 kg ae ha⁻¹ glyphosate plus 0.28 kg ae ha⁻¹ 2,4-D LVE was applied in 187 L ha⁻¹ water at 207 kPa using a tractor mounted

sprayer at 10-day intervals from May 1 to May 30 (four termination dates). The cover crops were rolled/crimped approximately 24 h after herbicide application. The herbicide was applied to ensure successful weed and cover crop control without reliance on mechanical control alone. Although we did not quantify weed emergence prior to herbicide application, we previously observed that few summer annual weeds emerge in a dense rye or hairy vetch cover crop prior to spring termination. A no cover crop treatment that also received the herbicide and rolling/crimping regime at each termination date was included to compare the effects of cover crop residue vs. no residue on weed emergence.

The roller/crimper used in this experiment was made from cylindrical steel well casing (3.2-m length x 51-cm diameter x 3.2-mm thickness) with metal slats spaced 10.2 cm apart welded onto the cylinder in a chevron pattern (Ashford and Reeves 2003) (Figure 4.1). The roller/crimper weighed 1520 kg and was front mounted on a John Deere 7700 tractor operated at 7.2 km h⁻¹. The cover crops were rolled/crimped in a direction perpendicular to the direction of sowing; thereby laying the cover crop down in a unidirectional pattern. Soybean (Chemgro 3340) was no-till drilled (432,400 seeds ha⁻¹) into the cover crop residue in 19 cm rows 10 days after rolling/crimping. Soybean was planted with a Great Plains (1006NT) no-till drill in the same direction as the roller/crimper.

Air temperature and precipitation were recorded at a weather station located within 0.25 km of the experiment. Supplemental irrigation was provided (2 cm in May 2005 and 2.5 cm in May and June 2006) to ensure successful soybean and weed emergence. Cover crop biomass was harvested immediately before herbicide application

in each planting date main plot by clipping all above-ground plant material from a single 0.5-m² quadrat in an area independent of future weed assessments. Biomass samples were dried at 50°C for one week prior to weighing.

The effect of cover crop surface residue and timing of residue management on weed suppression was determined by assessing weed seedling emergence at four and eight weeks after cover crop termination. Weed emergence was quantified by randomly placing two 0.25 m² quadrats within each planting by termination date subplot and counting the emerged weeds by species. Surviving weeds that appeared injured from the burndown herbicide application were not recorded.

Thermal time, using growing degree days, was used to evaluate the relationship between thermal time and cereal rye biomass accumulation. Growing degree days (GDD) were calculated using the following equation:

$$GDD = \frac{T_{\max} + T_{\min}}{2} - T_{base} \quad [1]$$

where T_{\max} is the maximum daily temperature, T_{\min} the minimum daily temperature, and T_{base} the base temperature (base temperature value where physiological activity and growth still occur) set at 4.4 °C (Nuttonson 1958). Cumulative GDD is the summation of daily GDD between a planting date and termination date. For mean temperatures less than T_{base} , GDD were assumed to be zero.

We utilized three thermal-based growth models to characterize cereal rye biomass using cumulative daily heat units; one driven solely by spring temperature (Spring_{GDD}); one based on cumulative heat units from the Fall and Spring (Total_{GDD}); and the final model based on separate effects of Spring and Fall heat units (Fall_{GDD} and Spring_{GDD}). The Spring_{GDD} and Total_{GDD} models have been used previously to evaluate crop growth

and development (Nuttonson 1958; Teasdale et al. 2004a). The Fall_{GDD} and Spring_{GDD} model was included because timing of fall cereal rye planting can influence the growth of cereal rye (Fowler 1983; Chapter 3). Spring GDD estimates were initiated on March 1 (Nuttonson 1958). Data collected in the sub-plots from the experiment described herein were fitted with linear regression using the following thermal-based growth models:

$$\text{Biomass} = \beta_0 + \beta_1(\text{Spring}_{\text{GDD}}) \quad [3]$$

$$\text{Biomass} = \beta_0 + \beta_1(\text{Total}_{\text{GDD}}) \quad [4]$$

$$\text{Biomass} = \beta_0 + \beta_1(\text{Fall}_{\text{GDD}}) + \beta_2(\text{Spring}_{\text{GDD}}) \quad [5]$$

where Biomass is the cover crop residue dry weight sampled prior to rolling/crimping; β_0 the intercept, and β_i are parameter coefficients defining the slope of the equation and the proportional relationship between Fall_{GDD} and Spring_{GDD}.

Data analysis. Analysis of variance (ANOVA) was conducted to test the effects of year, cultivar, and planting and termination dates on cover crop biomass accumulation using a proc mixed procedure in SAS v. 9.1 (SAS Institute Inc. 2004). Linear regression was used to determine the relationship between growth stage and GDD using a linear mixed models package (lm) in R 2.4 (R Development Core Team 2006). The adjusted coefficient of determination (R^2) was used as an indication of goodness of fit and the Akaike information criterion (AIC) was used for model selection (Johnson and Omland 2004). Analysis of covariance (ANCOVA) was applied to evaluate the effect of cereal rye cultivar on cover crop biomass with fall and spring GDD as covariates. ANOVA was used to examine differences in weed suppression among the residue treatments.

Weed community associations were examined using redundancy analysis (RDA) with CANOCO 4.5 (ter Braak and Smilauer 2002). RDA is well-suited for evaluating

weed community data as it reveals associations between systems attributes and weed communities (Reberg-Horton et al. 2006). A constrained form of principle component analysis, RDA identifies optimal linear models describing community structure and predicts species response. The regressive coefficients in RDA are constrained by factors in the experimental design as well as environmental gradients, which allows for hypothesis testing by partitioning treatment effects into individual factors (Reberg-Horton et al. 2006). The influence of cover crops on broad changes in the weed community was evaluated by grouping weedy species into one of the following three life history classes: summer annual broadleaves, summer annual grasses, and perennials. An RDA was performed where weed community was constrained by the following explanatory variables: field site, termination date, and the biomass and Spring GDD gradients. A Monte Carlo permutation was used to test for significant community gradients using 499 permutations. The significance of the community gradients was determined by calculating the proportion of F-statistics generated from the permuted environmental matrixes that were greater than the F-statistic calculated from the empirical species-environmental matrix. The environmental variables that significantly influenced species response were then determined by using a forward selection procedure on the environmental variables. Weed species count data were Hellinger-transformed (Legendre and Gallagher 2001) prior to analysis to standardize data by sample.

The RDA was considered a partial RDA because blocks were treated as covariables to remove the block effect. The degree of association of weed species groups and explanatory variables were visualized with biplots, developed in CanoDraw (bundled with CANOCO 4.5), in which the species and explanatory variables were plotted along

the orthogonal primary and secondary community gradients. Close proximity or an acute angle between weed group vectors and explanatory variables is indicative of a high degree of association, whereas vectors perpendicular to the weed species group are not correlated and those at 180° of the weed species group are negatively correlated.

Weed community response to the cover crop treatments was further tested with permutational multivariate analysis of variance, PERMANOVA (Anderson 2005). Using permutation methods, PERMANOVA simultaneously tests for the effects of multiple treatment factors on multiple response variables based on distance measures, retaining the structure of the experimental design (Anderson 2001; McArdle and Anderson 2001). A single distance measure is computed from community signatures and compared between samples to calculate a F-statistic. The Bray-Curtis distance measure (Beals 1984) was used and data were permuted 499 times.

We examined the contingency table of the weed community composition data using a frequency analysis (proc freq, SAS v. 9.1) to determine homogeneity of weed community structure (i.e., dominance distribution) among cover crop residue treatments across the termination dates. Differences were tested using Pearson's χ^2 test. A significant change in species composition and abundance where a change in the frequency distribution of weed counts resulting in a significant Pearson's χ^2 would indicate a change in dominance structure. Preliminary analysis showed significant differences between residue treatments for both field sites; therefore analysis was conducted by residue treatment across the termination dates by field site. When differences in community structure were found, species contributing most to the shift in dominance structure were identified as those with the highest cell χ^2 values. Where a high proportion of the test

statistic was skewed to a few weed species, the proportion of the total test statistic that these species represent was reported. ANOVA was also used to examine differences in weed emergence and suppression between the no residue and residue treatments. A log (weed count +1) transformation was completed on individual weed species emergence data when a lack of homogeneity of variances was found. All means comparisons were performed using the Tukey-Kramer method ($P < 0.05$) in SAS v. 9.1.

The weed community was evaluated in three ways: 1) total weed density, 2) three life history classes (i.e., annual broadleaves, annual grasses, and perennials), and 3) individual species. Univariate analysis was performed on total weed density; univariate and multivariate analysis were performed on annual broadleaves, annual grasses, and perennial weed density. Species with a relative abundance $\geq 3\%$ for at least one field site were included in the life history class analysis. Univariate analysis performed by species was only tested on weed populations representing $\geq 3\%$ of total weed abundance in both the 2005 and 2006 field sites.

RESULTS AND DISCUSSION

Cover crop biomass. Cover crop, planting date, and termination date significantly influenced biomass accumulation. Year was not a significant source of variation and there were no significant interaction terms (Table 4.1). ‘Aroostook’ rye growing in monoculture produced greater biomass than ‘Wheeler’ rye, and the cereal rye/hairy vetch mixture biomass was intermediate between the two rye cultivars (Table 4.2). Cover crop biomass increased when planted earlier in the fall and terminated later in the spring (Table 4.2). Cover crop biomass was influenced by fall planting date with mean biomass

accumulation ranging from 7,880 kg ha⁻¹ at the earliest planting date to 5,066 kg ha⁻¹ at the last planting date on October 15 (crop and termination date pooled). This represents a 65% increase in biomass from the last planting date in the fall to first planting date in late August; cover crop biomass increases with earlier planting. The greatest gain in cover crop biomass occurred between the latest planting dates (about 24% between Oct. 5 and 15), the lowest at the earlier planting dates (about 12% between Aug. 25 and Sept. 25). Spring termination date mean biomass levels ranged from about 4,050 up to 10,000 kg ha⁻¹ and averaged about 37% increase in biomass with each incremental delay in cover crop termination. Teasdale et al. (2004a) reported a 76 and 24% increase in hairy vetch biomass with delay in termination in a study pooled over three experimental sites in Maryland and New York comparing spring cover crop termination at the vegetative and flowering stages, respectively.

The range of the cereal rye/hairy vetch mixture dry matter produced (means ranged from 1,615 to 12,602 kg ha⁻¹; Figure 4.2) has not been previously evaluated. Ashford and Reeves (2003) reported 10,500 kg ha⁻¹ cover crop biomass in a study where cereal rye was terminated at the soft dough stage (a growth stage also represented in this study), and Vaughan and Evanylo (1998) reported 10,370 and 9,985 kg ha⁻¹ for cereal rye and rye/hairy vetch biomass, respectively, in a study that delayed desiccation until late May in Blacksburg, VA. The wide range of cover crop dry matter produced in this study is a result of late fall planting coupled with early termination producing the least amount of biomass and early fall planting with late spring termination resulting in the greatest biomass yield.

The rye/hairy vetch mixture was not fit to a thermal model since biomass accumulation for the two species mixture is dependent on the proportion of each in the mixture, which we did not investigate in this experiment. The three thermal-based phenological models used to simulate cereal rye growth and development used separate models for each cultivar of cereal rye biomass accumulation (Table 4.3). The Fall_{GDD} plus Spring_{GDD} model accounted for the greatest variation in rye biomass accumulation, and also had the lowest AIC values; therefore, this model was selected as the best predictor. Cultivars were analyzed separately because an ANCOVA of cereal rye biomass accumulation as a function of cultivar with Fall_{GDD} and Spring_{GDD} as covariates revealed no Cultivar*Fall_{GDD} or Cultivar*Spring_{GDD} interactions (Table 4.4). This result demonstrates that cultivar did not influence the slope of the regression between biomass and Fall_{GDD} or Spring_{GDD}; that is, the rate of biomass accumulation was similar for both rye cultivars. Although growth rates for the two cultivars were similar in the range of biomass observed, the rate of fall and/or early spring growth (observations not recorded) differed because differences in biomass accumulation by Julian day were observed (Table 4.2). As a result, the ANCOVA revealed similar slopes for the Fall_{GDD} and Spring_{GDD} by cultivar biomass accumulation, but the ANOVA revealed intercept differences (Table 4.1). These results show that heat units accumulated in the spring more strongly influence cover crop biomass than those accumulated during the fall.

Whereas previous approaches to estimating cereal rye development have centered on the accumulation of spring time GDD's (Nuttonson 1958), the wider range of planting dates included in this study influenced phenological development (Chapter 3). Incorporating the separate effects of fall and spring heat units in the model significantly

improved our ability to predict biomass accumulation. Late August and early September cereal rye planting dates have generally not been investigated in row crop production because timing of fall planted covers is limited based on cash crop removal (Westgate et al. 2005). However, cover crops are being used increasingly in a broad array of fruit, vegetable, grain, and forage crops, which allows for wider range of fall sowing dates (Veenstra et al. 2006; Curran et al. 2007). The thermal-based growth model was a useful approach for quantifying the variation in biomass accumulation associated with planting and termination dates. To extend the results of these findings to other sites, models used for forecasting are needed. Those models would also need to address regional variation in photoperiod, precipitation, and soil fertility (Ruffo et al. 2004; Malhi et al. 2006).

Weed response to residue management. The eight week emergence data was used for the weed community analysis because few differences in emergence patterns were observed between the four and eight week sampling dates and because the eight week assessment integrated a longer period for weed emergence. The weed species included in the analysis of the life history classes represented 88 and 93% of the total weed community emerging in residue treatments and 88 and 91% emerging in the no residue control in 2005 and 2006, respectively. These species included the following annual broadleaves: redroot pigweed (*Amaranthus retroflexus* L.), common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), and wild buckwheat (*Polygonum convolvulus* L.). Annual grass species included fall panicum (*Panicum dichotomiflorum* Michx.) and giant and yellow foxtail (*Setaria faberi* Herrm. and *S. glauca* L.). Perennial weeds included yellow nutsedge (*Cyperus esculentus* L.) and dandelion (*Taraxacum*

officinale Weber in Wiggers). These targeted weed species ranged from 3 to 39% of total abundance of weeds emerging in each year.

Cover crop type, planting date, and termination date were all significant sources of variation on total weed density (Table 4.5). While differences were relatively small, total weed density was lowest in the ‘Aroostook’ treatments (Table 4.6), which was likely the result of greater Aroostook biomass accumulation (Table 4.2). Although Wheeler is known to contain higher concentrations of known allelochemicals such as DIBOA (2,4-dihydroxy-1,4-(2H)benzoxazine-3-one) than some other rye cultivars (Reberg-Horton et al. 2005), physical impedance is likely the primary mechanism suppressing weeds in a cover crop surface residue. Teasdale and Mohler (2000) reported that quantity of residue was more important than the type of residue and showed that levels of weed suppression were similar under varying mulch types that included both allelopathic and highly weathered inert residues.

Earlier planting of winter-sown cover crops and delay in spring termination reduced weed densities. Suppression of annual broadleaves did not vary by cover crop, but was influenced by time of fall planting and spring termination. Annual grass density was reduced only in the late termination treatments in 2006 (Table 4.6). Perennial weeds were not influenced by cover crop type or the timing of cover crop management. For individual weed species, cover crop type did not affect weed emergence, while planting date effects were observed only for common lambsquarters (Table 4.5). In contrast, termination date influenced the density of a number of species including common lambsquarters, foxtail spp., dandelion, and common ragweed (Table 4.5). In general, the influence of cover crop planting and termination date resulted in lower weed population

densities at earlier planting and later termination dates. Since planting and termination dates define the growing season length for the cover crop, they directly influence cover crop biomass which in turn influences weed density. Earlier cover crop establishment resulted in greater biomass in the spring and reduced annual broadleaf weed density (Table 4.6). Common lambsquarters was the only annual broadleaf influenced by planting date, with a lower density in the first three planting dates compared to the final three dates. This result may be explained in part by its small seed. Seed size influences the success of weed emergence through residue mulches; small-seeded annual broadleaves, including common lambsquarters, are most sensitive to increasing surface residue (Mohler and Teasdale 1993; Teasdale and Mohler 2000). Delayed cover crop termination in spring had the greatest suppressive effect on cover crop biomass and weed density (Tables 4.2 and 4.6). However, the degree of synchrony between weed species emergence periodicity and cover crop biomass accumulation may also play an important role in defining the extent of weed suppression and the degree to which species are suppressed or successful.

Multivariate statistical analysis was performed on the density of annual broadleaves, annual grasses, and perennials to determine the extent to which cover crop treatments were acting on species groups in similar or unique ways. Planting date was not included in the RDA since there was no planting date by termination date interaction and preliminary ordinations indicated little influence of planting date on the species response. Therefore, fall GDD was not included because this analysis only investigated the effect of cover crop biomass as influenced by termination date. Ordination biplots from the RDA were used to interpret weed community associations with treatment factors and

environmental gradients (Figure 4.3). The RDA identified significant primary and secondary community gradients which are shown on the biplots as the horizontal and vertical axes, respectively (Figure 4.2; 1st axis: $F=31.25$, $P=0.002$; 2nd axis: $F=15.89$, $P=0.002$). Using forward selection, the primary axis was associated with field site ($F=58.41$, $P=0.002$), while the secondary axis was associated with the cover crop biomass gradient ($F=20.46$, $P=0.002$). Therefore, the greatest amount of variation in weed communities was attributed to field site followed by the gradient in cover crop biomass. Centroids for the rye cultivars and rye/hairy vetch mixture were closely associated with the intersection of the axes, indicating cover crop type has minimal influence on the weed life history classes. These results are consistent with the univariate analysis (Table 4.5).

Annual grass and broadleaf weed species were negatively associated with biomass as indicated by the weed species vectors pointing in an opposing direction of the biomass vector (Figure 4.3). Annual grasses were not correlated with field site as indicated by the right angle between the grass vector and field site. Annual broadleaf weeds were associated more with the 2005 field site and both annual broadleaves and grasses were correlated with earlier cover crop termination dates. Perennial weeds were strongly associated with the 2005 field site, but not correlated to the biomass gradient, and were weakly associated with the last termination date. The significant field site effect reflected the unique broadleaf and perennial weed communities at the two sites. This suggests that perennial weeds in this study were unaffected by increasing amounts of cover crop residue.

PERMANOVA, used to examine treatment factor effects on the selected weed life history classes, indicated that the weed community was significantly influenced by field

site and interaction between field site and termination date (Table 4.7). This corresponded to the significant community gradient observed in the biplot with the two field sites between years where perennial and annual broadleaf species were more strongly associated with 2005 than in 2006 (Figure 4.3). The field site by termination interaction can be explained by the association between increasing perennial and annual broadleaf weeds within the 2005 field site. Clearly the effects of cover crop biomass varied by weed species life history class and field site. However, field site variations and species-specific emergence patterns, and their interaction with varying cover crop biomass cannot be distinguished in the multivariate analysis (ordination and PERMANOVA). These questions were addressed in greater detail by evaluating weed populations in the following section.

Weed species dominance and suppression. Variation in the weed species response was further studied using a frequency analysis, performed separately for the residue and no residue treatments, to evaluate how the dominance structure changes across the termination dates. Termination date significantly influenced dominance structure in both cover crop residue and no residue treatments and in both field sites (Figure 4.4 and 5; 2005 - residue: $P < 0.001$; no residue: $P < 0.0001$; 2006 - residue: $P=0.0106$; no residue: $P=0.0149$). Those species accounting for the greatest proportion of the χ^2 test statistic most strongly influence the community. For the no residue treatment, the species having the greatest influence in dominance structure were yellow nutsedge, common lambsquarters, and wild buckwheat in 2005, and common lambsquarters, giant foxtail, and common ragweed in 2006. These species accounted for greater than 75 and 80% of these differences in 2005 and 2006, respectively. For the residue treatment, differences in

the dominance structure were most influenced by yellow nutsedge and common lambsquarters (>65%) in 2005. The dominance structure was more evenly distributed among the different species in the residue treatment in 2006.

Changes in the dominance structure across termination dates can be explained by the weed emergence patterns in the no residue treatment, and the suppressive effects of the cover crop mulch in the residue treatment (Figure 4.6). Delay in cover crop termination selected for later emerging annual weeds (e.g., foxtail spp. and wild buckwheat) and the perennial, yellow nutsedge, which has an extended emergence period. In the residue treatments, we attribute differences in the dominance structure across termination dates to increased control of summer annual weeds as cover crop biomass increased, whereas the perennials were not substantially influenced by this gradient.

Cover crop residues did not affect weed density in 2005 (Figure 4.6). Lower weed abundance in the control and in the residue plots in 2005 was likely the result of a drier summer (Figure 4.7). Moore et al. (1994) found weeds emerged 10 days after rainfall events of 10 mm or more when the rains followed a dry period. In 2006, the study site received greater than 10 cm of rainfall and irrigation in June, whereas only three cm fell during the same period in 2005 (Figure 4.7). Common lambsquarters density was reduced 67 to 77% in the residue vs. no residue treatments across termination dates in 2006 (Figure 4.6). Cover crop residue reduced foxtail spp. by 85% at the May 20 termination date and common ragweed by 79% at the first termination date (May 1). Higher dandelion densities were observed when cover crop biomass was low and although not significant, there was a trend for greater foxtail spp. density in the low residue treatments. Yellow nutsedge was not affected by cover crop biomass in either year.

The variations observed in weed species abundance and suppression (Figure 4.6) help to clarify the treatment effects observed in the RDA. The no residue treatment reveals the differences in abundance for annual and perennial weed densities between the 2005 and 2006 field sites; this was particularly true for common lambsquarters and yellow nutsedge. The dominance of yellow nutsedge and increasing abundance at the final termination date in 2005 explains the strong association between yellow nutsedge and the 2005 field site and the weak association with May 30 termination date (Figure 4.3). While not significant, the lower amount of cover crop biomass at the earlier termination dates in 2005 compared to 2006 may have contributed to the lack of differences observed in common lambsquarters density at the 2005 field site compared to the 2006 field site in the residue vs. no residue treatments (Figure 4.6). As a result, this may have produced the weak associations observed with broadleaf weeds at the 2005 field site (Figure 4.3).

The success of weeds like yellow nutsedge underscores the need to study the entire weed community when assessing a change in management practice. In contrast to summer annual weeds, yellow nutsedge emerges from energy rich vegetative structures over a prolonged time period and appears to be well-adapted to high residue cover cropping practices. Yellow nutsedge continued to emerge even in the May 30 termination treatments and was not influenced by increasing cover crop biomass. This is consistent with other studies that found perennials are less influenced by surface residues (Facelli and Pickett 1991). In contrast, the annual broadleaves were strongly influenced by increasing cover crop biomass. Previous research has demonstrated that small-seeded summer annual weeds are more strongly affected by cover crop residues than are large

seeded annuals (Putnam and DeFrank 1983; Mohler and Teasdale 1993; Teasdale and Mohler 2000; Bhowmik and Inderjit 2003). Early emerging summer annuals are more competitive at earlier termination dates when cover crop residue levels are lower, particularly at higher densities as exemplified by common lambsquarters in the 2006 field site. In this study, the delay in termination and subsequent increase in cover crop biomass decreased summer annual weed populations regardless of species. However, larger-seeded summer annual weeds such as velvetleaf (*Abutilon theophrasti*), a species not common across our study site, are less sensitive to surface mulches (Mohler and Teasdale 1993) and could still be problematic.

Differences in timing of weed emergence and sensitivity to cover crop surface residues can influence weed species dominance in a given field season; these effects can result in longer-term population influences. The lower densities observed in the residue treatments may have been the result of fatal germination or of the altered light and temperature soil environment, which may have influenced seed germination (e.g., foxtail spp. at May 20 2006; Figure 4.6). This can be distinguished from inherent lower proportional emergence at the end of a species emergence period (e.g., foxtail spp. at May 30 2006; Figure 4.6). The timing of cover crop control influences the timing and duration at which environmental cues required for the initiation of weed germination are satisfied. Manipulating the nature and timing of cultural practices such as delaying cover crop management can selectively affect weed populations by shifting the community structure to less competitive weed species. Characteristics of a positive weed management shift could be less competitive species (small-seeded summer annuals); later weed emergence and growth relative to that of the crop; and less weed abundance due to

synchrony between management timing and a lower range of a weeds emergence periodicity. However, our results underscore the importance of the preexisting weed community. Where yellow nutsedge was present at the outset of the experiment its abundance increased in the residue treatments which resulted in an undesirable weed community shift. Rotational tillage along with a diverse crop rotation could play an important role in reducing the shift to perennial weeds in higher residue systems (Tørresen et al. 2003; Buhler et al. 1994; Gill and Arshad 1995).

The weed management implications of this research largely highlight the benefit of delaying cover crop termination but this must be tempered with concerns about how such delays affect the following crop. Shorter season cash crop species and cultivars will be needed with later cover crop termination dates. Alternatively, some research has reported that seeding directly into the living cover crop and then suppressing the cover crop 1 to 3 weeks later may be feasible (Drinkwater et al. 2000). Optimizing between reductions in cash crop yield, weed suppression, and the higher market value of organic crops should also be considered. To accomplish this optimization, future work should evaluate the tradeoffs between weed suppression, cash crop stand density and yield, and crop and weed growth rates. Additionally, identifying opportunities across a crop rotation that target problem weed species (e.g., yellow nutsedge) will be necessary for the success of reduced-tillage systems that reduce or eliminate herbicide use.

CONCLUSION

When evaluating weed emergence and suppression from cover crop surface residues in reduced and no-till cropping systems, both weed emergence periodicity and its synchrony with cover crop growth and weed sensitivity to cover crop surface residues

must be considered. This work corroborates previous studies documenting species-specific responses to cover crop surface mulches, but also considers the species-specific germination dynamics that occur over a temporal biomass gradient as cover crops mature. Selecting and managing cover crops that complement weed species emergence periodicity and their susceptibility to cover crop residue can enhance ecologically based weed management in reduced and no-till crop production systems.

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Table 4.1. Analysis of variance for biomass as influenced by year, cover crop, termination date, and planting date.

Effect	Biomass		
	Df	F value	P > F
Cover crop (CC)	2	11.02	0.0049
Termination date (TD)	3	460.49	< 0.0001
CC X TD	6	0.46	0.8370
Planting date (PD)	5	65.35	< 0.0001
CC X PD	10	1.53	0.1265
TD X PD	15	1.32	0.1860
CC X TD X PD	30	0.81	0.7569
Year	-	-	0.2403

Table 4.2. Mean cover crop biomass as influenced by cultivar, planting date, and termination date main effects, pooled across years. Mean comparison was performed by crop (planting and termination date pooled), planting date (crop and termination date pooled), and termination date (crop and planting date pooled) independently, with different lower case letters indicating significant differences ($P < 0.05$) using the Tukey-Kramer method.

Treatment	Biomass	
	---- kg ha ⁻¹ ----	
<u>Crop</u>		
Aroostook	7259	a
Wheeler	6508	b
Rye/Hairy vetch	6876	ab
<u>Planting Date</u>		
August 25	7880	a
September 5	7904	a
September 15	7161	b
September 25	7016	b
October 5	6260	c
October 15	5066	d
<u>Termination Date</u>		
May 1	4051	a
May 10	5809	b
May 20	7599	c
May 30	10,066	d

Table 4.3. Thermal-based biomass models predicting cover crop biomass accumulation (years pooled). The parameter estimates characterize the effects of growing degree days (GDD) on biomass accumulation of the cover crops. Included are adjusted R^2 values and Akaike Information criteria (AIC) for goodness of fit and model selection, respectively.

Thermal models		β_0	Total β_1	Fall β_1	Spring β_2	Adj. R^2	AIC
Aroostook	Total _{GDD}	1340.39	4.21	-	-	0.3687	3541.54
	Spring _{GDD}	-1051.57	-	-	14.41	0.711	3390.96
	Fall _{GDD} vs. Spring _{GDD}	-2845.96	-	2.188	14.38	0.794	3326.95
Wheeler	Total _{GDD}	641.80	4.18	-	-	0.4198	3497.37
	Spring _{GDD}	-1386.29	-	-	13.69	0.743	3340.75
	Fall _{GDD} vs. Spring _{GDD}	-3262.33	-	2.28	13.66	0.848	3240.45

Table 4.4. Analysis of covariance (ANCOVA) of biomass as influenced by year and cover crop with fall and spring growing degree days (GDD) as covariates. The effects of crop on the slope of the response of cover crop biomass to fall (FallGDD*Crop) and spring (SpringGDD*Crop) is assessed by the associated p-value growing degree days provided by the ANCOVA.

Effect	Biomass
	Probability > F
Crop	0.4323
FallGDD	< 0.0001
FallGDD*Crop	0.9522
SpringGDD	< 0.0001
SpringGDD*Crop	0.1265
Year	0.2554

Table 4.5. Analysis of variance for weed species as influenced by year, cover crop, termination date, and planting date. Selection of weed species was based on relative abundance (> 3% of total abundance) and economic importance.

Effect	df	Total weed density P > F	Broadleaf P > F	Grass P > F	Perennial P > F	Common lambsquarters P > F	Foxtail spp. P > F	Common ragweed P > F	Yellow nutsedge P > F	Dandelion P > F
Cover crop (CC)	2	**	0.5532	0.321	0.0657	0.4705	0.2945	0.8002	0.1135	0.6156
Planting date (PD)	5	***	**	0.1468	0.1688	***	0.2690	0.1830	0.2077	0.1412
CC X PD	10	0.5412	0.4100	0.7830	0.0999	0.1085	0.8377	0.6096	0.0801	0.6656
Termination date (TD)	3	***	***	***	0.9710	**	*	***	0.2017	***
PD X TD	15	0.9266	0.4246	0.1188	0.2901	0.1776	0.1028	0.9907	0.7451	0.8301
Crop X TD	6	0.7289	0.3452	0.5165	0.9206	0.3861	0.1078	0.0628	0.8238	0.5266
CC X TD X PD	30	0.8905	0.6511	0.6742	0.9546	0.5866	0.4399	0.7904	0.8474	0.4470
Year	-	0.2403	0.2410	***	0.2409	0.2453	0.3160	***	0.2403	***

* indicates a significant effect of treatment factor at $p \leq 0.05$

** indicates a significant effect of treatment factor at $p \leq 0.01$

*** indicates a significant effect of treatment factor at $p \leq 0.001$

Table 4.6. Mean weed population density as influenced by cultivar, planting date, and termination date main effects, pooled across years unless otherwise presented. Mean comparison was performed by planting date, and termination date independently, with different lower case letters indicating significant differences ($P < 0.05$) using the Tukey-Kramer method. A dash (-) indicates a lack of significance in the data.

Treatment		Total Weed density	Broadleaves	Grasses		Perennials	Common lambsquarters	Foxtail spp.	Common ragweed		Yellow nutsedge	Dandelion			
				2005	2006				2005	2006		2005	2006		
			-----										plants m-2	-----	
Cover Crop	Aroostook	26a	-	-	-	-	-	-	-	-	-	-	-		
	Wheeler	33b	-	-	-	-	-	-	-	-	-	-	-		
	R/HV	31ab	-	-	-	-	-	-	-	-	-	-	-		
Planting Date	August 25	27a	11ab	-	-	-	6ab	-	-	-	-	-	-		
	September 5	27a	10a	-	-	-	5a	-	-	-	-	-	-		
	September 15	30b	12ab	-	-	-	6a	-	-	-	-	-	-		
	September 25	30b	13ab	-	-	-	7ab	-	-	-	-	-	-		
	October 5	36c	14b	-	-	-	7ab	-	-	-	-	-	-		
	October 15	36c	16b	-	-	-	9b	-	-	-	-	-	-		
Termination -Date	May 1	36a	16a	7a	13a	-	10a	9a	-	2a	-	4a	7a		
	May 10	33b	15ab	6a	9b	-	9ab	6ab	-	2a	-	5a	5ab		
	May 20	26c	12b	6a	2c	-	5bc	4b	-	2a	-	3ab	3bc		
	May 30	24d	6c	4a	1c	-	2c	2c	-	0b	-	1c	1c		

Table 4.7. Multivariate analysis of variance table using permutational multivariate analysis of variance (PERMANOVA) of treatment factors.

Effect	Weed Community		
	df	F value	P(perm)
Field Site	1	69.39	0.002
Cover crop (CC)	2	1.30	0.618
Termination date (TD)	3	1.72	0.240
Field Site*CC	2	1.49	0.174
Field Site*TD	3	5.79	0.002
CC*TD	6	0.83	0.634
Field Site*CC*TD	6	0.73	0.810

Figure 4.1. Photograph of a front-mounted roller/crimper constructed by Penn State University. The roller/crimper is 3.2-m in length by 51-cm diameter by 3.2-mm thickness and weighs 1520 kg.



Figure 4.2. Mean biomass accumulation of cover crops, harvested prior to rolling/ crimping, by cultivar, planting date (Julian date), and termination date ● = May 1, ○ = May 10, ▼ = May 20, and △ = May 30 (years pooled). Bars represent standard error of the means.

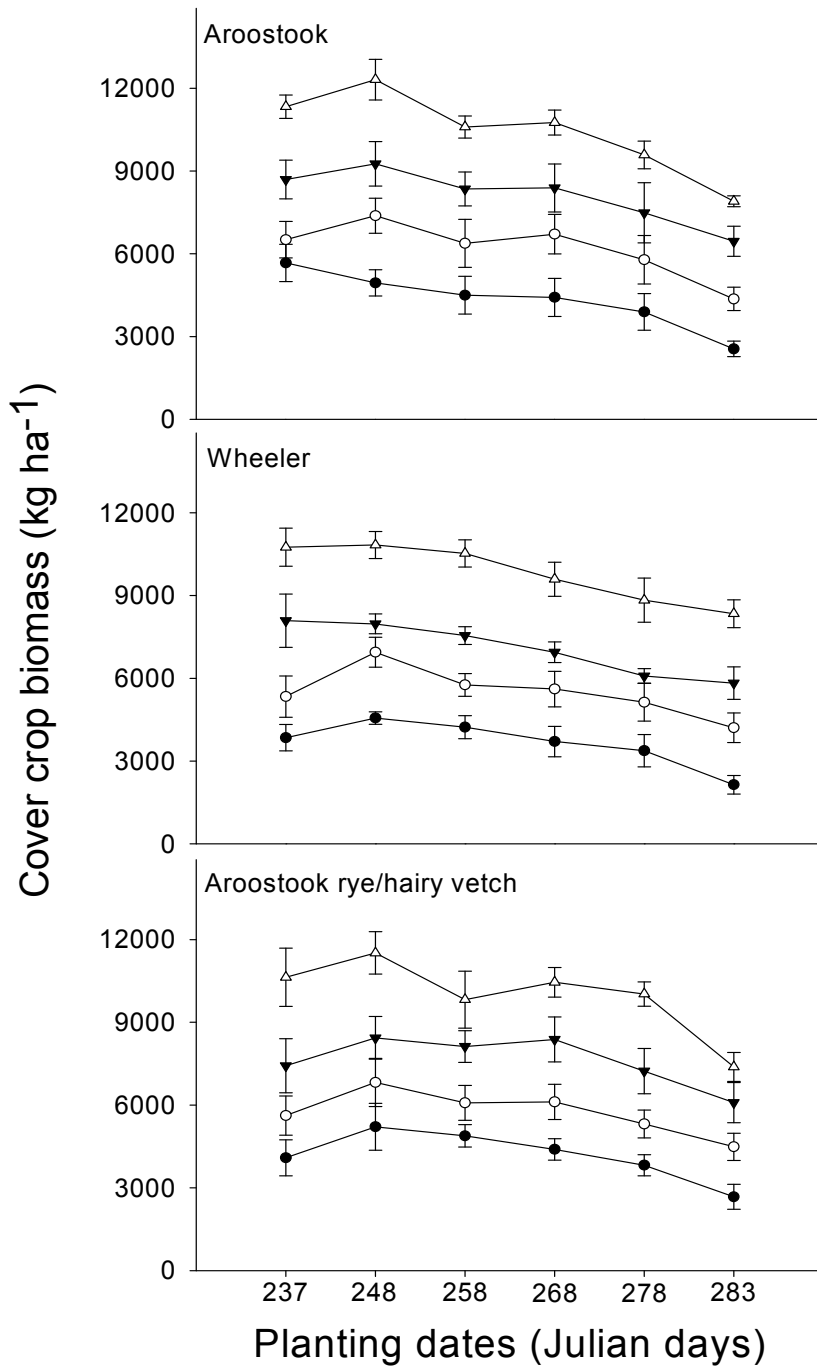


Figure 4.3. Biplot ordinations from a redundancy analysis displaying the associative relationships between weed communities categorized by grass, broadleaf, and perennial species and the explanatory variables: year (■), cover crop (◆), termination date (●), biomass accumulation (---), and Spring heat units (GDD) (---). The percentage of variation explained by the primary and secondary axis is included in parentheses. Weed community data were Hellinger transformed prior to analysis.

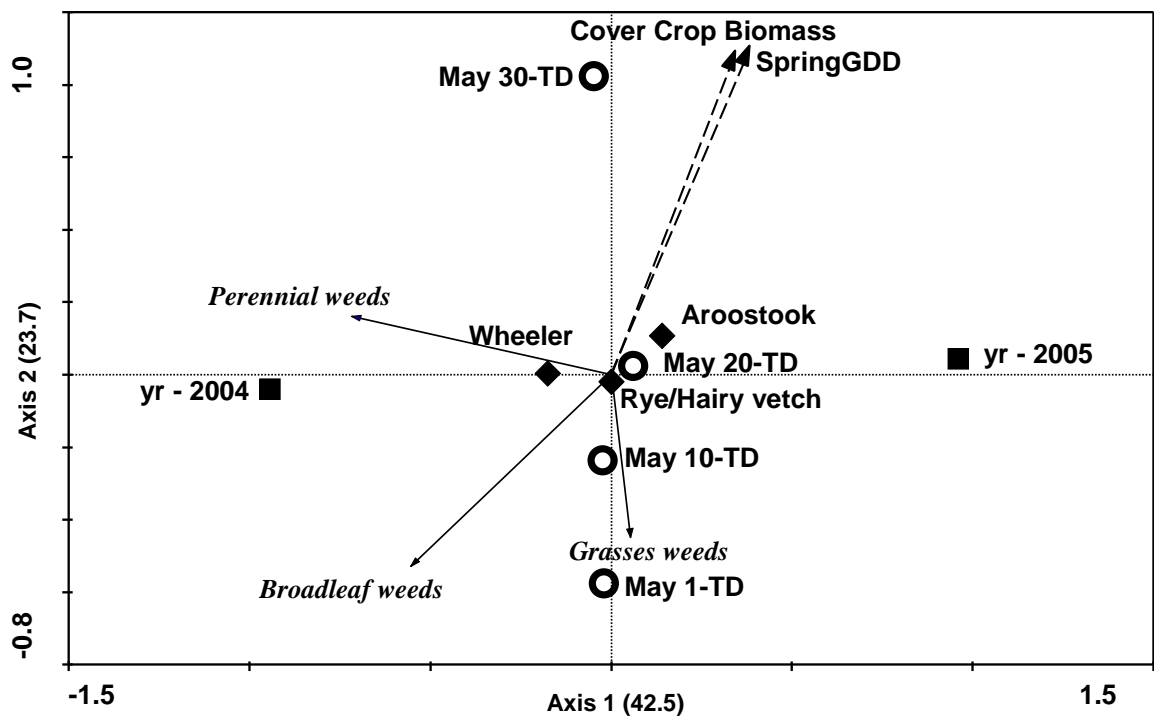


Figure 4.4. Relative weed species abundance characterizing the species (CYPES - yellow nutsedge; CHEAL - common lambsquarters; SET spp. - foxtail spp.; AMARE-redroot pigweed; TAROF - dandelion; POLCO - wild buckwheat; AMBAR - common ragweed) dominance structure within the 2005 field site across the spring termination dates (■ = May 1, ■ = May 10, ■ = May 20, ■ = May 30), for the residue treatments. Variations in the species dominance structure across the termination dates were assessed by the associated χ^2 provided by frequency analysis.

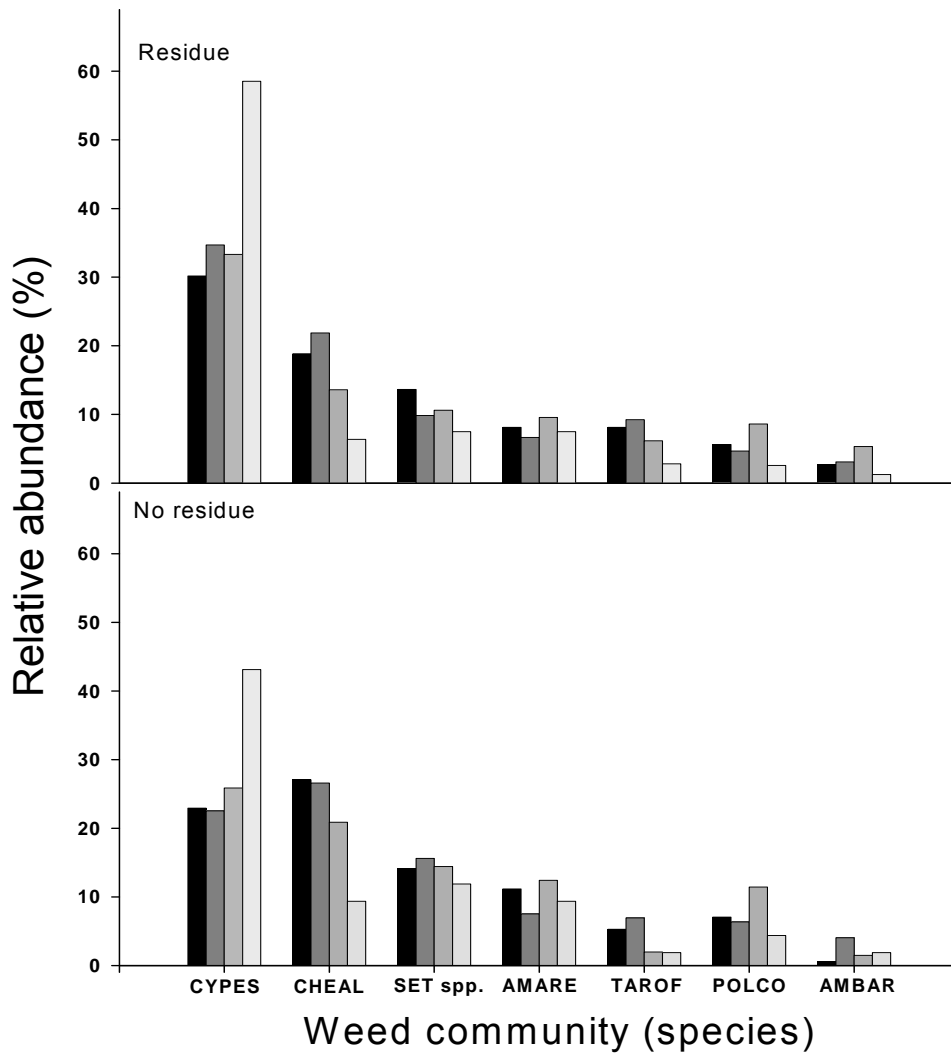


Figure 4.5. Relative weed species abundance characterizing the species (CYPES – yellow nutsedge; CHEAL - common lambsquarters; SET spp.- foxtail spp.; TAROF - dandelion; PANDI – fall panicum; AMBAR – redroot pigweed) dominance structure within the 2006 field site across the spring termination dates (■ = May 1, ■ = May 10, ■ = May 20, ■ = May 30), for the residue treatments. Variations in the species dominance structure across the termination dates were assessed by the associated χ^2 provided by frequency analysis.

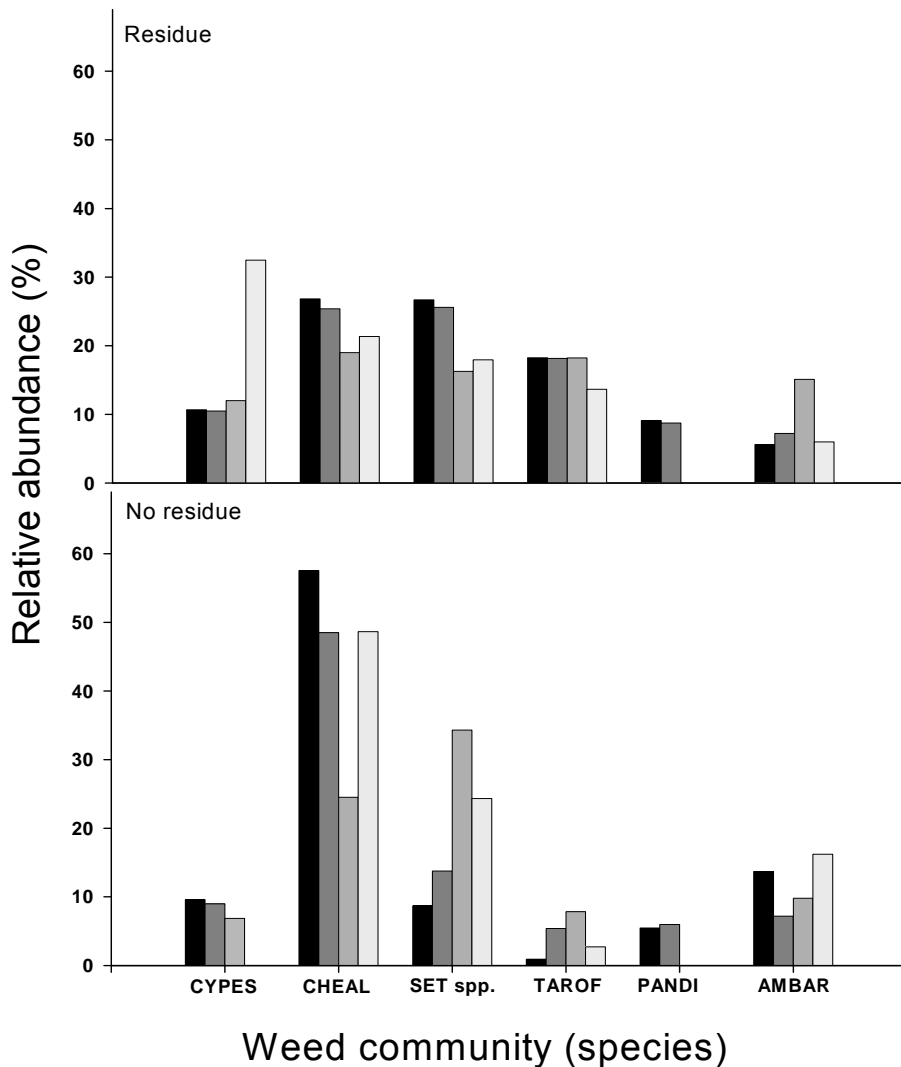


Figure 4.6. Weed population as a function of cover crop termination date in the 2005 and 2006 field sites (cover crop and planting date pooled) for the residue and no residue treatments. An analysis of variance and mean comparison was conducted on selected weed species (CHEAL - Common lambsquarters; AMBAR - common ragweed; TAROF - dandelion; CYPES- yellow nutsedge) at each termination date, with * indicating significant difference ($P < 0.05$; $x = P < 0.1$) between control and residue plots using the Tukey-Kramer method. Weed population data were overlaid with biomass accumulation for relating weed emergence with cover crop biomass.

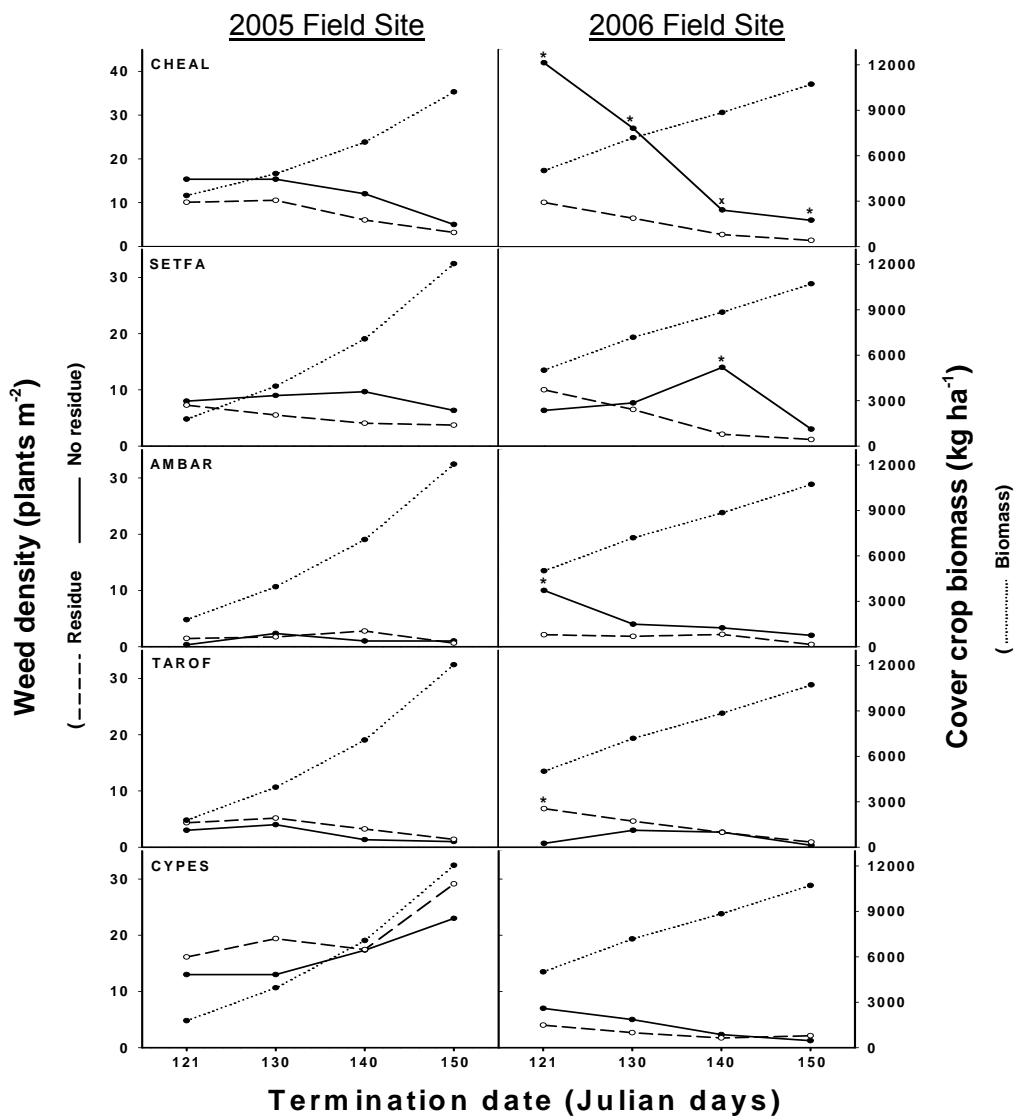
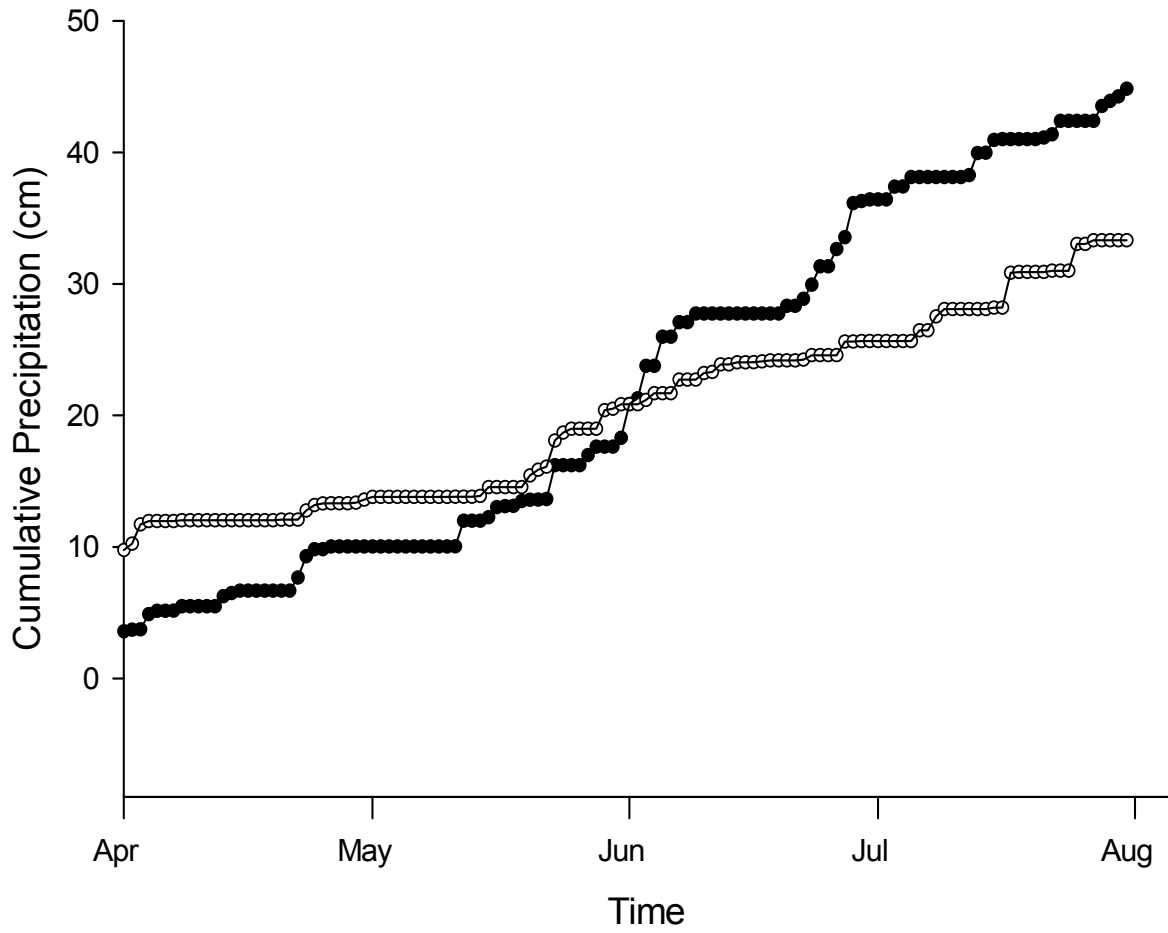


Figure 4.7. Cumulative daily precipitation \circ = 2006 and \bullet = 2005 in Rock Springs, Pennsylvania, USA for the 2005 and 2006 cropping seasons.



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EDUCATION

Ph.D. Agronomy (2008) The Pennsylvania State University, University Park, PA
M.S. Soil Science (2003) The Pennsylvania State University, University Park, PA.
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WORK EXPERIENCE

Graduate Research Assistant: (2003-present); Penn State University, PA
Forest Technician: (1999-2000) Warren Wilson College, Swannanoa, NC
Farm Assistant and Apprentice:
 (1998) Apple Pond Farming Center, Callicoon Center, NY:
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PLANT MODELING WORKSHOPS

2006 European Weed Research Society (Modeling Plant – Plant)
2006 Weed Science Society of America (Statistical assessment of dose-response curves with free software)

TEACHING EXPERIENCE

Teaching Assistant - Principles in Weed Management (2006) Penn State University
 Sustainable Agriculture Science and Policy (2005) Penn State University
Guest Lecturer - Principles in Weed Management (2005) Penn State University
 Science in Motion: Crucial Soils Investigation (2004) Centre County Educators
Instructor - Introduction to Soil Science Laboratory (2000-2004) Penn State University

GRANTS

\$168,000 - -CSREES Northeast Integrated Pest Management (6/2007 – 12/2009)
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HONORS AND AWARDS

2006 Graduate student oral paper competition (1st place), Northeast Weed Science Society of America
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PEER-REVIEWED PUBLICATIONS

Mirsky, S.B., L.E. Lanyon, and B.A. Needelman. 2007. Evaluating soil management using particulate and chemically labile soil organic matter fractions. *Soil Science Society of America Journal*. (*In press*)
Mirsky, S.B., L.E. Lanyon, and B.A. Needelman. 2007 Mechanical grinding for particulate organic matter analysis. *Communications in Soil Science and Plant Analysis*. (*In press*)

EXTENSION PUBLICATIONS

Mortensen, D.A., W.S. Curran, M.R. Ryan, A.G. Hulting, and **S.B. Mirsky**. 2006. Weed germination periodicity: When do weeds wake up? The College of Agricultural Sciences, Penn State University, University Park.
Mirsky, S.B., and W.S. Curran. 2005. The life and death of a summer annual weed: Why seeds matter. Penn State University Cooperative Extension, Crop Management and Extension Group In-service Training. [CD-ROM]. The College of Agricultural Sciences, Penn State University, University Park.