High Residue Cover Crops for Annual Weed Suppression in Corn and Soybean Production and Potential for Hairy Vetch (*Vicia villosa*) to be Weedy

Kara Brooke Pittman

Thesis submitted to the faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science in Life Sciences

In

Plant Pathology, Physiology, and Weed Science

Michael L. Flessner, Chair
E. Scott Hagood
Jacob N. Barney

December 8, 2017
Blacksburg, VA

Keywords: biomass, C:N ratio, germination, horseweed, lignin, weed suppression

High Residue Cover Crops for Annual Weed Suppression in Corn and Soybean Production and Potential for Hairy Vetch (*Vicia villosa*) to be Weedy

Kara B. Pittman

Abstract

After termination, cover crop residue can suppress weeds by reducing sunlight, decreasing soil temperature, and providing a physical barrier. Experiments were implemented to monitor horseweed suppression from different cover crops as well as two fall-applied residual herbicide treatments. Results suggest that cover crops, other than forage radish in monoculture, can suppress horseweed more consistently than flumioxazin + paraquat or metribuzin + chlorimuron-ethyl. Cover crop biomass is positively correlated to weed suppression. Subsequent experiments were designed to determine the amount of weed suppression from different cover crop treatments and if carbon to nitrogen (C:N) ratios or lignin content are also correlated to weed suppression or cover crop residue thickness. Results indicate that cereal rye alone and mixtures containing cereal rye produced the most biomass and suppressed weeds more than hairy vetch, crimson clover, and forage radish alone. Analyses indicate that lignin, as well as biomass, is an important indicator of weed suppression. While cover crops provide many benefits, integrating cover crops into production can be difficult. Hairy vetch, a legume cover crop, can become a weed in subsequent seasons. Multiple experiments were implemented to determine germination phenology and viability of two hairy vetch cultivars, Groff and Purple Bounty, and to determine when viable seed are produced. Almost all germination occurred in the initial cover crop growing season for both cultivars. Both cultivars had <1% of viable seed at the termination of the experiment. These results indicate that seed dormancy is not the primary cause of weediness.

High Residue Cover Crops for Annual Weed Suppression in Corn and Soybean Production and Potential for Hairy Vetch (*Vicia villosa*) to be Weedy

Kara B. Pittman

General Audience Abstract

Cover crops are grown in the time between cash crop production, such as corn or soybeans. These crops are not grown for profit but mainly for environmental benefits such as reducing erosion and increasing soil organic matter and water infiltration. Another benefit of cover crops is the ability to suppress weeds. Cover crops can suppress weeds while they are actively growing by competing for resources such as light, water, and nutrients. After the cover crops have been terminated, or killed prior to cash crop planting, the residue can form a mulch layer on the soil surface which acts to suppress weeds by reducing the amount of sunlight that reaches the soil surface, decreasing soil temperature, and providing a physical barrier to slow weed growth.

Horseweed is a problematic weed for growers to control and the number of herbicide options that growers can utilize is decreasing due to herbicide resistance. This weed has small seed and multiple germination periods, which cover crops have the ability to target. Experiments were designed to compare horseweed suppression from different cover crop monocultures and mixtures with suppression obtained from two fall-applied residual herbicide programs. The cover crop species used were cereal rye, crimson clover, hairy vetch, and forage radish. The cover crops were planted and herbicides applied in the fall. Data collected included horseweed counts, visible suppression ratings, and horseweed biomass taken in the following corn or soybean growing season. All cover crop treatments suppressed horseweed as compared to the nontreated check, with the exception of forage radish alone. The fall-applied herbicides did not perform as

well as the cover crops. Results indicate that integration of cover crops is a viable tactic for horseweed management.

As cover crop biomass increases the level of weed suppression also increases. Experiments were implemented to measure the level of weed suppression and to determine if the composition of the cover crop residue is important in weed suppression. Monocultures and mixtures of the same four cover crop species listed above were grown prior to corn and soybean production. At cover crop termination, samples were taken to determine biomass, carbon to nitrogen (C:N) ratio, and lignin content. Cereal rye and mixtures containing cereal rye provided > 55% weed suppression 6 weeks after cover crop termination. Analyses also indicated that lignin, as well as biomass, is an important predictor of weed suppression after termination.

While cover crops have many benefits, there can be some complications. Hairy vetch is a legume cover crop species that has the ability to suppress weeds but can also become weedy in subsequent crops. Experiments were performed to track germination and seed viability of two hairy vetch cultivars, Groff and Purple Bounty as well as determine when seeds are added to the soil seedbank. Over the course of the experiment, Groff had greater germination than Purple Bounty by 30% in the initial germination periods. Both cultivars had <1% of seed still viable at the end of the experiment. Also, both cultivars produce viable seed in mid-June. The results from these experiments indicate that seed dormancy is not the primary cause of weediness in hairy vetch and that if proper termination occurs prior to mid-June, seeds will not be added to the soil seedbank.

Acknowledgements

Throughout this process, I have received so much support and assistance and for that I have truly been blessed. I first must thank Dr. Michael Flessner, for this opportunity and for the time you've given and patience you've shown in teaching me how to become better scientist. Thank you to Drs. Scott Hagood and Jacob Barney who have offered guidance and helped plan these projects. My labmates, Shawn Beam, Steven Haring, Ranjeet Randhawa, and Lucas Rector, who have put in countless hours with me in the field, critiqued my writing, and have become people I consider friends. Our technician, Kevin Bamber, and former technician, Tyler Hoskins, for always boosting morale and offering assurance when I felt I might fail. It has been an honor to work with all of you and without you, my research would not have been possible. I need to thank my parents, Jerry and Kathy Pittman for always wanting the best for me and for teaching me to have the courage to follow my passion. I also need to thank my friends who have become like family. Without their encouragement and kindness, this journey would have been much more difficult.

Table of Contents

List of Tables

Literature Review

Potential for Cover Crop Use in Weed Management

In the United States, weed interference can cause a 50% decrease in corn (*Zea mays* L.) yield and a 52% decrease in soybean (*Glycine max* L. Merr.) yield (Soltani et al. 2016, 2017). Herbicides are the primary weed control method, and in the U.S. herbicide usage has increased four-fold from 1966 to 1989 (Liebman 2001). In 1997, about $4 billion of herbicides were applied to crops (Pimentel 1997). Herbicide use has continued to increase from 1990 until 2015 in six major crops in the United States: corn, soybeans, rice (*Oryza sativa* L.), cotton (*Gossypium hirsutum* L.), and spring and winter wheat (*Triticum aestivum* L.) (Kniss 2017). As herbicide usage increases and production intensifies, there is a need for integrative weed management practices in production systems where cover crops can provide many benefits to growers.

Any repeated weed management technique puts pressure on weed populations to adapt and evolve resistance to the control method. This isn't just true with herbicides; continuous hand-weeding of barnyardgrass (*Echinochloa crus-galli* L. P. Beauv.) in rice has led to the selection of biotypes that are visually indistinguishable from the crop (Barrett 1983). The less often a management practice is used, the less likely it is that weeds will develop resistance to that method of control (Herbicide Resistance Action Committee 2017).

At the end of 2017, there were 554 cases of herbicide resistance in the United States (Heap 2017). Even with the increase in resistance cases, there have been no new herbicide modes of action introduced for the past 25 years, with the last introduction being hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors (Duke 2011). The reason for the decline in introductions can be attributed to the adoption of glyphosate-resistant crops, first introduced in 1996, consolidation of the industry that would discover new pesticides, and the increase in regulations surrounding the agrochemical industry (Duke and Cerdeira 2005; Duke 2011). With the lack of new modes of action, some growers have adopted an integrated herbicide approach which includes multiple modes of actions per growing season, using tank mixes, and proper use of preemergence herbicides to combat herbicide resistance. However, there are other practices that do not include herbicides that can be added to weed management plans to control difficult weeds (Harker and O'Donovan 2013).

Integrated weed management (IWM), a method in which growers use multiple tactics such as physical, chemical, cultural, and biological practices to control weeds, is not a new concept but is becoming increasingly necessary for resistance management. It is important to note that IWM is not about exclusion of any one technique but rather varying the techniques used to control weeds (Harker and O'Donovan, 2013).

The Weed Science Society of America's 1981 meeting held a symposium focused on IWM in which topics such as weed biology, crop manipulation, and extension implementation of IWM practices were presented, showing that this isn't a new idea but something that has been discussed for decades (Thill et al. 1991). The trend towards weed management diversification has also been noticed in publication topics over time. From 1952 to1989 there was a 10% increase in weed biology articles, which is important knowledge for implementing IWM practices, and a 15% decrease in articles pertaining to herbicide use (Thill et al. 1991). Since this time period, from 1995 through 2011, those trends have changed. There has been a slight increase in integrated weed management articles but a much larger increase in the number of articles that pertain to weed management through the use of herbicides. Over this time period, there were 9,964 weed control articles while there were only 697 articles published about integrated weed management (Harker and O'Donovan, 2013). While these trends show that research dealing with herbicides is still very relevant in weed science. Integrated weed management research is steadily finding a niche.

Sustainable agricultural practices are necessary when confronting increasingly intensive farming practices and a changing climate (Bajwa et al. 2015). Practicing IWM, especially tailoring specific programs to farms or cropping systems, can improve environmental quality, conserve renewable resources, and ensure economic feasibility (Swanton and Weise 1991).

Other Benefits of Cover Crops and Incentives for Use

With this renewed interest in sustainable agriculture, it has renewed interest in cover crops (Liebman et al. 2001). Cover crops are a living ground cover that is grown in the time between desirable cash crop production (Wszelaki and Broughton 2012). Cover crops reduce soil erosion, increase soil organic matter, and suppress pests (Burket et al. 1997; Dabney et al. 2001; Wyland et al. 1996). There are many different plant species that are used as cover crops and these crops provide benefits to growers in terms of soil health, and productivity. Legume cover crops have the ability to fix nitrogen that can enhance cash crop growth (Coombs et al. 2017). Winter cover crops have the potential to increase yields by increasing nitrogen and water use efficiency in spring planted crops (Miguez and Bollero 2005).

The Virginia Agricultural Cost-Share Program (VACS) provides financial incentives to growers and operators to implement approved Best Management Practices. One priority practice endorsed by the VACS is including cover crops in crop rotation. Guidelines for the cost share program are to meet planting and termination deadlines dictated by region as well as obtaining a successful stand to protect the area through the winter. Planting dates range from October 25th in the mountain and valley areas of Virginia through November 30th for the cities of Chesapeake and Virginia Beach. Growers participating in the program cannot terminate their cover crops before March 15th (Virginia Dept. of Conservation and Recreation 2017). One of the major reasons the cost-share program is available is because the close proximity of growers to the Chesapeake Bay. Winter cover crop adoption can lead to a 50% reduction in N leaching, particularly in drier seasons (Fraser et al. 2013).

Suppression of Horseweed Through Using Cover Crops

Horseweed, or marestail (*Conyza canadensis* L. Cronquist) is a native plant of North America that can behave as a summer or winter annual (Regehr and Bazzaz 1979). This plant has many weedy characteristics such as the ability to grow to heights of 1.8 m to outcompete other plants, the ability to expand beyond its native range, and relatively high fecundity, capable of producing up to 200,000 seeds per plant (Bajwa et al. 2016; Buhler 1992; Weaver 2001). Horseweed can detrimentally affect crop yield with reported 25% yield loss in soybeans with 13.3 plants m^{-2} (Trezzi et al. 2013). Horseweed is especially problematic in no-till situations because horseweed seed readily germinates at the soil surface. Studies have shown that no seedlings will emerge if seeds are buried at a depth of 0.5 cm or deeper in the soil profile (Nandula et al. 2006).

Horseweed fruits are composed of an achene and a pappus, a modified calyx that aids in wind dispersal by slowing the settlement velocity of the seeds (Andersen 1993; Uva et al. 1997). There have been various studies to determine the distance in which horseweed seeds can be dispersed. Andersen (1993) researched the settlement velocity of 19 wind-dispersed Asteraceae species by releasing fruits, achene with an intact pappus, down a plexiglass tube and timing their descent. The settlement velocity for horseweed was found to be 0.278 m s^{-1}, which was the slowest of the species included in this study. In wind-tunnel testing, the settlement velocity between seeds varied between 0.134 to 0.512 m s^{-1} and dispersal distances were extrapolated to reach potential distances of 154 m (Dauer et al. 2006). The results found in these studies do not always translate into field settings. Research done in field settings shows evidence that intact horseweed seeds are found in the planetary boundary layer, which is the less-turbulent air that extends from about two times the height of the plant canopy up to 2 kilometers (Lowry and Lowry 1989). This height can facilitate long distance dispersal of seed in a single flight (Shields et al. 2006). Horseweed is also self-compatible and Smisek (1995) reported that on average 96% of horseweed florets were self-pollinated, which is attributed to pollen being released before the capitula is fully open. This self-compatibility and long distance seed transport increases the potential for spread of herbicide resistant horseweed plants.

Glyphosate-resistant horseweed was first reported in Delaware after three years of continuous glyphosate applications for weed control in glyphosate-resistant soybeans (VanGessel 2001). With the widespread use of glyphosate tolerant crops with glyphosate as the sole herbicide used in these systems, selection pressure for glyphosate-resistant weeds is very high. In the United States, glyphosate tolerant crop seed is planted on a higher proportion of soybean acres than corn acres, about 94% to 88%, respectively (Livingston et al. 2015). Using glyphosate as the sole herbicide in these systems is also much higher in soybean than corn (Benbrook 2016; Livingston et al. 2015). There have also been populations of horseweed that have become resistant to triazine herbicides and paraquat (Weaver 2001; Smisek et al. 1998). Biotypes of horseweed showing multiple resistances to glyphosate and ALS-inhibiting herbicides have been found in Ohio and Indiana (Kruger et al. 2008).

Differences in growth, seed production, or internal processes of herbicide resistant plants can affect their persistence in a population (Green 2007). If the herbicide resistance trait is not advantageous in any other circumstance other than the presence of that herbicide, the populations of herbicide resistant weeds can be reduced over time without the presence of the herbicide selection pressure. It has been shown in atrazine-resistant jimsonweed (*Datura stramonium* L.) that taking advantage of the fitness penalty associated with herbicide resistance through different crop management practices reduced the population of resistant weeds (Williams et al. 1995; Zhang et al. 1999).

In some glyphosate-resistant weeds, such as rigid ryegrass (*Lolium rigidum* Gaudin) and Italian ryegrass (*Lolium perenne* L.), there does seem to be a substantial fitness penalty associated with the resistant individuals in the population. Once glyphosate was no longer applied to those plants, the population declined significantly over time (Preston et al. 2009). However, there have been multiple studies in which the physical characteristics of glyphosate-resistant and -susceptible horseweed have been compared and the results have been variable. Davis et al. (2009a) conducted a field study in Butler, Indiana in which glyphosate-resistant and -susceptible horseweed populations were collected and transplanted into a soybean field. These plants were monitored and no differences were detected in height, width, leaf area, or dry weight. In a four-year weed management study, the ratio of glyphosate-resistant horseweed to glyphosate-susceptible horseweed in the study population was 3:1 but after years of spray programs that consisted of residual preplant herbicides followed by non-glyphosate postemergent herbicides that ratio shifted to 1:6 (Davis et al. 2009a). Another study comparing glyphosate-resistant and glyphosate-susceptible weed populations and their competitive effects on grapevines in the San Joaquin Valley in California showed that the glyphosate-resistant population accumulated twice as much shoot and total biomass as its susceptible counterparts (Alcorta et al. 2011). This lack of reduction in competitive ability among glyphosate-resistant horseweed populations in the San Joaquin Valley was also observed in other studies (Shrestha et al. 2007 and 2010).

There are multiple preplant burndown options for glyphosate-resistant horseweed. Eubank et al. (2008) found that horseweed control was > 90% four weeks after treatment by the use of glyphosate at 1.25 kg ha^{-1} plus 2,4-D at 0.84 kg ae ha^{-1} or dicamba at 0.28 kg ae ha^{-1}. Paraquat only partially controlled horseweed at rates of 0.84 kg ai ha^{-1} or 0.98 kg ai ha^{-1}. Glufosinate performed better when applied alone at 0.47 kg ai ha^{-1} with at least 88% of the horseweed controlled. Horseweed has historically been difficult to control in soybean prior to the introduction of glyphosate tolerant soybeans because of the lack of postemergent herbicides that could be used for control (Bruce and Kells 1990; Moseley and Hagood 1990). With newly introduced stacked herbicide tolerant traits in crop, there might be more options to control glyphosate-resistant horseweed in-crop. With dicamba tolerant soybeans, Byker et al. (2013), noted that dicamba applied preplant at 0.6 kg ae ha^{-1} followed by a postemergent application consistently provided over 86% control. These options provide some control of glyphosate-resistant horseweed in a burndown application, but in a glyphosate-tolerant soybean crop, dicamba cannot be applied during the season to control weed escapes (Byker et al. 2013).

Management practices to control glyphosate-resistant horseweed can include applying herbicides like those listed above but often crop rotation, fall-applied herbicides, or growing a winter crop can reduce the number of horseweed plants in subsequent corn and soybean crops. Davis et al. (2007 and 2009b) followed these specific management practices over four years to document what factors influenced the population of glyphosate-resistant horseweed. Crop rotation did not affect horseweed populations within the first two years but by the end of year four, plots in continuous soybean had a greater horseweed density as compared to the soybean-corn rotation, 2.9 to 1.4 plants m^{-2}, respectively, at 4 months after postemergent herbicides were applied. Also, spring-applied preplant herbicides were more effective in reducing horseweed populations early through mid-season than fall-applied herbicides, 0 plants m^{-2} compared to 6 plants m^{-2} at the timing of postemergent application. The winter wheat cover crop used in this experiment had variable results. In some years, the cover crop reduced the amount of horseweed but other years the winter cover crop was less efficient. However, the winter cover crop was never more effective than a fall or spring-applied herbicide in reducing horseweed populations (Davis et al. 2007 and 2009b).

While research has been done to investigate the effectiveness of different herbicides and application timing on control of horseweed, focus is now shifting to the effectiveness of more diverse management practices. There is little research that evaluates cover crop monocultures and mixtures for horseweed suppression and compares that to suppression afforded by fall-applied herbicides.

Cover Crop Degradation and Weed Suppression

Cover crops suppress weed growth by reducing the amount of sunlight, water, and/or nutrients or by producing alleopathic compounds that inhibit weed germination or growth. Once the cover crop is terminated, it forms a mulch layer, which can suppress summer annual weeds (Mirsky et al. 2013). As the cover crop degrades after termination, the mulch layer becomes thinner and develops more gaps, which allow for weeds to germinate and grow through the residue layer and become competitive in the cash crop (Teasdale and Mohler, 2000).

Litter degradation has been studied mostly in forest settings to elucidate information about nutrient cycling. These are often long term studies but much can be gleaned from the first stages of litter decomposition. Zhang et al. (2008) support this notion through their study that compared litter components of *Arabidopsis thaliana* (L.) Heynh., such as lignin, cellulose, and nitrogen, and found that they fall into similar ranges that are comparable to those found in most of the literature found in these forest studies.

The three main drivers of litter decomposition are climate, litter chemistry, and soil organisms (Lavelle et al. 1993; Swift et al. 1979). Since climate and the soil biota are inherent properties of a location, litter chemistry and management will determine the rate of cover crop degradation. Previous studies have shown that the most established patterns for litter decay are correlated with the initial ratios of C:N, lignin:N or lignin:cellulose (Aerts 1997; Hobbie 2008; Melillo et al. 1982).

Certain levels of these compounds are correlated to the mass-loss relationships of litter. For example, nitrogen and phosphorous are thought to be rate-enhancing factors while lignin is thought of as a rate-retarding compound (Fogel and Cromack 1977). In an experiment looking at leaf litter decomposition rate from various hardwoods, plants with a lower lignin to nitrogen ratio lost mass more quickly than hardwoods with a higher ratio. Beech (*Fagus sp.*) with a lignin:N ratio of 27:1 degraded at a much slower rate than that of Ash (*Fraxinus sp.*) that had a ratio of 14:1 (Melillo et al. 1982). The reasoning behind these components being drivers is that lignin is thought to protect the more easily broken down litter components from microbial attack by surrounding the cellulose and hemicellulose within the plant cell walls (Berg and McClaugherty 2003). Nitrogen, which acts in the opposite manner, is thought to relieve any nitrogen limitation for decomposers to break down carbon contained in the litter (Berg and Staaf 1980). In long-term degradation studies, the most nutrient-rich litters decomposed at a faster rate in the first 12 to 18 months than those with lower nutrient densities (Berg and Ekbohm 1990). Cover crop residues will not persist through multiple years of management and fertilization. Fertilization will lead to an increase in mass-loss of the cover crop mulch. Research has shown that using pelletized poultry litter after cover crop termination increased the rate at which the cover crop degraded. Loss of the cover crop biomass was minimal when the pelletized poultry litter was subsurface banded (Poffenbarger et al. 2015).

When choosing cover crops, some growers will plant a mixture of legumes and non-legumes to supply both carbon and nitrogen to reach a balance of providing nutrients to the crop while also reducing nitrogen leaching (Sainju et al. 2005). Non-legume cover crops, like cereal rye (*Secale cereale* L.), have high carbon to nitrogen ratios, and will often not have an effect on crop yield (Kuo and Jelum 2002). Including legumes in this mix will increase nitrogen content and lower the carbon to nitrogen ratio of the cover crops (Ranells and Wagger 1996).

Mixing cover crop species can also lead to an increase in biomass, which is another major factor in suppressing weeds (Wortman et al. 2012). Sainju et al. (2005) showed that a cereal rye and hairy vetch (*Vicia villosa* Roth) biculture produced more biomass than either species in monoculture.

Research has shown that a mulch residue layer on the soil surface can suppress weeds and that different residues perform differently, but there is a lack of connection made between properties of the residue and the duration of weed suppression after termination. Teasdale and Mohler (2000) found that, in general, weed emergence declined with an increasing mulch rate for any type of mulch used. The experiment used multiple cover crop species and more traditional mulch types like bark chips and leaf litter. Looking more specifically at hairy vetch and cereal rye, two popular cover crop species, Mohler and Teasdale (1993) found that cereal rye residue was better able to suppress summer annual weeds. After termination and early in the growing season more weeds emerged in the hairy vetch residue as opposed to cereal rye and that trend continued through 16 weeks after cover crop termination. It would require a greater initial biomass of hairy vetch to achieve the same amount of weed suppression that would be afforded by a modest rate of cereal rye (Mohler and Teasdale 1993).

Differences in weed emergence between different cover crop residues can be attributed to different degradation rates of the cover crop residue and the weed species present. With less residue, more light can reach the soil surface and increase soil temperature. Mohler and Teasdale (1993) reported that for the first month after initiation of the experiment, mimicking cover crop termination, the rate of light penetration between hairy vetch and cereal rye cover crops were similar. After the initial one-month degradation period, hairy vetch allowed more transmitted light through the residue while transmission through cereal rye remained largely unchanged. Some weed species are more sensitive to cover crop residue on the soil surface. Smaller seeds such as redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.) are much more sensitive to cover crop residue than larger seeded species like giant foxtail (*Setaria faberi* Herrm.) and velvetleaf (*Abutilon theophrasti* Medik.). Larger seeds have an advantage when it comes to breaking through the physical barrier of that mulch layer as compared to smaller seeds (Teasdale and Mohler 2000).

Finney et al. (2016) looked more closely at biomass and C:N ratios to determine how they affect ecosystem services such nitrogen retention, weed suppression, and yield. This study showed that biomass is positively correlated with weed suppression whereas C:N ratio is more indicative of nitrogen retention and yield. This study focused on weed suppression and other ecosystem effects during the cover crop growing season rather than after termination.

Biomass is a widely-reported characteristic for cover crops in weed suppression research but there is little research that investigates the role of litter components that could also contribute to litter degradation and weed suppression.

Hairy Vetch Seed Bank Dynamics

Hairy Vetch (*Vicia villosa* Roth) is a legume native to Europe and Western Asia. This species has been adopted in the Midwest, Mid-Atlantic, and Northeastern United States because of its ability to convert atmospheric nitrogen into plant available nitrogen as well as survive harsher winters than other legume cover crops (Sustainable Agriculture Research and Education 2012; Undersander et al. 1990). As a winter cover crop, hairy vetch can improve soil quality, reach higher biomass levels than other legumes, and convert plant unavailable nitrogen to plant available nitrogen at a rate of 50 to 190 kg N ha^{-1} (Hartwig and Ammon 2002; Stute and Posner 1993; Teasdale et al. 2004).

Despite these possible benefits, some growers are hesitant to plant hairy vetch because of potential management problems such as regrowth after termination and persistence of seeds in the soil (Snapp et al. 2005; Teasdale and Shirley 1998). Dimorphic seed coats, hard and soft, can be found in hairy vetch populations. Hard seed coats can lead to volunteer hairy vetch in subsequent crops. Volunteer hairy vetch can become problematic in winter wheat and perennial tree fruit cropping systems (Aarssen et al. 1986). Reduced tillage systems where hairy vetch is mowed or terminated using a roller crimper can also be problematic because of regrowth from incomplete termination (Boydston and Williams 2011). In instances where hairy vetch regrowth has occurred, from incomplete termination, crop yield reductions have been found due to competition (Curran et al. 2015).

Hairy vetch can be controlled with herbicides although it may require an extra application beyond that of a normal herbicide program. Field experiments in Pennsylvania and Maryland were conducted to investigate different herbicides and timings to determine what will best control hairy vetch in winter wheat. This study found that clopyralid provided the most consistent control of hairy vetch at preemergence as well as postemergent application timings, but dicamba alone or with 2,4-D also provided >95% control (Curran et al. 2015; Mischler et al. 2010).

Hairy vetch seed dormancy is often blamed if hairy vetch becomes problematic in subsequent crops. Jacobsen et al. (2010) tested hairy vetch from nine commercial seed sources that would be available in the Northeastern United States and found that among these seed sources there were varying degrees of seed dormancy ranging from 1 to 21%. Seed dormancy in hairy vetch has been attributed to source of the seed or maternal environment (Jannink et al. 1997). Multiple studies have reported that scarification treatments can overcome seed dormancy (Jacobsen et al. 2010; Mirsky et al. 2015). With scarification treatments, seed bank persistence was completely eliminated 6 months after burial. Seed that hadn't been scarified still had 1 to 7% viability after 6 months (Mirsky et al. 2015).

Seed burial depth also plays a role in seed bank persistence. Mirsky et al. (2015) found that seeds buried to a depth of 15 cm had reduced emergence and increased seed bank loss compared to seeds that were buried to 3 cm. The loss in seeds, or seeds unaccounted for, from the 15 cm burial depth was very high, up to 55% at the Maryland location.

Another primary factor that affects volunteer hairy vetch in subsequent crops is the lack of complete death at termination, or the potential of adding seeds to the seed bank from a delay in termination (Snapp et al. 2005). Mischler et al. (2010) investigated roller-crimping at different growth stages of hairy vetch to see what timing would provide the most complete control. Their results showed rolling alone when the plants were at early-pod set successfully terminated hairy vetch. Another study suggests that terminating earlier at late bloom is more appropriate for complete termination (Hoffman et al. 1993). Some instances of regrowth were found in every stage of termination but regrowth was lowest if termination occurred in early-pod set (Mischler et al. 2010).

When selecting hairy vetch cultivars, flowering time is critical because that is when it is most appropriate to terminate by non-chemical means to prepare fields for planting of a cash crop. There have been very few registered cultivars of hairy vetch released, Maul et al. (2011) have used molecular and observational techniques to evaluate 64 accessions that are in the USDA National Plant Germplasm System. One cultivar 'AU Early Cover' was bred in the southeastern United States to fit into corn and small grain farmer's rotation (Surrency et al. 1995). From that selection, 'Groff' was derived and selected over time to be more winter hardy. The end result was a later flowering date, about 20 days after its 'AU Early Cover' parent. 'Purple Bounty' is a cultivar that was developed at the USDA-ARS Beltsville Agricultural Research Center from a selection of cold hardy individuals from an established early flowering parental line, P1561947. These two cultivars, Purple Bounty and Groff, do have similar C:N ratios from green up and through flowering (Maul et al. 2011).

The two cultivars of interest 'Purple Bounty' and 'Groff' are an early flowering cultivar and later flowering cultivar, respectively, in Virginia. The goal of the experiment involving these two cultivars is to compare germination over a period of two years, starting with seeds sown in the fall to simulate planting and more sown in the spring to simulate additions to the seed bank from incomplete termination. This mapping over time will show when the seeds will have a flush of germination and compare that to timings in cash crop programs. A companion part to this experiment will compare these two cultivars with respect to pod number and seed viability at different termination timing to determine if and how many seeds are being added to the seed bank if termination is delayed.

Literature Cited

Aarssen LW, Hall IV, Jensen KIN (1986) The biology of Canadian weeds 76. *Vicia angustifolia* L., *V. cracca* L., *V. sativa* L., *V. tetrasperma* (L.) Schreb. and *V. villosa* Roth. Can J Plant Sci 66:711-737

Aerts R (1997) Climate, leaf litter chemistry and leaf litter decomposition in terrestrial ecosystems-a triangular relationship. Oikos 79:439-449

Alcorta M, Fidelibus MW, Steenwerth KL, Shrestha A (2011) Competitive effects of glyphosate-resistant and glyphosate-susceptible horseweed (*Conyza canadensis*) on young grapevines (*Vitis vinifera*). Weed Sci 59:489-494

Andersen MC (1993) Diaspore morphology and seed dispersal in several wind-dispersed Asteraceae. Am J Bot 80:487-492

Bajwa AA, Mahajan G, Chauhan BS (2015) Nonconventional weed management strategies for modern agriculture. Weed Sci 63:723-747

Bajwa AA, Sadia S, Ali HH, Jabran K, Peerzada AM, Chauhan BS (2016) Biology and management of two important *Conyza* weeds: a global review. Environ Sci Pollut Res Int 23:24694-24710

Barrett SCH (1983) Crop mimicry in weeds. Econ Bot 37:255–282

Benbrook CM (2016) Trends in glyphosate herbicide use in the United States and globally. Environ Sci Eur DOI 10.1186/s12302-016-0070-0

Berg B, Ekbohm G (1991) Litter mass-loss rates and decomposition patterns in some needle and leaf litter types. Long-term decomposition in a Scots pine forest. VII. Can J Bot 69:1449-1456

Berg B, McClaugherty C (2003) Plant litter: decomposition, humus formation, carbon sequestration. New York: Springer. Pp 53-83

Berg B, Staaf H (1980) Decomposition rate and chemical changes of Scots pine needle litter. II. Influence of Chemical Composition. Ecol Bull 32:373-390

Boydston RA, Williams MM (2011) Rye and vetch manageement for no-till snap bean production. Proc. Weed Sci. Soc. America 51:145

Bruce JA, Kells JJ (1990) Horseweed (*Conyza canadensis*) control in no-tillage soybeans (*Glycine max*) with preplant and preemergence herbicides. Weed Technol 4:642-647

Buhler DD (1992) Population dynamics and control of annual weeds in corn (*Zea mays*) as influenced by tillage systems. Weed Sci 40:241-248

Burket JZ, Hemphill DD, Dick RP (1997) Winter cover crops and nitrogen management in sweet corn and broccoli rotations. Hort Science 32:664-668

Byker HP, Soltani N, Robinson DE, Tardif FJ, Lawton MB, Sikkema PH (2013) Control of glyphosate-resistant horseweed (*Conyza canadensis*) with dicamba applied preplant and postemergence in dicamba-resistant soybean. Weed Technol 27:492-496

Coombs C, Lauzon JD, Deen B, Van Eerd LL (2017) Legume cover crop management on nitrogen dynamics and yield in grain corn systems. Field Crops Res 201:75-85

Curran WS, Wallace JM, Mirsky S, Crockett B (2015) Effectiveness of herbicides for control of hairy vetch (*Vicia villosa*) in winter wheat. Weed Technol 29:509-518

Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plan 32:1221-1250

Davis VM, Gibson KD, Bauman TT, Weller SC, Johnson WG (2007) Influence of weed management practices and crop rotation on glyphosate-resistant horseweed population dynamics and crop yield. Weed Sci 55:508-516

Davis VM, Gibson KD, Bauman TT, Weller SC, Johnson WG (2009b) Influence of weed management practices and crop rotation on glyphosate-resistant horseweed (*Conyza canadensis*) population dynamics and crop yield – Years III and IV. Weed Sci 57:417-426

Davis VM, Kruger GR, Stachler JM, Loux MM, Johnson WG (2009a) Growth and seed production of horseweed (*Conyza canadensis*) populations resistant to glyphosate, ALS-Inhibiting, and multiple (glyphosate + ALS-inhibiting) herbicides. Weed Sci 57:494-504

Dauer JT, Mortensen DA, Humston R (2006) Controlled experiments to predict horseweed (*Conyza canadensis*) dispersal distances. Weed Sci 54:484-489

Duke SO (2011) Why have no new herbicide modes of action appeared in recent years? Pest Manag Sci 68:505-512

Duke SO, Cerdeira AL (2005) Transgenic herbicide-resistant crops: current status and potential for the future. Outlooks on Pest Management 16:208-211

Eubank TW, Poston DH, Nandula VK, Koger CH, Shaw DR, Reynolds DB (2008) Glyphosate-resistant horseweed (*Conyza canadensis*) control using glyphosate-, paraquat-, and glufosinate-based herbicide programs. Weed Technol 22:16-21

Finney DM, White CM, Kaye JP (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agron J 108:39-52

Fogel R, Cromack Jr. K (1977) Effect of habitat and substrate quality on Douglas fir litter decomposition in western Oregon. Can J Bot 55:1632-1640

Fraser PM, Curtin D, Harrison-Kirk T, Meenken ED, Beare MH, Tabley F, Gillespie RN, Francis GS (2013) Winter nitrate leaching under different tillage and winter cover crop management practices. Soil Sci Soc Am J 77:1391-1401

Green JM (2007) Review of glyphosate and ALS-inhibiting herbicide crop resistance and resistant weed management. Weed Technol 21:547-558

Harker KN, O'Donovan JT (2013) Recent weed control, weed management, and integrated weed management. Weed Technol 27:1-11

Hartwig NL, Ammon HU (2002) Cover crops and living mulches. Weed Sci 50:688-699

Heap I (2017) The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/Graphs/GeoChart.aspx Accessed: November 4, 2017

Herbicide Resistance Action Committee (2017) Best Management Practices. http://hracglobal.com/prevention-management/best-management-practices Accessed: July 12, 2017

Hobbie SE (2008) Nitrogen effects on decomposition- a five-year experiment in eight temperate sites. Ecology 89:2633-2644

Hoffman ML, Regnier EE, Cardina J (1993) Weed and corn (*Zea mays*) responses to a hairy vetch (*Vicia villosa*) cover crop. Weed Technol 7:594-599

Jacobsen KL, Gallagher RS, Burnham M, Bradley BB, Larson ZM, Walker CW, Watson JE (2010) Mitigation of seed germination impediments in hairy vetch. Agron J 102:1346-1351

Jannink J, Merrick LC, Liebman M, Dyck EA, Corson S (1997) Management and winter hardiness of hairy vetch in Maine. University of Maine. Tech. Bull. 167

Kniss AR (2017) Long-term trends in the intensity and relative toxicity of herbicide use. Nat Commun DOI: 10.1038/ncomms14865

Kruger GR, Davis VM, Weller SC, Stachler JM, Loux MM, Johnson WG (2008) Frequency, distribution, and characterization of horseweed (*Conyza canadensis*) biotypes with resistance to glyphosate and ALS-inhibiting herbicides. Weed Sci 57:652-659

Kuo S, Jellum EJ (2002) Influence of winter cover crop and residue management on soil nitrogen availability and corn. Agron J 94:501-508

Lavelle P, Blanchart E, Martin A, Martin S, Spain A (1993) A hierarchical model for decomposition in terrestrial ecosystems: application to soils of the humid tropics. Biotropica 25:130-150

Liebman M, Mohler CL, Staver CP (2001) Ecological management of agricultural weeds: Cambridge University Press. Pp 1-20

Livingston M, Fernandez-Cornejo J, Unger J, Osteen C, Schimmelpfennig D, Park T, Lambert D (2015) The economics of glyphosate resistance management in corn and soybean production. https://www.ers.usda.gov/webdocs/publications/45354/52761_err184.pdf?v=42207 Accessed: August 16, 2017

Lowry WP, Lowry PP (1989) Fundamentals of biometeorology: interactions of organisms and the atmosphere – the physical environment. Volume I. McMinnville, OR: Peavine. 310 p

Maul J, Mirsky S, Emche S, Devine T (2011) Evaluating a germplasm collection of the cover crop hairy vetch for use in sustainable farming systems. Crop Sci 51:2615-2625

Melillo JM, Aber JD, Muratore JF (1982) Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology 63:621-626

Mirsky SB, Ryan MR, Teasdale JR, Curran WS, Reberg-Horton CS, Spargo JT, Wells MS, Keene CL, Moyer JW (2013) Overcoming weed management challenges in cover crop–based organic rotational no-till soybean production in the Eastern United States. Weed Technol 27:193-203

Mirsky SB, Wallace JM, Curran WS, Crockett BC (2015) Hairy vetch seedbank persistence and implications for cover crop management. Agron J 107:2391-2400

Mischler R, Duiker SW, Curran WS, Wilson D (2010) Hairy vetch management for no-till organic corn production. Agron J 102:355-362

Mohler CL, Teasdale JR (1993) Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. Weed Res 33:487-499

Moseley CM, Hagood Jr. ES (1990) Horseweed (*Conyza canadensis*) control in full-season no-till soybeans (*Glycine max*). Weed Technol 4:814-818

Miguez FE, Bollero GA (2005) Review of corn yield response under winter cover cropping systems using meta-analytic methods. Crop Sci 45:2318-2329

Nandula VK, Eubank TW, Poston DH, Koger CH, Reddy KN (2006) Factors affecting germination of horseweed (*Conyza canadensis*). Weed Sci 54:898-902

Pimentel, D (1997) Techniques for reducing pesticides: environmental and economic benefits. John Wiley and Sons, Chichester, UK. Pp 456

Poffenbarger HJ, Mirsky SB, Weil RR, Kramer M, Spargo JT, Cavigelli MA (2015) Legume proportion, poultry litter, and tillage effects on cover crop decomposition. Agron J 107:2083-2096

Preston C, Wakelin AM, Dolman FC, Bostamam Y, Boutsalis P (2009) A decade of glyphosate-resistant *Lolium* around the world: mechanisms, genes, fitness, and agronomic management. Weed Sci 57:435-441

Ranells NN, Wagger MG (1996) Nitrogen release from grass and legume cover crop monocultures and bicultures. Agron J 88:777-782

Regehr DL, Bazzaz FA (1979) The population dynamics of *Erigeron canadensis*, a successional winter annual. J Ecol 67:923-933

Sainju UM, Whitehead WF, Singh BP (2005) Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agron J 97:1403-1412

Shields EJ, Dauer JT, VanGessel MJ, Neumann G (2006) Horseweed (*Conyza canadensis*) seed collected in the planetary boundary layer. Weed Sci 54:1063-1067

Shrestha A, Hanson BD, Fidelibus MW, Alcorta M (2010) Growth, phenology, and intra-specific competition between glyphosate-resistant and glyphosate-susceptible horseweed (*Conyza canadensis*) in the San Joaquin Valley of California. Weed Sci 58:147-153

Shrestha A, Hembree KJ, Va N (2007) Growth stage influences level of resistance in glyphosate-resistant horseweed. California Agric. 61:67-70

Smisek A, Doucet C, Jones M, Weaver S (1998) Paraquat resistance in horseweed and Virignia pepperweed from Essex County, Ontario. Weed Sci 46:200-204

Smisek AJJ (1995) The evolution of resistance to paraquat in populations of *Erigeron canadensis* L. M.S. Thesis. London, Ontario. The University of Western Ontario 102 p

Snapp SS, Swinton SM, Laharta R, Mutch D, Black JR, Leep R, Nyiraneza J, O'Neil K (2005) Evaluating cover crops for benefits, costs, and performance within cropping system niches. Agron J 97:322-332

Soltani N, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2016) Potential corn yield losses from weeds in North America. Weed Technol 30:979-984

Soltani N, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2017) Perspectives on potential soybean yield losses from weeds in North America. Weed Technol 31:148-154

Stute J, K, Posner JL (1993) Legume cover crop options for grain roatations in Wisconsin. Agron J 85:1128-1132

Sustainable Agriculture Research and Education (2012) Managing cover crops profitably. 3rd edn. Maryland: United Book Press, Inc. Pp 142-151

Surrency ED, Owsley CM, Kirkland MS, McCracken, Raymer PL, Hargrove W, Day JL, Mosjidis JA (1995) Registration of ‘Americus’ hairy vetch. Crop Sci 35:1222

Swanton CJ, Weise SF (1991) Integrated weed management- the rationale and approach. Weed Technol 5:657-663

Swift MJ, Heal OW, Anderson JM (1979) Decomosition in terrestrial ecosystems. Berkley: University of California Press. 372 p

Teasdale JR, Devine TE, Mosjidis JA, Bellinder RR, Beste CE (2004) Growth and development of hairy vetch cultivars in the Northeastern United States as influenced by planting and harvesting date. Agron J 96:1266-1271

Teasdale JR, Mohler CL (2000) The quantitative releationship between weed emergence and the physical properties of mulches. Weed Sci 48:385-392

Teasdale JR, Shirley DW (1998) Influence of herbicide application timing on corn production in a hairy vetch cover crop. J Prod Agric 11:121–125

Thill DC, Lish JM, Callihan RH, Bechinski EJ (1991) Integrated weed management- A component of integrated pest management- a critical review. Weed Technol 5:648-656

Trezzi M, Balbinot Jr. A, Benin G, Debastiani F, Patel F, Miotto Jr. E (2013) Competitive ability of soybean cultivars with horseweed (*Conyza bonariensis*). Planta Daninha 31:543-550

Undersander DJ, Ehlke NJ, Kaminski AR, Doll, JD, Kellin, KA (1990) Alt. Field Crops Manual. Univ. of Wisconsin-Madison Cooperative Extension, Madison. https://www.hort.purdue.edu/newcrop/afcm/vetch.html Accessed on: February 17, 2015

Uva RH, Neal JC, DiTomaso JM (1997) Weeds of the Northeast. Ithaca, New York: Cornell University Press. Pp 136-137

VanGessel MJ (2001) Glyphosate-resistant horseweed from Delaware. Weed Sci 49:703-705

Virginia Department of Conservation and Recreation (2017) Program Year 2017 Virginia Agricultural Cost-Share (VACS) BMP Manual. http://dswcapps.dcr.virginia.gov/htdocs/agbmpman/csmanual.pdf Accessed: March 22, 2017

Weaver SE (2001) The biology of Canadian weeds. 115. *Conyza canadensis*. Can J Plant Sci 81:867-875

Williams MM, Jordan NR, Yerkes C (1995) The fitness cost of triazine resistance in Jimsonweed (*Datura stramonium* L.). Am Midl Nat 133:131-137

Wortman SE, Francis CA, Bernards ML, Drijber RA, Lindquist JL (2012) Optimizing cover crop benefits with diverse mixtures and an alternative termination method. Agron J 104: 1425-1435

Wszelaki A, Broughton S (2012) Cover crops and green manures. University of Tennessee Extension. Ext. Pub. W235-G.

https://extension.tennessee.edu/publications/Documents/W235-G.pdf Accessed on: July 23, 2017

Wyland LJ, Jackson LE, Chaney WE, Klonsky K, Koike ST, Kimple B (1996) Winter cover crops in a vegetable cropping system: Impacts on nitrate leaching, soil water, crop yield, pests, and management costs. Agric Ecosyst Environ 59:1-17

Zhang D, Hui D, Luo Y, Zhou G (2008) Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors. J Plant Ecol 1:85-93

Zhang J, Salas ML, Jordan NR, Weller SC (1999) Biorational approaches to managing *Datura stramonium*. Weed Sci 47:750-756

Horseweed (*Conyza canadensis* L. Cronquist) Suppression from Cover Crop Mixtures and Fall-Applied Residual Herbicides

Abstract

Horseweed is a problematic weed to control, especially in no-tillage situations. Increasing cases of herbicide resistance has exacerbated the problem, necessitating alternative control options and an integrated weed management approach. Field experiments were conducted to evaluate horseweed suppression from monocultures and mixtures of cover crops and two fall-applied residual herbicide treatments in Blacksburg and Blackstone, Virginia from 2015 to 2017. Once the cover crops were terminated in late spring using a roller crimper, corn and soybeans were planted. Data collected were: horseweed counts before cover crop termination, visible suppression ratings during cash crop production, and horseweed biomass at cash crop harvest. All cover crop monocultures and mixtures suppressed horseweed as compared to the nontreated check, with the exception of forage radish alone, which winterkilled offering no competition in late winter or biomass to contribute to weed suppression after termination. In 2016, horseweed suppression from cover crops was >50% 4 weeks after termination (WAT) and fell to 10 to 48% suppression 8 WAT. In 2017, all cover crops, with the exception of forage radish in monoculture, provided >95% suppression until 10 WAT. Flumioxazin + paraquat provided suppression comparable to the cover crops during the 2016 cash crop season, providing >83% suppression 4 WAT, but failed to perform as well in 2017, providing <46% suppression throughout the cash crop growing season. Metribuzin plus chlorimuron-ethyl did not suppress horseweed, providing <10% suppression, in either year. These results indicate that fall planted

cover crops suppress horseweed and could be an effective part of an integrated weed management program.

Horseweed (*Conyza canadensis* L. Cronquist), also known as marestail, is a native plant to North America where it can behave as a summer or winter annual with peak germination times in May and in late-August to early-September in Illinois and Massachusetts (Regehr and Bazzaz 1979; Bhowmik and Bekech 1993). This weed can also produce up to 200,000 seeds per plant that are wind dispersed (Bhowmik and Bekech 1993). Horseweed fruits are composed of an achene and a pappus, which aids in wind dispersal and seed can travel over 150 meters from the mother plant (Andersen 1993; Dauer et al. 2006). Horseweed is especially problematic in no-till situations as horseweed seed readily germinates at the soil surface. Studies have shown that no seedlings will emerge if seeds are buried at a depth of 0.5 cm or deeper in the soil profile (Nandula et al. 2006).

Horseweed can be a challenging weed to control and can detrimentally affect crop yield with reported 25% yield loss in soybeans with 13.3 plants m^{-2} (Trezzi et al. 2013). In soybeans, control is difficult because of the lack of effective postemergent herbicide options (Bruce and Kells 1990; Moseley and Hagood 1990). Herbicide options are further limited with herbicide resistant horseweed populations. Currently, 18 countries have reported herbicide resistance in horseweed, and in the United States, horseweed is resistant to five site of action groups (Heap 2017). Glyphosate-resistant horseweed was first found in Delaware in 2001, and biotypes with multiple resistances to glyphosate (WSSA group 9) and ALS-inhibiting (WSSA group 2) herbicides have been reported in Ohio and Indiana (Kruger et al. 2008; VanGessel 2001). Therefore, alternative horseweed control methods are necessary.

Growing a winter cover crop or applying residual herbicides have had variable effects on horseweed. Growing a winter cover crop reduced horseweed populations in some years but wasn’t as effective as a fall-applied or spring-applied herbicides (Davis et al. 2007, 2009). Other methods of non-chemical suppression for horseweed could include crop rotation and tillage (Brown and Whitwell 1988; Davis et al. 2007, 2009).

Cover crops have two periods of potential weed suppression: while the cover crop is actively growing, where weeds are suppressed through competition, and after termination, when the cover crop residue creates a mulch layer on the soil surface (Hayden et al. 2012; Mirsky et al. 2013). This mulch layer reduces the amount of light that reaches the soil surface, reduces soil temperature, and creates a physical barrier to suppress weeds (Mirsky et al. 2013). With horseweed able to behave as a summer or winter annual, cover crops have the potential to target both germination periods (Regehr and Bazzaz 1979; Bhowmik and Bekech 1993). Horseweed germination is not affected by shade; therefore, reducing sunlight is not a method of suppression by cover crops (Górski et al. 1977).

While fall-applied herbicides can control horseweed, control will not persist into the subsequent summer growing season (Davis et al. 2010; Owen et al. 2009). The efficacy of residual herbicides is variable. Herbicide dissipation will vary depending on herbicide choice, soil moisture, soil pH, microbial activity, and tillage (Flint and Witt 1997; Loux and Reese 1992; Moyer et al. 2010; Shaner and Hager 2014; Weber 1990). Another confounding factor is that most horseweed germinates in spring (Davis and Johnson 2008). Fall-applied herbicides without residual activity can result in increased horseweed populations by controlling competing winter annual weeds and decreasing competition for resources (Davis et al. 2010).

Due in large part to herbicide resistance, growers are looking for alternative options to control horseweed. Cover crops could have a place as part of an integrated approach to suppress this weed. There is little research that evaluates different cover crop monocultures and mixtures for horseweed suppression. The objective of this study is to evaluate cover crop monocultures and mixtures for horseweed suppression and compare that to suppression afforded by two fall-applied residual herbicide treatments.

Materials and Methods

Study Sites. Studies were conducted to examine the ability of fall-planted cover crops to suppress horseweed and to compare suppression afforded by cover crops to the suppression afforded by two fall-applied residual herbicide treatments. Locations for this study were Blacksburg, Virginia at Kentland Farm (37.192913, -80.573942), which is located in the New River flood plain in a Ross soil (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls) and in Blackstone, Virginia at the Southern Piedmont Agricultural Research and Extension Center (37.082840, -77.972062) in an Appling coarse sandy loam (fine, kaolinitic, thermic, Typic Kanhapludults). The Kentland Farms location was previously in corn and was planted no-till while the Blackstone location was previously in sod and was prepped for planting by disking the area to create a seedbed. Both locations received a pre-plant herbicide application of glyphosate (Roundup Powermax, Monsanto Company, St. Louis, MO) at 1.26 kg ae ha^{-1}.

Experimental Design. This experiment was designed as a split-split block with the main block being a fall planted cover crop treatment or fall-applied herbicide in a randomized complete block with four replications. A nontreated check was included. The cover crop or herbicide treatment was first split at cash crop planting, which was either corn (*Zea mays* L.) or soybeans (*Glycine max* L. Merr.). These cash crop blocks were divided again on the basis of horseweed management. One block left horseweed uncontrolled through the season and in the other, horseweed was controlled through the first 8 weeks of the cash crop growing season (i.e. weedy or weed free). Experimental main blocks were 46.4 m^2 with cash crop sub-blocks divided into 23.2 m^2 and horseweed controlled/uncontrolled blocks were 11.6 m^2.

Main block treatments for this experiment include four different cover crops in monoculture and mixtures of these cover crops, two fall residual herbicides, and a nontreated check (no cover crop or fall-applied herbicide). Cover crops used were cereal rye (*Secale cereale* L.) (Elbon South; Green Cover Seeds, Bladen, NE), forage radish (*Raphanus sativus* L.) (Nitroradish; Green Cover Seeds), hairy vetch (*Vicia villosa* Roth.) (TNT; Green Cover Seeds), and crimson clover (*Trifolium incarnatum* L.) (Dixie; Green Cover Seeds). Due to a lack of seed availability in 2015, the monoculture plot of cereal rye was planted using a variety not stated (Southern States, Richmond, VA). Monoculture rates were cereal rye at 125 kg ha^{-1}, hairy vetch at 28.0 kg ha^{-1}, crimson clover at 22.4 kg ha^{-1}, and forage radish at 8.96 kg ha^{-1}. Three two-way mixtures were included of cereal rye at 50.4 kg ha^{-1} with hairy vetch at 20.2 kg ha^{-1}, cereal rye at 50.4 kg ha^{-1} with crimson clover at 15.7 kg ha^{-1}, and cereal rye at 69.4 kg ha^{-1} and forage radish at 4.48 kg ha^{-1}. There were two three-way cover crop mixtures as well, both contained cereal rye at 38.1 kg ha^{-1} and forage radish at 2.2 kg ha^{-1}, each with one legume. In these three-way mixtures, hairy vetch was planted at 16.8 kg ha^{-1} and crimson clover at 13.4 kg ha^{-1}. These seeding rates are on the high end of recommended rates from the Virginia Natural Resources Conservation Service (Anonymous 2015). The herbicide treatments were metribuzin at 0.092 kg ai ha^{-1} + chlorimuron-ethyl at 0.0153 kg ai ha^{-1} (Canopy; E.I. du Pont de Nemours and Company, Wilmington, DE) + nonionic surfactant at 0.25% v v^{-1} and flumioxazin (Valor; Valent U.S.A. Corporation Agricultural Products, Walnut Creek, CA) at 0.107 kg ai ha^{-1} + paraquat (Gramoxone SL 2.0; Syngenta Crop Protection, LLC, Greensboro, NC) at 0.7 kg ai ha^{-1} + crop oil concentrate (Southern States, Richmond, VA) at 1.0% v v^{-1}.

Field Management and Data Collection. Treatments were applied (cover crops drilled to a depth of 3 to 4 cm) and herbicides applied on October 20, 2015 in Blackstone. In 2016, treatments were applied on September 28th and October 14th in Blacksburg and Blackstone, respectively. Therefore the study was conducted across three site-years.

Cover crop treatments were terminated by two sequential passes with a roller crimper 2 weeks apart with the initial pass in Blackstone on May 3, 2016. In 2017, termination occurred on April 26 and May 2 for Blackstone and Blacksburg, respectively. After the second pass, corn and soybeans were planted into the rolled cover crop residue. Corn, variety P1197AM (DuPont Pioneer; Johnston, IA) in 2016 and variety DKC62-08 (DeKalb; DeKalb, IL) in 2017, was planted at a rate of 61,775 seeds ha^{-1}. Soybean, variety P46T21R (DuPont Pioneer; Johnston, IA) in 2016 and variety AG48X7 (Asgrow; Kalamazoo, MI) in 2017 was planted at 327,408 seeds ha^{-1}. Both crops were planted on 76 cm rows with four rows per plot. Plots were fertilized at planting with 22.7 kg of 0-25-25 at planting. Corn plots received 27.3 kg of 46-0-0 applied at planting and when the corn reached 0.3m tall. Horseweed free plots were maintained weed free by spot treating horseweed with a 2% v v^{-1} glyphosate solution through 8 weeks after cash crop planting. No other weed control measures were used in this experiment.

Horseweed counts were made in late March in a 0.37 m^2 quadrat per plot. At cover crop termination, above ground biomass samples from a 0.09 m^2 area were taken. These samples were divided into the desired cover crop species and dried at 66°C for three days for mass determination. Cover crop biomass at termination was the same for corn and soybean experiments, since these experiments utilized larger blocks for logistical reasons until cash crop planting. Visible weed suppression ratings were taken on a two-week interval after cash crop planting on a 0 to 100 scale with 0 being complete infestation and 100 being complete suppression of the plot as compared to the no cover crop control (Frans et al. 1986). Ratings were discontinued when the weed suppression offered by the cover crop was negligible compared to the no cover crop control.

Plots were harvested on September 15, 2016 and October 13, 2016 for corn and soybeans, respectively in Blackstone, using a small plot combine. In 2017, corn was harvested on October 3rd and October 17th in Blackstone and Blacksburg, respectively. Soybeans were harvested on October 23, 2017 in Blackstone and October 27, 2017 in Blacksburg. Yield was evaluated from the middle two rows in each plot and adjusted for moisture to 15.5% for corn and 13% for soybeans. Just prior to harvest, 0.09 m^2 quadrats of horseweed above ground biomass were collected in subplots where horseweed was not controlled during the cash crop growing season and dried to determine biomass. In 2017, 0.25 m^2 quadrats were used because of lower horseweed densities.

Data analysis was conducted using JMP (JMP Pro 12; SAS Institute, Inc., Cary, NC). Main effects of treatment, year, location, block, and interactions of year and location with treatment were included in the model. For the cover crop biomass analysis, the forage radish treatment, herbicide treatments, and the nontreated check were excluded because there was no cover crop biomass in these plots. The nontreated check was also excluded in the visible rating analyses. If the overall ANOVA was significant ($p<0.05$), a means separation was used with Fisher's Protected $LSD_{\alpha=0.05}$ to compare across treatments. Yield data were analyzed by treatment using a model where main effects were location, year, block, and how the blocks were maintained (horseweed controlled/weed free or horseweed left uncontrolled/weedy). Interactions of location and year with weedy or weed free were also included.

Results and Discussion

Horseweed Counts before Termination. The interaction between year and treatment was not significant ($p = 0.990$) but location and treatment was significant ($p<0.001$) so data were pooled across year but analyzed separately by location (Table 1). The density of horseweed was greater in Blacksburg than Blackstone; the nontreated check had 94 and 25 plants m^{-2}, respectively (Table 2). Plots treated with metribuzin + chlorimuron-ethyl had more horseweed present than the nontreated check with 152 and 26 plants m^{-2} in Blacksburg and Blackstone, respectively. Cover crop mixtures containing cereal rye resulted in greater suppression than both the fall-applied residual herbicide treatments and mixtures not containing cereal rye with <7 plants m^{-2}, with the exception of crimson clover in Blacksburg with no horseweed present.

These findings are similar to those of Hayden et al. (2012), who reported decreases in winter annual weed presence when competing with an actively growing cover crop. Cereal rye and cereal rye + hairy vetch performed better in suppression of winter annual weeds as compared to hairy vetch alone, 72 and 66 plants m^{-2} as compared to 159 plants m^{-2}. The performance of forage radish in this experiment is in contrast to findings in Maryland where forage radish suppressed weeds through late March, compared to the no cover check (Lawley et al. 2011). Lawley et al. (2011) planted their cover crops much earlier, in September rather than mid-October, allowing for more biomass to accumulate before a killing frost occurred. In this study the forage radish did not completely winterkill, permitting some biomass to remain until corn planting (Lawley et al. 2011).

Cover Crop Biomass at Termination. Data from herbicide and nontreated plots were excluded from this analysis as no biomass was present at the time of cover crop termination. The interaction between year and treatment as well as location and treatment were not significant (p=0.06 and p=0.16) (Table 3). Cover crop data are presented pooled across locations but separated by year because visible suppression rating data and horseweed biomass at termination for both corn and soybeans were split by year due to a significant year by treatment interaction. In the 2015-16 experiment, biomass ranged from 0 to 7,916 kg ha^{-1} and in 2016-17, biomass ranged from 216 to 11,449 kg ha^{-1} (Table 4). Forage radish completely winterkilled in 2015-16 but not in 2016-17. Monocultures of crimson clover, hairy vetch, and forage radish produced the least biomass each year with <2076 kg ha^{-1} in 2015-16 and <4939 kg ha^{-1} in 2016-17.

The biomass accumulation is similar to that reported in Maryland, Pennsylvania, and Georgia with most monocultures and mixtures ranging from 3,000 to 7,000 kg ha^{-1} (Finney et al. 2016; Mirsky et al. 2013; Sainju et al. 2005). Wiggins et al. (2016) reported less biomass in Tennessee ranging from 2,000 to 4,000 kg ha^{-1}. In 2016-17, biomass of hairy vetch + cereal rye, crimson clover + cereal rye, and hairy vetch + forage radish + cereal rye exceeded 8,000 kg ha^{-1}, which is more than typically reported.

Visible Horseweed Suppression. Visible rating data were considered separately for corn and soybean. Rating data were collected through 10 weeks after termination (WAT) in 2016-17 but only through 8 WAT in Blackstone in 2015-16, indicating that cover crop biomass suppressed horseweed in at least one treatment for at least 8 WAT. The interaction between year and treatment was significant ($p<0.05$) at the 4, 6, and 8 WAT rating dates for both corn and soybeans with the exception of the soybean 6 WAT rating (p=0.47), so data were pooled across locations but separated by year (Table 5 and 7). In both corn and soybean, cover crop treatments performed similarly with the exception of forage radish alone. The monoculture treatment of forage radish had 0% suppression through all rating dates as the forage radish winterkilled and there was no biomass present after termination (Tables 6 and 8). In 2015-16, horseweed suppression from any cover crop monoculture and mixture was >54% as compared to the nontreated check 4 WAT with the exception of forage radish alone. Hairy vetch and forage radish + cereal rye had 80 and 81% horseweed suppression, respectively 4 WAT. By 8 WAT, horseweed suppression from the cover crops was <46%. In 2016-17, cover crop containing treatments, excluding forage radish, performed very well across all rating dates ending in >90% suppression 10 WAT. Forage radish did not winterkill during the 2016-17 growing season and provided 35 to 55% suppression across rating dates.

Multiple studies support the finding that cover crops suppress various summer annual weeds as compared to a no cover check after termination. Often in these studies, cereal rye and cereal rye containing mixtures provide better suppression than legumes or forage radish alone (Cornelius et al. 2017; Lawley et al. 2014; Mohler and Teadale 2000; Teasdale and Mohler, 1993; Wayman et al. 2014). The results of this study indicate that for horseweed suppression, hairy vetch and crimson clover are able to suppress horseweed at the same level as cereal rye and cereal rye containing mixtures (Tables 6 and 8).

Flumioxazin + paraquat provided horseweed suppression that was comparable to that of cover crops with 83% suppression at 4 WAT and decreasing to 28% 8 WAT in 2015-16. The next year, flumioxazin + paraquat provided 30 to 45% suppression across all rating dates. Metribuzin + chlorimuron-ethyl provided poor control: <20% horseweed suppression across all rating dates in both years.

These findings are in contrast to those of Cornelius et al. (2017), who found that cover crops have the ability to suppress weeds throughout the soybean season as compared to a no cover check but not more successfully than a fall herbicide program. The fall herbicide treatment used was glyphosate + 2,4-D + sulfentrazone + chlorimuron-ethyl (Cornelius et al. 2017). The difference in herbicide treatment could explain the difference in performance in summer annual weed suppression.

Horseweed Biomass at Harvest. The interaction between year and treatment was significant in corn (p=0.002) but not in soybean (p=0.207), however, both were split by year to be better able to compare horseweed and cover crop biomass data (Table 9). In corn, both years were significant but in soybean, the first year was not significant (p=0.263). For any cover crop monoculture or mixture, with the exception of forage radish alone and crimson clover in the 2016 corn, horseweed biomass present at harvest was less than the nontreated check. In the 2016 corn, the nontreated check had 593 g m^{-2} horseweed biomass and all cover crop treatments had <480 g m^{-2}, with the exception of forage radish and crimson clover, which had >850 g m^{-2} of horseweed biomass at harvest (Table 10). In 2017 in both corn and soybean, the nontreated check had >337 g m^{-2} as compared to <90 g m^{-2} for all other cover crop treatments not including forage radish in monoculture. The metribuzin + chrlorimuon-ethyl treatment had similar horseweed biomass compared to the nontreated check across both years. Results with flumioxazin + paraquat were more variable, performing similarly to the nontreated check in both years of the corn experiment but having less horseweed biomass present in 2016-17 in soybeans.

These findings are in contrast to those of Davis et al. (2007 and 2009), which found that a winter wheat cover crop was not as effective in suppressing horseweed as compared to a fall-applied residual herbicide in both corn and soybean. This study, however, tested different fall-applied herbicides. In 2015-16, flumioxazin + paraquat was comparable to most cover crop treatments. The next year, flumioxazin + paraquat did not provide as much suppression. This lack of activity can be attributed to warmer and wetter winter weather conditions that encouraged herbicide degradation. The increase in horseweed presence in the metribuzin + chlorimuron-ethyl treatment as compared to the nontreated check is similar to what Davis et al. (2010) reported with horseweed populations between fall-applied glyphosate + 2,4-D and their nontreated check. The herbicide application controlled some weed species, which eliminated limitations on elements necessary for plant growth that were taken advantage of by the horseweed.

Soybean and Corn Yield. For soybean yield, no interactions were significant and data were pooled across locations and years (Table 12). Differences in yield between horseweed free and weedy yield were detected for cereal rye, all of the two-way cover crop mixtures, hairy vetch + forage radish + cereal rye, metribuzin + chlorimuron-ethyl, and the nontreated check (Table 13). Every treatment, with the exception of forage radish in monoculture, showed greater yields in the horseweed free blocks as compared to the weedy blocks.

For corn yield, no interactions were significant, therefore data were pooled across locations and years (Table 11). No differences were detected in yield between weedy and horseweed free blocks for all treatments with the exception of forage radish, metribuzin + chlorimuron-ethyl, and the nontreated check (Table 13). In these treatments, the horseweed free subblocks yielded more than the weedy subblocks by at least 1200 kg ha^{-1}.

The differences in corn yield for the forage radish, flumioxazin + paraquat, and nontreated check align with greater horseweed biomass at harvest found within these treatments suggesting that horseweed was the reason for the difference seen in yield. Other research has reported that horseweed can cause losses in yield. Trezzi et al (2013) reported 25% yield loss in soybeans with 13 plants m^{-2} and Steckel and Gwathmey (2009) reported 46% yield losses in cotton with 20 to 25 plants m^{-2}. However, there are more differences seen between horseweed controlled and horseweed not controlled in the soybean yield. This difference could be due to the weediness of the experiment as a whole. No weed control measures were employed, other than spot-treating horseweed in the relevant sub-blocks and in the initial experimental treatments, so the fields were naturally very weedy which could have impacted the yield results.

In summary, cover crop treatments provided greater horseweed suppression in 2016-17 than 2015-16, which could be attributed to lesser horseweed populations in 2015-16 and competition from other weeds present in the plots. All cover crop treatments, with the exception of forage radish alone, provided some suppression of horseweed, although in 2016, that suppression did not persist throughout the cash crop growing season. The fall-applied herbicides in this experiment did not perform as well as cover crops in suppressing horseweed. Flumioxazin + paraquat provided control in 2015-16 but did not perform well in 2016-17, while metribuzin + chlorimuron-ethyl did not suppress horseweed in either year. Incorporation of a cover crop into corn or soybean production could be used as a weed management tactic to suppress horseweed.

Literature Cited

Andersen MC (1993) Diaspore morphology and seed dispersal in several wind-dispersed Asteraceae. Am J Bot 80:487-492

Anonymous (2015) Virginia NRCS Cover Crop Planning Manual 1.0. https://efotg.sc.egov.usda.gov/references/public/VA/VA_TN10_Agronomy.pdf. Accessed: Nov 13, 2017

Bhowmik PC, Bekech MM (1993) Horseweed (*Conyza canadensis*) seed production, emergence, and distribution in no-tillage and conventional-tillage corn (*Zea mays*). Agronomy (Trends in Agricultural Science) 1:67-71

Brown SM, Whitwell T (1988) Influence of tillage on horseweed, *Conyza canadensis*. Weed Technol 2:269-270

Bruce JA, Kells JJ (1990) Horseweed (*Conyza canadensis*) control in no-tillage soybeans (*Glycine max*) with preplant and preemergence herbicides. Weed Technol 4:642-647

Cornelius CD, Bradley KW (2017) Influence of various cover crop species on winter and summer annual weed emergence in soybean. Weed Technol 31:503-513

Dauer JT, Mortensen DA, Humston R (2006) Controlled experiments to predict horseweed (*Conyza canadensis*) dispersal distances. Weed Sci 54:484-489

Davis VM, Gibson KD, Bauman TT, Weller SC, Johnson WG (2007) Influence of weed management practices and crop rotation on glyphosate-resistant horseweed population dynamics and crop yield. Weed Sci 55:508-516

Davis VM, Johnson WG (2008) Glyphosate-resistant horseweed (*Conyza canadensis*) emergence, survival, and fecundity in no-till soybean. Weed Sci 56:231-236

Davis VM, Kruger GR, Stachler JM, Loux MM, Johnson WG (2009) Growth and seed production of horseweed (*Conyza canadensis*) populaitons resistant to glyphosate, ALS-inhibiting, and multiple (Glyphosate + ALS-Inhibiting) herbicides. Weed Sci 57:494-504

Davis VM, Kruger GR, Young BG, Johnson WG (2010) Fall and spring preplant herbicide applications influence spring emergence of glyphosate-resistant horseweed (*Conyza canadensis*). Weed Technol 24:11-19

Flint JL, Witt WW (1997) Microbial degradation of imazaquin and imazethapyr. Weed Sci 45:586-591

Frans R, Talbert R, Marx D, Crowley H (1986) Experimental design and techniques for measuring and analyzing plant responses to weed control practices. P 29-46 in Camper ND ed. Research Methods in Weed Science. 3rd ed. Southern Weed Sci Society

Górski T, Górska K, Nowicki J (1977) Germination of seeds of various herbaceous species under leaf canopy. Flora 166:249-259

Hayden ZD, Brainard DC, Henshaw B, Ngouajio M (2012) Winter annual weed suppression in rye–vetch cover crop mixtures. Weed Technol 26:818-825

Heap I (2017) The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/Summary/Species.aspx Accessed: August 28, 2017

Kruger GR, Davis VM, Weller SC, Stachler JM, Loux MM, Johnson WG (2008) Frequency, distribution, and characterization of horseweed (*Conyza canadensis*) biotypes with resistance to glyphosate and ALS-inhibiting herbicides. Weed Sci 57:652-659

Lawley YE, Weil RR, Teasdale JR (2012) Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. Agron J 103:137-144

Loux MM, Reese KD (1992) Effect of soil pH on adsorption and persistence of imazaquin. Weed Sci 40:490-496

Mirsky SB, Ryan MR, Teasdale JR, Curran WS, Reberg-Horton CS, Spargo JT, Wells MS, Keene CL, Moyer JW (2013) Overcoming weed management challenges in cover crop–based organic rotational no-till soybean production in the Eastern United States. Weed Technol 27:193-203

Mohler CL, Teasdale JR (1993) Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. Weed Res 33:487-499

Moseley CM, Hagood Jr. ES (1990) Horseweed (*Conyza canadensis*) control in full-season no-till soybeans (*Glycine max*). Weed Technol 4:814-818

Moyer JR, Coen G, Dunn R, Smith AM (2010) Effects of landscape position, rainfall, and tillage on tesidual herbicides. Weed Technol 24:361-368

Nandula VK, Eubank TW, Poston DH, Koger CH, Reddy KN (2006) Factors affecting germination of horseweed (*Conyza canadensis*). Weed Sci 54:898-902

Owen LN, Steckel LE, Koger CH, Main CL, Mueller TC (2009) Evalutation of spring and fall burndown application timings on control of glyphosate-resistant horseweed (*Conyza canadensis*) in no-till cotton. Weed Technol 23:335-339

Regehr DL, Bazzaz FA (1979) The population dynamics of *Erigeron canadensis*, a successional winter annual. J Ecol 67:923-933

Shaner D, Hager A (2014) Detecting and confirming accelerated atrazine dissipation in Illinois. Weed Technol 28:432-434

Steckel LE, Gwathmey CO (2009) Glyphosate-resistant horseweed (*Conyza canadensis*) growth, seed production, and interference in cotton. Weed Sci 57:346-350

Teasdale JR, Mohler CL (2000) The quantitative releationship between weed emergence and the physical properties of mulches. Weed Sci 48:385-392

Trezzi M, Balbinot Jr. A, Benin G, Debastiani F, Patel F, Miotto Jr. E (2013) Competitive ability of soybean cultivars with horseweed (*Conyza bonariensis*). Planta Daninha 31:543-550

VanGessel MJ (2001) Glyphosate-resistant horseweed from Delaware. Weed Sci 49:703-705

Wayman S, Cogger C, Benedict C, Burke I, Collins D, Bary A (2014) The influence of cover crop variety, termination timing and termination method on mulch, weed cover and soil nitrate in reduced-tillage organic systems. Renew Agr Food Syst 30:450-460

Weber JB (1990) Behavior of dinitroaniline herbicides in soils. Weed Technol 4:394-406

Wiggins MS, Hayes RM, Steckel LE (2016) Evaluating Cover crops and herbicides for glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) control in cotton. Weed Technol 30: 415-422

Table 1. Effects table for horseweed counts in Blacksburg and Blackstone, Virginia in 2016 and 2017.

Model Effects	Blacksburg	Blackstone
	---------probability > F-----------	
Block	0.885	0.135
Year	-[a]	0.666
Treatment	**<0.001**	**0.004**
Year*Treatment[b]	-	ns[c]

[a] - denotes a term not included in the model.

[b] * denotes an interaction.

[c] Abbreviation: ns, term not significant and removed from the model.

Table 2. Horseweed counts taken at the end of the cover crop growing season in Blacksburg and Blackstone, Virginia in 2016 and 2017.

Treatment	Blacksburg [a]	Blackstone [b]
	------------plants m^{-2}	-----------
Cereal Rye	1 cd	2 c
Crimson Clover	0 d	4 c
Hairy Vetch	7 cd	10 bc
Forage Radish	52 bc	16 abc
Crimson Clover + Cereal Rye	2 cd	4 c
Hairy Vetch + Cereal Rye	2 cd	1 c
Forage Radish + Cereal Rye	3 cd	0 c
Crimson Clover + Forage Radish + Cereal Rye	4 cd	0 c
Hairy Vetch + Forage Radish + Cereal Rye	7 cd	3 c
Flumioxazin + Paraquat	34 cd	7 c
Metribuzin + Chlorimuron-ethyl	153 a	27 a
Nontreated Check	94 b	26 ab
p-value	<0.001	0.004

[a] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

[b] Blackstone data were pooled across 2016 and 2017.

Table 3. Effects table for cover crop biomass in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 field experiments.

Model Effects	2015-16	2016-17
	----------probability > F------------	
Block	0.573	**0.002**
Location	- [a]	**<0.001**
Treatment	**<0.001**	**<0.001**
Location*Treatment[b]	-	ns[c]

[a] - denotes a term not included in the model.

[b] * denotes an interaction.

[c] Abbreviation: ns, term not significant and removed from the model.

Table 4. Cover crop biomass prior to cash crop planting in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 field experiments.

Treatment	2015-16[a]	2016-17[b]
	----------kg ha^{-1}------------	
Cereal Rye	7413 ab	7801 bc
Crimson Clover	2077 d	3431 e
Hairy Vetch	1194 de	4940 de
Forage Radish	0 e	217 f
Crimson Clover + Cereal Rye	5277 c	9496 ab
Hairy Vetch + Cereal Rye	7916 a	8265 bc
Forage Radish + Cereal Rye	5498 c	6711 cd
Crimson Clover + Forage Radish + Cereal Rye	5823 bc	7636 bc
Hairy Vetch + Forage Radish + Cereal Rye	4167 c	11449 a
p-value	<0.001	<0.001

[a] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

[b] Data were pooled across Blacksburg and Blackstone locations.

Table 5. Effects table for visible horseweed suppression ratings in soybean in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 field experiments.

		2015-16			2016-17		
Model Effects	4 WAT	6 WAT	8 WAT	4 WAT	6 WAT	8 WAT	10 WAT
		--------------------------------------	-probability > F-	-------------------------------------			
Block	**0.012**	0.084	**0.001**	0.327	0.893	0.274	0.121
Location	- [a]	-	-	0.108	**0.046**	0.201	0.355
Treatment	**<0.001**	**<0.001**	**0.013**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Location*Treatment [b]	-	-	-	ns [c]	ns	ns	ns

[a] - denotes a term not included in the model.

[b] * denotes an interaction.

[c] Abbreviation: ns, term not significant and removed from the model.

Table 6. Visible horseweed suppression ratings in soybean in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 field experiments.

	2015-16[a]			2016-17[b]			
Treatment	4 WAT [c]	6 WAT	8 WAT	4 WAT	6 WAT	8 WAT	10 WAT
	-------------------------------% suppression-------------------------------						
Cereal Rye	69 ab	41 ab	5 b	100 a	83 a	96 a	95 a
Crimson Clover	64 ab	30 bc	25 ab	96 a	98 a	99 a	94 a
Hairy Vetch	70 ab	58 ab	44 a	98 a	100 a	99 a	100 a
Forage Radish	0 c	0 c	0 b	36 b	49 bc	53 b	49 b
Crimson Clover + Cereal Rye	54 b	64 a	43 a	100 a	86 a	98 a	98 a
Hairy Vetch + Cereal Rye	80 a	63 ab	46 a	100 a	98 a	96 a	99 a
Forage Radish + Cereal Rye	81 a	61 ab	21 ab	100 a	74 ab	98 a	95 a
Crimson Clover + Forage Radish + Cereal Rye	76 ab	71 a	40 a	100 a	85 a	96 a	96 a
Hairy Vetch + Forage Radish + Cereal Rye	78 ab	63 ab	44 a	100 a	86 a	100 a	96 a
Metribuzin + Chlorimuron-ethyl	13 c	0 c	0 b	0 c	19 c	8 c	6 c
Flumioxazin + Paraquat	83 a	56 ab	28 ab	31 b	46 bc	44 b	42 b
p-value	<0.001	0.0002	0.013	<0.001	<0.001	<0.001	<0.001

[a] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

[b] Data were pooled across Blacksburg and Blackstone location.

[c] Abbreviation: WAT, weeks after termination.

Table 7. Effects table for visible horseweed suppression ratings in corn in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 field experiments.

	2015-16			2016-17			
Model Effects	4 WAT	6 WAT	8 WAT	4 WAT	6 WAT	8 WAT	10 WAT
	----------probability > F----------						
Block	**0.039**	0.455	**<0.001**	0.609	0.211	0.408	0.349
Location	- [a]	-	-	0.112	0.911	0.564	0.064
Treatment	**<0.001**	**0.001**	**0.003**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Location*Treatment [b]	-	-	-	ns [c]	ns	ns	ns

[a] - denotes a term not included in the model.

[b] * denotes an interaction.

[c] Abbreviation: ns, term not significant and removed from the model.

Table 8. Visible horseweed suppression ratings in corn in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 field experiments.

	2015-16[a]			2016-17[b]			
Treatment	4 WAT [c]	6 WAT	8 WAT	4 WAT	6 WAT	8 WAT	10 WAT
	----------------------------% suppression-------------------------------						
Cereal Rye	60 bc	41 ab	11 cd	97 a	96 a	98 a	98 a
Crimson Clover	60 bc	24 bc	23 bcd	93 a	85 a	86 a	96 a
Hairy Vetch	73 abc	59 ab	38 abc	99 a	100 a	99 a	98 a
Forage Radish	0 d	0 c	4 d	43 b	45 b	46 b	56 b
Crimson Clover + Cereal Rye	49 c	58 bc	35 abc	98 a	84 a	99 a	98 a
Hairy Vetch + Cereal Rye	83 ab	63 a	53 a	100 a	100 a	100 a	100 a
Forage Radish + Cereal Rye	83 ab	59 ab	36 abc	98 a	98 a	96 a	98 a
Crimson Clover + Forage Radish + Cereal Rye	74 ab	71 a	38 abc	100 a	100 a	99 a	100 a
Hairy Vetch + Forage Radish + Cereal Rye	78 ab	64 a	48 ab	99 a	100 a	100 a	100 a
Metribuzin + Chlorimuron-ethyl	13 d	0 c	5 d	3 c	0 c	0 c	3 d
Flumioxazin + Paraquat	90 a	43 ab	50 a	31 b	34 b	19 c	30 c
p-value	<0.001	0.001	0.003	<0.001	<0.001	<0.001	<0.001

[a] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

[b] Data were pooled across Blacksburg and Blackstone locations.

[c] Abbreviation: WAT, weeks after termination.

Table 9. Effects test for horseweed biomass collected at corn and soybean harvest in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 experiments.

	Soybean		Corn	
Model Effects	2015-16	2016-17	2015-16	2016-17
	---------------------probability > F--------------------			
Block	0.345	0.065	0.207	**0.022**
Location	- [a]	0.059	-	0.461
Treatment	0.263	**<0.001**	**<0.001**	**<0.001**
Location*Treatment [b]	-	ns [c]	-	ns

[a] - denotes a term not included in the model.

[b] * denotes an interaction.

[c] Abbreviation: ns, term not significant and removed from the model.

Table 10. Horseweed biomass at corn and soybean harvest in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 field experiments.

Treatment	Soybean[a]		Corn[b]	
	2015-16	2016-17	2015-16	2016-17
	-------------------------g m^{-2}-------------------------			
Cereal Rye	569	53 b	489 cd	90 bc
Crimson Clover	319	16 b	855 abc	21 c
Hairy Vetch	180	5 b	480 cd	4 c
Forage Radish	599	123 b	880 ab	215 ab
Crimson Clover + Cereal Rye	701	3 b	384 de	0 c
Hairy Vetch + Cereal Rye	460	7 b	71 e	7 c
Forage Radish + Cereal Rye	725	11 b	344 de	14 c
Crimson Clover + Forage Radish + Cereal Rye	182	11 b	292 de	0 c
Hairy Vetch + Forage Radish + Cereal Rye	341	5 b	319 de	0 c
Flumioxazin + Paraquat	831	74 b	327 de	268 a
Metribuzin + Chlorimuron-ethyl	310	305 a	1011 a	356 a
Nontreated Check	644	359 a	593 bcd	337 a
p-value	0.263	<0.001	<0.001	<0.001

[a] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

[b] Data were pooled across Blacksburg and Blackstone locations for both soybean and corn.

Table 11. Effects table for corn yield in Blacksburg and Blackstone, Virginia in 2016 and 2017.

Model Effects	Cereal Rye (CR)	Crimson Clover (CC)	Hairy Vetch (HV)	Forage Radish (FR)	CC + CR	HV + CR	FR + CR	CC + FR + CR	HV + FR + CR	Metribuzin + Chlorimuron-ethyl	Flumioxazin + Paraquat	Nontreated Check
				---probability > F--								
Block	0.423	0.743	0.975	0.357	0.678	0.593	0.056	0.147	0.378	0.527	0.466	0.389
Location	**0.001**	0.2	0.216	0.171	**0.018**	**0.003**	**<0.001**	**<0.001**	**<0.001**	**0.009**	0.11	0.118
Year	**0.028**	**0.037**	0.103	0.106	0.243	**0.044**	**0.011**	**0.02**	**0.043**	**0.04**	0.296	**0.04**
Weed/Weed Free	0.075	0.148	0.971	**0.001**	0.204	0.454	0.319	0.299	0.767	**<0.001**	0.067	**<0.001**
Location*Weed/Weed Free [a]	ns [b]	ns	ns	ns	ns	ns	ns	ns	ns	**0.011**	ns	ns
Year*Weed/Weed Free	ns	ns	ns	**0.4**	ns	ns	ns	ns	ns	ns	ns	**0.015**

[a] * denotes an interaction.

[b] Abbreviation: ns, term not significant and removed from the model.

Table 12. Effects table for soybean yield in Blacksburg and Blackstone, Virginia in 2016 and 2017.

Model Effects	Cereal Rye (CR)	Crimson Clover (CC)	Hairy Vetch (HV)	Forage Radish (FR)	CC + CR	HV + CR	FR + CR	CC + FR + CR	HV + FR + CR	Metribuzin + Chlorimuron-ethyl	Flumioxazin + Paraquat	Nontreated Check
	--probability > F--											
Block	0.405	0.351	**0.023**	0.186	**0.006**	0.134	0.276	0.626	**0.025**	0.574	0.056	**0.008**
Location	0.45	0.968	0.943	0.582	**0.005**	0.418	0.731	0.989	0.137	0.075	0.38	**0.003**
Year	0.129	0.261	0.779	0.454	**0.005**	0.373	0.292	0.884	**0.011**	0.118	**0.017**	**0.002**
Weed/Weed Free	**0.025**	0.155	0.059	**0.024**	**0.023**	**0.045**	**0.002**	0.052	**0.018**	**0.03**	0.152	**0.01**
Location*Weed/Weed Free [a]	ns [b]	ns	ns	ns	ns	ns	**0.017**	ns	ns	ns	ns	ns
Year*Weed/Weed Free	ns	ns	ns	ns	ns	ns	**0.021**	ns	ns	ns	ns	ns

[a] * denotes an interaction.

[b] Abbreviation: ns, term not significant and removed from the model.

Table 13. Corn and soybean yield from weedy and weed free subblocks in Blacksburg and Blackstone, Virginia in 2016 and 2017.

	Cereal Rye (CR) [a]	Crimson Clover (CC)	Hairy Vetch (HV)	Forage Radish (FR) [b]	CC + CR	HV + CR	FR + CR	CC + FR + CR	HV + FR + CR	Metribuzin + Chlorimuron-ethyl	Flumioxazin + Paraquat	Nontreated Check
	--------	--------	--------	--------	--------	--------	kg ha^{-1}	--------	--------	--------	--------	--------
Corn												
Weed Free	3979	4248	2694	3116 a	4724	4129	4076	4950	4994	4192 a	3422	2427 a
Weedy	2592	2546	2659	279 b	3242	3455	3937	3858	5316	374 b	1433	1183 b
p-value	0.075	0.148	0.971	0.04	0.203	0.454	0.319	0.298	0.767	<0.001	0.067	<0.001
Soybean												
Weed Free	1138 a	887	753	105 a	1087 a	1062 a	1196 a	969	833 a	709 a	674	764 a
Weedy	331 b	442	343	334 b	452 b	502 b	303 b	469	411 b	139 b	291	209 b
p-value	0.025	0.155	0.059	0.024	0.023	0.045	0.002	0.052	0.018	0.03	0.152	0.01

[a] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected

$LSD_{\alpha=0.05}$.

[b] Data were pooled across locations and years.

Cover Crop Litter Components and their Effect on Summer Annual Weed Suppression in Corn and Soybean

Abstract

Cover crop residue can act as a mulch and suppress weeds by reducing sunlight, decreasing soil temperature, and providing a physical barrier for growth. As this residue degrades, the stress put on weed species is reduced and weed suppression diminishes. Biomass of cover crop residue is positively correlated to weed suppression, but little research is available regarding the composition of cover crop residue and the potential effects on weed suppression. Field experiments were conducted in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 to evaluate summer annual weed suppression from different cover crop monocultures and mixtures and determine if cover crop litter properties contribute to weed suppression. Cover crop monocultures and mixtures of cereal rye, crimson clover, hairy vetch, and forage radish were planted in the fall and terminated in late spring. After termination, corn and soybeans were planted. At cover crop termination, samples were taken to determine biomass, carbon to nitrogen (C:N) ratio, and percent lignin of the cover crop residue. Visible weed suppression ratings and residue thickness measurements were taken on two-week intervals following cover crop termination for 10 weeks. At 6 weeks after termination (WAT), cover crop treatments containing cereal rye provided between 55 and 86% weed suppression. When considering the analysis of the components, percentage of lignin as well as biomass of the cover crop contributed to weed suppression in soybeans 6 WAT. Initial C:N ratio as well as lignin were important in determining residue thickness 6 WAT. In the weed free subblocks there was no difference detected between treatments in corn or soybean yield. These results indicate that cover crops can suppress summer

annual weeds without impacting cash crop yield and that cover crop quality (i.e. lignin content and C:N ratio) as well as quantity (biomass) are important for weed suppression.

Cover crops can provide many agroecosystem benefits such as reducing soil erosion, increasing soil organic matter, and increasing nitrogen and water use efficiency in subsequent crops (Burket et al. 1997; Dabney et al. 2001; Miguez and Bollero 2005). Cover crop species are selected to fulfill a certain need and inherently have different benefits and characteristics. Forage radish (*Raphanus sativus* L.) roots can grow through compacted soils and provide channels for subsequent crop roots to grow deeper (Chen and Weil 2010; William and Weil 2004). Cereal rye (*Secale cereale* L.), in addition to high biomass accumulation, also has allelopathic compounds, specifically benzoxazinoids, which inhibit plant growth and may be especially useful in organic weed management (Schulz et al. 2013). Legumes, such as crimson clover (*Trifolium incarnatum* L.) and hairy vetch (*Vicia villosa* Roth), can contribute nitrogen to subsequent cash crops (Coombs et al. 2017; Ranells and Wagger 1996). Mixes of different species can reap the benefits of more than just one species and can lead to an increase in biomass accumulation (Finney et al. 2016; Sainju et al. 2005).

Another potential benefit of cover crops is suppression of weeds, which can cause up to 50% yield loss in both corn and soybean production (Soltani et al. 2016, 2017). There are two main periods of weed suppression offered by cover crops: the first while the cover crop is actively growing; the second, which is the focus herein, is after the cover crop is terminated, and the residue creates mulch layer on the soil surface (Hayden et al. 2012; Mirsky et al. 2013). This mulch layer reduces the amount of sunlight that reaches the soil surface, reduces soil temperature, and provides a physical barrier for weed seedlings (Mirsky et al. 2013; Mohler and Teasdale 1993; Teasdale and Mohler 2000). This layer can result in the delayed germination of weed seeds (Bhowmik and Bekech 1993). In general, more biomass will result in greater weed suppression (Finney et al. 2016; Mohler and Teasdale 1993). However, as the cover crop residue degrades, the mulch layer becomes thinner and weed suppression effects diminish (Mohler and Teasdale 1993).

At termination, cover crop residue begins to break down, the rate of which depends on climate, litter chemistry, and soil organisms among other factors (Lavelle et al. 1993; Swift et al. 1979). When determining the mass-loss relationships of residue, most established patterns for decay correlate to the initial ratios of C:N, lignin:N or lignin:cellulose (Aerts 1997; Hobbie 2008; Melillo et al. 1982). Nitrogen and phosphorus are degradation rate-enhancing factors while lignin is thought of as a rate-retarding compound (Fogel and Cromack 1977). Nitrogen eliminates limitations on decomposers to break down the carbon contained in the residue while lignin and other carbon compounds protect the more easily broken down components within the cell walls (Berg and McClaugherty 2003).

Cover crop species also have different propensities for biomass accumulation and quality traits like carbon-to-nitrogen (C:N) ratios, lignin, cellulose, and hemicellulose content, suggesting they may vary in litter decomposition and thus weed suppression (Clark 2012). Research indicates that biomass is positively correlated with weed suppression and C:N ratios are positively correlated with nitrogen retention during the cover crop growing season. However, C:N ratios have also been found to be negatively correlated with corn yield (Finney et al. 2016). While research has shown that >75% of annual weed emergence is reduced when biomass residue rates exceed 8,000 kg ha^{-1}; though, it is not known what role litter quality contributes to weed suppression or duration of that suppression (Mirsky et al. 2013; Teasdale and Mohler 2000). The objective of this study is to evaluate the differences in biomass accumulation and litter components of monocultures and mixtures of cereal rye, hairy vetch, crimson clover, and forage radish and correlate these quantity and quality metrics to duration of weed suppression after termination.

Materials and Methods

Study Sites. Studies were conducted to evaluate summer annual weed suppression from fall-planted cover crops after termination and determine the duration of weed suppression based on cover crop residue quantity and quality. Field experiments were conducted in Blacksburg, Virginia at Kentland Farms (37.192913, -80.573942) in a Ross soil (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls) in the New River flood plain and Blackstone, Virginia at the Southern Piedmont Agricultural and Research Extension Center (37.082840, -77.972062) in a Durham coarse sandy loam (fine-loamy, siliceous, semiactive, thermic Typic Hapludults). The Blacksburg location was previously in corn and was planted no-till while the Blackstone field was previously in sod and was prepped for planting by disking the area to create a seedbed for planting. Both sites received a pre-plant application of glyphosate (Roundup Powermax, Monsanto Company, St. Louis, MO) at 1.26 kg ae ha^{-1}.

Experimental Design. To evaluate how biomass and litter components affect weed suppression after termination, a split-split block experiment with 4 replications were implemented. The main treatment, implemented as a randomized complete block design, was the cover crop monoculture or mixture. These large blocks were split by cash crop, which was either corn (*Zea mays* L.) or soybeans (*Glycine max* L. Merr.). The cash crop subblocks were split again and maintained in weedy and weed free subblocks after cover crop termination through the duration of the experiment. Area of the main cover crop treatment blocks was 46.4 m^2 , cash crop subblocks were 23.2 m^2, and weedy/weed free subblocks were 11.6 m^2.

Treatments. The experiment had 9 treatments and a no cover check. Cover crop treatments consisted of monocultures of cereal rye, hairy vetch, crimson clover, forage radish, and mixtures of these cover crops (Table 14). Seeds were purchased from Green Cover Seeds (Bladen, NE) and varieties are as listed: cereal rye (Elbon South), forage radish (Nitroradish), hairy vetch (TNT), and crimson clover (Dixie). A no cover crop treatment was included as a control. Seeding rates are on the high end of the recommended range suggested by the Virginia Department of Agriculture and Consumer Sciences (Anonymous 2015).

Plot Maintenance and Data Collection. For this experiment, cover crops were drilled on October 22, 2015 in Blacksburg and October 20, 2015 in Blackstone. In 2016, the experiment were planted on September 28th and October 14th in Blacksburg and Blackstone, respectively.

Cover crops were terminated on April 26, 2016 and May 3, 2016 in Blacksburg and Blackstone, respectively. In 2017, termination occurred on April 26 and May 2 for Blackstone and Blacksburg, respectively. The cover crops were terminated using a roller crimper followed by an application of glyphosate (Roundup Powermax; Monsanto Company, St. Louis, MO) at 1.26 kg ae ha^{-1}. Prior to termination, above ground biomass samples were taken from a 0.09 m^2 area, separated into individual cover crop species, and dried for mass determination.

After drying, each sample was weighed. Cover crop samples were then coarsely ground, homogenized, and subsequently analyzed for carbon, nitrogen, lignin, cellulose, and hemicellulose content (Feed and Water Analysis Lab; University of Georgia). For two and three cover crop species mixtures, carbon, nitrogen, lignin, cellulose, and hemicellulose content were determined by using the mass of each species in the sample to calculate a weighted average for the whole sample.

Corn and soybeans were planted approximately two weeks after termination: May 9, 2016 in Blacksburg and May 19, 2016 in Blackstone. In 2017, planting dates were May 10th and May 15th in Blackstone and Blacksburg, respectively. The cash crops were planted on 76 cm rows with four rows of cash crop per plot. Corn, variety P1197AM (DuPont Pioneer; Johnston, IA) in 2016 and variety DKC62-08 (DeKalb; DeKalb, IL) in 2017, was planted at 61,775 seeds ha^{-1}. Soybeans, variety P46T21R (DuPont Pioneer) in 2016 and variety AG48X7 (Asgrow; Kalamazoo, MI) in 2017, were planted at 327,408 seeds ha^{-1}. Both corn and soybean blocks received 22.7 kg of 0-25-25 at planting. Corn blocks received a total of 54.54 kg of 46-0-0 split applied at planting and again when the corn reached 0.3 m in height.

To control weeds in the weed free sub-blocks, preemergence herbicides were applied at planting. Atrazine at 1.48 kg ai ha^{-1} + *S*-metolachlor at 1.43 kg ai ha^{-1} + mesotrione at 0.19 kg ai ha^{-1} (Lexar EZ; Syngenta Crop Protection, LLC, Greensboro, NC) were applied in corn blocks and sulfentrazone at 0.305 kg ai ha^{-1} + chlorimuron-ethyl at 0.038 kg ai ha^{-1} (Authority XL; FMC Corporation, Philadelphia, PA) were applied in the soybean blocks. Both corn and soybean weed free blocks were maintained with glyphosate (Roundup Powermax; Monsanto Company) at 1.26 kg ae ha^{-1} postemergent applied throughout the season as needed whenever weeds reached 10 cm in height.

After termination, visible weed suppression ratings were taken every two weeks until the cover crops no longer suppressed weeds as compared to the no cover crop check. Suppression ratings were assessed on a scale of 0 to 100 with 0 being no suppression and 100 being complete suppression compared to the no cover crop check (Frans et al. 1986). At the same time as the visible weed suppression ratings, height measurements of the cover crop residue were taken in three random subsamples per plot to assess the thickness of the residue over time. Data analysis focused on 6 weeks after termination (WAT) data, which was 4 weeks after cash crop planting in each experiment. This time was chosen as this is typically when postemergent herbicide applications are made.

The middle two rows of the cash crop were harvested for yield. In Blackstone, corn was harvested on September 15, 2016 and October 3, 2017. Soybeans were harvested on October 13, 2016 and October 23, 2017. In Blacksburg, corn was harvested on October 26 2016 and October 17 2017 and soybeans were harvested on November 17, 2016 and October 27, 2017. Harvest weights were adjusted to 15.5% moisture for corn and 13% for soybeans.

Data were analyzed using JMP (JMP Pro 12; SAS Institute, Inc., Cary, NC). For the visible weed suppression data analysis, the no-cover check was excluded. Treatment, year, location, block, and interactions of year and location with treatment were included in the model. If the overall ANOVA was significant, a means separation was used with Fisher's Protected $LSD_{\alpha=0.05}$ to compare across treatments.

To analyze the predictors of weed suppression in the visible rating data, there was a high percentage of 0s, which prevented normality of the data set. Forage radish and no-cover check treatments were excluded from the analysis because there was no biomass at cover crop termination. First a 0, no weed suppression, or 1, any weed suppression present, was assigned to all data points and generalized linear model with a binomial distribution and logit link was used to detect what treatments had no weed suppression 6 WAT. Those data points were then excluded for the second part of the analysis. Subsequently, the remaining data, were normalized by using an arcsine transformation. Treatment, block, year, location, interactions of treatment with year and location, as well as nested effects of biomass, C:N ratio, and percent lignin in treatment were included in the model. For the residue thickness data, the data had to be log-transformed for normality. The model effects were treatment, block, year, location, interactions of treatment with year and location, as well as nested effects of biomass, C:N ratio, and percent lignin within treatment. The no-cover check and forage radish plots were excluded from this analysis as well.

For cash crop yield, weedy and weed free yield were assessed separately. Main effects of year, location, treatment, and block as well as interactions between year and treatment as well as location by treatment were included in the model. If the overall ANOVA was significant, a means separation using Fischer's Protected $LSD_{\alpha=0.05}$ was used to investigate treatment differences.

Results and Discussion

Cover Crop Biomass and Litter Components. Biomass ranged from 3663 to 8751 kg ha^{-1} with cereal rye and cereal rye containing mixtures having more biomass than crimson clover or hairy vetch alone (Table 15). Cereal rye alone had greater percent total carbon and carbon containing compounds as compared to the rest of the treatments. Hairy vetch and crimson clover had the lowest carbon with the mixtures falling in the middle range. The legumes had greater percent total nitrogen than cereal rye alone or any mixtures containing cereal rye. The C:N ratio of cereal rye alone was 36:1 and hairy vetch and crimson clover had C:N ratios of 17:1 and 12:1, respectively. The mixtures of cereal rye and a legume fell between this range.

The biomass and C:N ratios found in this experiment are similar to those found by Sainju et al. (2005) and Finney et al. (2016) in Pennsylvania and Georgia with biomasses ranging from 2,000 to 8,000 kg ha^{-1} for monocultures and mixtures like those included in this experiment. The C:N ratios also align with those seen in this experiment ranging from 10 to 57, with legumes having lower C:N ratios than grasses and mixtures between the two falling into that middle range (Finney et al. 2016; Sainju et al. 2005).

Visible Weed Suppression. For both corn and soybean, there was a significant location by treatment interaction (p<0.001) 6 WAT, so data are presented separately by location but pooled across years (Table 16). In Blacksburg, the predominant summer annual weed species that composed visible weed suppression ratings were large crabgrass (*Digitaria sanginalis* L. Scop.), pitted morningglory (*Ipomoea lacunosa* L.), and redroot pigweed (*Amaranthus retroflexus* L.). Treatment was significant (p<0.001). Cereal rye alone and cover crop mixtures containing cereal rye resulted in 66 to 85% weed suppression, which was greater than hairy vetch, crimson clover, and forage radish alone in which weed suppression was <18% for both corn and soybean ratings (Table 17). In Blackstone, where the predominant weed species were large crabgrass and carpetweed (*Mollugo verticillata* L.), treatment was also significant (p<0.001) for both corn and soybeans. Cereal rye alone provided 79% weed suppression in soybeans and 81% suppression in corn. Hairy vetch and crimson clover performed similarly to cereal rye containing mixtures providing 46 to 63% weed suppression. Forage radish alone afforded <20% weed suppression (Table 17).

These results are similar to those of Mohler and Teasdale (1993) where any cover crop initially suppressed weeds but cereal rye was better able to suppress weeds for longer as compared to hairy vetch. The hairy vetch cover crop decomposed more quickly than the rye, allowing for greater weed emergence later in the cash crop growing season.

Impact of Litter Components on Weed Suppression. Comparing across possible predictors of weed suppression, biomass, lignin, and C:N ratio were chosen because they are not strongly correlated with one another as indicated by coefficient of determination values <0.3 (data not shown).

The generalized linear model showing presence or absence of weed suppression 6 WAT in soybeans was significant ($p<0.001$) and a contingency plot indicates that 38% of hairy vetch and crimson clover plots did not provide any weed suppression. With those data excluded, the nested effect of C:N ratio in treatment was not significant ($p=0.343$) and was removed from the model (Table 18). The nested effect of biomass and lignin within treatment were both significant ($p=0.004$ and $p=0.045$, respectively). The significance of these nested values indicate that there is a relationship between both biomass and lignin with weed suppression 6 WAT. This also indicates that C:N ratio is not associated with weed suppression in soybeans at this time.

Weed suppression in corn ratings 6 WAT do not follow the same pattern as the soybeans; none of the nested effects were significant (Table 18). This would indicate that cover crop biomass, C:N ratio, and lignin are not associated with weed suppression 6 WAT in corn. This is most likely due to the nitrogen applications made in corn that were not made in soybean. This excess nitrogen could have encouraged weed growth and increased degradation of the cover crop residue as seen in research by Poffenbarger et al. (2015).

Log-transformed residue thickness 6 WAT in the nested effects of lignin and C:N ratio within treatment was significant ($p=0.024$ and $p=0.032$, respectively) but not in biomass at termination ($p=0.179$) (Table 18). This finding indicates that cover crop residue thickness 6 WAT is more closely associated with C:N ratio and lignin content than biomass.

While biomass is repeatedly associated with weed suppression, it might not be the only factor that is important (Finney et al. 2016; Mohler and Teasdale 1993). Lignin content, often studied in forestry settings, is known an important indicator of loss of mass over time (Hobbie

2008; Melillo et al. 1982). Current findings support that cover crop quality, as well as quantity, is important as an indicator of weed suppression.

Cash Crop Yield. In each treatment, the corn and soybean yields were greater in the weed free subblocks than in the weedy subblocks. In the plots where weeds were allowed to grow throughout the season, there was a significant location by treatment interaction for the corn yield (p=0.01) but not for soybean yield (p=0.499) (Table 19). With the corn yield analyzed separately by location, treatment was significant (p<0.001) for the Blacksburg location. Yields were greater in plots with a cover crop than those without a cover crop (forage radish alone and no cover check (Table 20). This difference is attributed to the cover crop suppressing weeds through the early part of the season so weeds did not compete with the corn until later, potentially after the critical weed free period for corn had passed. The critical weed free period for corn is from the 3-leaf stage to the 14-leaf stage (Hall et al. 1992; Gantoli et al. 2013). The main effect of treatment was not significant for soybean yield (p=0.108) (Table 20). The critical weed free period for soybean falls between V4 and R3 growth stages (Van Acker et al. 1993; Mulugeta and Boerboom 2000). The later critical weed free period for soybean allowed time for the cover crop residue to degrade and for weeds to grow and compete with the soybeans whereas the residue suppressed weeds through part of if not all of the critical weed free period for corn.

For the weed free yield, there was no significant interaction between year and treatment and location and treatment for both corn and soybean yields so data were pooled across both treatment and location. Treatment was not significant for corn (p=0.139) or soybean (p=0.723) indicating that cover crops did not impact cash crop yield relative to the no cover check. Corn yields ranged from 2881 to 5703 kg ha^{-1} and soybean yields ranged from 1649 to 2078 kg ha^{-1} (Table 20). Previous research indicates winter cover crops can have variable responses on corn yield, increasing, decreasing, or having no effect (Miguez and Bollero 2005; Finney et al. 2016). In soybean production, cover crops also haven't shown positive or negative effects on yield in the first year, which match the results found in this experiment (Reddy 2001; Reddy et al. 2003; Wortman et al. 2012). These results indicate that in the first year of implementation that cover crops do not have an effect on corn or soybean yield.

In summary, cover crops, specifically cereal rye and cereal rye containing mixtures, have the ability to suppress summer annual weeds >60% through 6 WAT, which is 4 weeks after cash crop planting without negatively impacting corn or soybean yield. Predictors for determining the level of weed suppression that can be obtained is variable with biomass, C:N ratio, and lignin all showing the possibility to be associated with weed suppression or residue thickness.

Literature Cited

Aerts R (1997) Climate, leaf litter chemistry and leaf litter decomposition in terrestrial ecosystems-a triangular relationship. Oikos 79:439-449

Anonymous (2015) Virginia NRCS Cover Crop Planning Manual 1.0. https://efotg.sc.egov.usda.gov/references/public/VA/VA_TN10_Agronomy.pdf. Accessed: Nov 13, 2017

Berg B, McClaugherty C (2003) Plant litter: decomposition, humus formation, carbon sequestration. New York: Springer. Pp 53-83

Bhowmik PC, Bekech MM (1993) Horseweed (*Conyza canadensis*) seed production, emergence, and distribution in no-tillage and conventional-tillage corn (*Zea mays*). Agronomy (Trends in Agricultural Science) 1:67-71

Burket JZ, Hemphill DD, Dick RP (1997) Winter cover crops and nitrogen management in sweet corn and broccoli rotations. Hort Science 32:664-668

Chen G, Weil RR (2010) Penetration of cover crop roots through compacted soils. Plant Soil 331:31-43

Coombs C, Lauzon JD, Deen B, Van Eerd LL (2017) Legume cover crop management on nitrogen dynamics and yield in grain corn systems. Field Crops Res 201:75-85

Clark A, ed (2012) Managing Cover Crops Profitably. 3rd edn. SARE Outreach: College Park, MD. 245 p

Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plan 32:1221-1250

Finney DM, White CM, Kaye JP (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agron J 108:39-52

Fogel R, Cromack Jr. K (1977) Effect of habitat and substrate quality on Douglas fir litter decomposition in western Oregon. Can J Bot 55:1632-1640

Frans R, Talbert R, Marx D, Crowley H (1986) Experimental design and techniques for measuring and analyzing plant responses to weed control practices. P 29-46 in Camper ND ed. Research Methods in Weed Sci. 3rd ed. Southern Weed Sci Society

Gantoli G, Ayala VR, Gerhards R (2013) Determination of the critical period for weed control in corn. Weed Technol 27:63-71

Hall MR, Swanton CJ, Anderson GW (1992) The critical period of weed control in grain corn (*Zea mays*). Weed Sci 40:441-447

Hayden ZD, Brainard DC, Henshaw B, Ngouajio M (2012) Winter annual weed suppression in rye–vetch cover crop mixtures. Weed Technol 26:818-825

Hobbie SE (2008) Nitrogen effects on decomposition- a five-year experiment in eight temperate sites. Ecology 89:2633-2644

Lavelle P, Blanchart E, Martin A, Martin S, Spain A (1993) A hierarchical model for decomposition in terrestrial ecosystems: application to soils of the humid tropics. Biotropica 25:130-150

Liebman M, Mohler CL, Staver CP (2001) Ecological management of agricultural weeds: Cambridge University Press. Pp 1-20

Melillo JM, Aber JD, Muratore JF (1982) Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology 63:621-626

Miguez FE, Bollero GA (2005) Review of corn yield response under winter cover cropping systems using meta-analytic methods. Crop Sci 45:2318-2329

Mirsky SB, Ryan MR, Teasdale JR, Curran WS, Reberg-Horton CS, Spargo JT, Wells MS, Keene CL, Moyer JW (2013) Overcoming weed management challenges in cover crop–based organic rotational no-till soybean production in the eastern United States. Weed Technol 27:193-203

Mohler CL, Teasdale JR (1993) Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. Weed Res 33:487-499

Mulugeta D, Boerboom CM (2000) Critical time of weed removal in glyphosate-resistant *Glycine max*. Weed Sci 48:35-42

Poffenbarger HJ, Mirsky SB, Weil RR, Kramer M, Spargo JT, Cavigelli MA (2015) Legume proportion, poultry litter, and tillage effects on cover crop decomposition. Agron J 107:2083-2096

Ranells NN, Wagger MG (1996) Nitrogen release from grass and legume cover crop monocultures and bicultures. Agron J 88:777-782

Reddy KN (2001) Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*). Weed Technol 15:660-668

Reddy KN, Zablotowicz RM, Locke MA, Koger CH (2003) Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. Weed Sci 51:987-994

Sainju UM, Whitehead WF, Singh BP (2005) Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agron J 97:1403-1412

Schulz M, Marocco A, Tabaglio V, Macias FA, Molinillo JM (2013) Benzoxazinoids in rye allelopathy - from discovery to application in sustainable weed control and organic farming. J Chem Ecol 39:154-74

Soltani N, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2016) Potential corn yield losses from weeds in North America. Weed Technol 30:979-984

Soltani N, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2017) Perspectives on potential soybean yield losses from weeds in North America. Weed Technol 31:148-154

Swift MJ, Heal OW, Anderson JM (1979) Decomosition in Terrestrial Ecosystems. Berkley: University of California Press

Teasdale JR, Mohler CL (2000) The quantitative releationship between weed emergence and the physical properties of mulches. Weed Sci 48:385-392

Van Acker RC, Swanton CJ, Weise SF (1993) The critical period of weed control in soybean [*Glycine max* (L.) Merr.]. Weed Sci 41:194-200

Williams SM, Weil RR (2004) Cover crop root channels may alleviate soil compaction effects on soybean crop. Soil Sci Soc Am J 68:1403-1409

Wortman SE, Francis CA, Bernards ML, Drijber RA, Lindquist JL (2012) Optimizing cover crop benefits with diverse mixtures and an alternative termination method. Agron J 104:1425-1435

Table 14. Cover crop monoculture and mixture seeding rates.

Cover Crop Species 1	Cover Crop Species 2	Cover Crop Species 3	Species 1 Seeding Rate	Species 2 Seeding Rate	Species 3 Seeding Rate
			------------------	kg ha^{-1}	------------------
Cereal Rye	---	---	125.4	---	---
Crimson Clover	---	---	28	---	---
Hairy Vetch	---	---	22.4	---	---
Forage Radish	---	---	8.96	---	---
Cereal Rye	Crimson Clover	---	50.4	15.68	---
Cereal Rye	Hairy Vetch	---	50.4	20.16	---
Cereal Rye	Forage Radish	---	69.4	4.48	---
Cereal Rye	Forage Radish	Crimson Clover	38.08	2.2	13.4
Cereal Rye	Forage Radish	Hairy Vetch	30.08	2.2	16.8

Table 15. Cover crop biomass and litter components by treatment in Blackstone and Blacksburg in 2016 and 2017. Shown by mean ± standard error.

Treatment[a]	Carbon	Nitrogen	Cellulose	Hemicellulose	Lignin	C:N Ratio [b]	Biomass
	--	----------	----------%----------	----------	--		kg ha^{-1}
Cereal Rye	45 ± 1.1	1 ± 0.07	34 ± 0.5	32 ± 1	6 ± 0.5	36 ± 2	7393 ± 728
Crimson Clover	43 ± 1.7	2.7 ± 0.1	29 ± 1	7 ± 0.3	4 ± 0.2	17 ± 1.1	4259 ± 406
Hairy Vetch	44 ± 1.3	4 ± 0.2	26 ± 1	8 ± 0.4	5 ± 0.1	12 ± 0.7	3664 ± 357
Crimson Clover + Cereal Rye	45 ± 1.3	2 ± 0.1	33 ± 0.4	26 ± 2	6 ± 0.46	28 ± 1.6	8257 ± 599
Hairy Vetch + Cereal Rye	45 ± 1.3	2 ± 0.2	31 ± 0.8	28 ± 2.3	6 ± 0.4	25 ± 0.5	7718 ± 785
Forage Radish + Cereal Rye	45 ± 1.1	1 ± 0.04	33 ± 0.7	32 ± 1	6 ± 0.5	36 ± 2.2	6587 ± 449
Crimson Clover + Forage Radish + Cereal Rye	47 ± 3	2 ± 0.1	34 ± 1.8	28 ± 2.6	6 ± 0.6	27 ± 1.5	8750 ± 1001
Hairy Vetch + Forage Radish + Cereal Rye	44 ± 1	2 ± 0.2	31 ± 0.6	26 ± 1.9	6 ± 0.5	24 ± 0.4	6538 ± 594

a Data were pooled across location and year.

b Abbreviation: C:N, Carbon to Nitrogen.

Table 16. Effects table for weed suppression ratings 6 weeks after termination in corn and soybean in 2016 and 2017.

	Soybean		Corn	
Model Effects	Blacksburg	Blackstone	Blacksburg	Blackstone
	----------------------------probability > F---------------------------			
Block	0.137	**<0.001**	**0.035**	**<0.001**
Year	**0.001**	**0.004**	**<0.001**	**<0.001**
Treatment	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Year*Treatment [a]	**0.013**	ns [b]	**0.034**	ns

[a] * denotes an interaction.

[b] Abbreviation: ns, term not significant and removed from the model.

Table 17. Weed suppression ratings 6 WAT in corn and soybean in 2016 and 2017.

Treatment	Soybean		Corn [a]	
	Blacksburg [b]	Blackstone [c]	Blacksburg [d]	Blackstone
	---------------------------%-------------------------			
Cereal Rye (CR)	79 ab	82 a	84 a	79 a
Crimson Clover (CC)	14 c	63 ab	18 b	59 abc
Hairy Vetch (HV)	5 c	58 b	1 bc	47 c
Forage Radish (FR)	1 c	20 c	0 c	16 d
CC + CR	82 ab	67 ab	86 a	62 abc
HV + CR	66 b	74 ab	69 a	77 ab
FR + CR	85 a	57 b	82 a	63 abc
CC + FR + CR	81 ab	58 b	82 a	55 bc
HV + FR + CR	72 ab	65 ab	72 a	61 abc
p-value	<0.001	<0.001	<0.001	<0.001

[a] Data were pooled across year for soybean and corn rating data.

[b] Ratings in Blacksburg are a combination of ratings for large crabgrass, pitted morninglory, and redroot pigweed.

[c] Weed suppression in Blackstone are the combined ratings for large crabgrass and carpetweed.

[d] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

Table 18. Analysis of variance for visible annual weed control ratings in soybean and corn, and residue thickness 6 weeks after termination as influenced by year, location, treatment, biomass, C:N ratio and percent lignin.

Model Effects	Soybean Ratings	Corn Ratings	Residue Thickness
	----------------------------probability > F	-------------------------------	
Year	0.686	0.858	**<0.001**
Location	0.139	0.255	**0.013**
Treatment	**0.019**	0.109	**<0.001**
Block	**<0.001**	**0.016**	0.463
Year*Treatment [a]	ns [b]	ns	ns
Location*Treatment	**0.001**	ns	ns
Biomass [Treatment] [c]	**0.004**	0.104	0.179
C:N Ratio [Treatment]	ns	0.059	**0.032**
Lignin [Treatment]	**0.045**	0.441	**0.024**

[a] * denotes an interaction.

[b] Abbreviation: ns, not significant ($p>0.05$) and effect removed from the model.

[c] [ ] denotes a nested effects.

Table 19. Effects table for corn and soybean yield in weedy and weed free subblocks in Blacksburg and Blackstone, Virginia in 2015-16 and 2016-17 field experiments.

	Corn			Soybean	
	Weedy		Weed Free	Weedy	Weed Free
Model Effects	Blacksburg	Blackstone			
	-----------------------------	-probability > F-	---------------------------		
Block	0.775	**<0.001**	**0.001**	0.319	**0.015**
Year	0.551	**0.004**	**<0.001**	0.864	**<0.001**
Location	- [a]	-	0.191	**<0.001**	**<0.001**
Treatment	**<0.001**	**0.402**	0.139	0.108	0.723
Year*Treatment [b]	ns [c]	ns	ns	ns	ns
Location*Treatment	-	-	ns	ns	ns

[a] - denotes a term not included in the model.

[b] * denotes an interaction.

[c] Abbreviation: ns, term not significant and removed from the model.

Table 20. Corn and soybean yield for weedy and weed free subblocks in Blacksburg and Blackstone, Virginia in 2016 and 2017.

	Corn			Soybean	
	Weedy		Weed Free [a]	Weedy	Weed Free
Treatment	Blacksburg [b]	Blackstone			
	----------------	----------------	kg ha^{-1}	----------------	----------------
Cereal Rye (CR)	3711 ab	2228	5888	758	1649
Crimson Clover (CC)	2117 bcd	2132	4759	554	1732
Hairy Vetch (HV)	1313 d	2256	4531	379	1697
Forage Radish (FR)	1711 cd	1041	3010	754	1978
CC + CR	4460 a	1986	5104	769	1983
HV + CR	4377 a	2284	5327	884	2021
FR + CR	4018 a	2213	4754	914	2077
CC + FR + CR	3273 abc	2292	4665	830	1723
HV + FR + CR	3486 ab	1973	5058	995	2019
No Cover Check	697 d	1850	4438	857	1799
p value	<0.001	0.402	0.139	0.108	0.723

[a] Data were pooled across year and location.

[b] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

Assessing the Germination and Seed Maturation Phenology of Hairy Vetch (*Vicia villosa* Roth) as it Relates to Weediness in Subsequent Crops

Abstract

Hairy vetch (*Vicia villosa* Roth) is a leguminous winter cover crop species that is desirable for its ability to fix nitrogen, gain large amounts of biomass, and winter hardiness. However, this species is also known to become a weed in subsequent crops. Dormant seeds, or seeds that germinate after the cover crop growing season, are thought to be the cause. Experiments were conducted to determine germination phenology and viability of two hairy vetch cultivars in Blacksburg and Blackstone, Virginia from 2015 through 2017. Companion seed set experiments were also conducted to determine when these cultivars produce viable seed. 'Groff' and 'Purple Bounty' seed were sown in October 2015 and May 2016 and germination was tracked until June 2017. Subsequently, seeds were recovered and tested for viability. Groff had greater germination than Purple Bounty, 93% and 62%, respectively, in the initial cover crop growing period for fall-sown seed. Both cultivars had <2% germination after the initial planting period. Both cultivars had <1% of seed recovered that was still viable at the end of the experiment. In the seed set experiment, hairy vetch was planted in the fall, and pods and seeds were collected in the spring and summer from both cultivars, and a germination assay was performed to determine when viable seed were produced. Both cultivars produced seed starting in late May, but most seed were not viable until mid-June. These results indicate that seed dormancy is not the primary cause of hairy vetch becoming weedy in subsequent crops as nearly all germination occurred during the cover crop growing season, when it is desirable. Also, if termination occurs before mid-June in Virginia, it is unlikely that viable seed will be added to the seedbank.

Hairy vetch is a legume that is native to Europe and Western Asia but has been adopted as a cover crop in the Midwest, mid-Atlantic, and Northeastern United States. Legumes are popular as cover crops because of their ability to convert atmospheric nitrogen into plant available forms, and hairy vetch, specifically, can survive harsher winter conditions than other leguminous species (Clark 2012; Undersander et al. 1990). Additionally, hairy vetch has been shown to enhance soil organic matter, improve water filtration, and suppress weeds (Frye et al. 1988; Hartwig and Ammon 2002; Stute and Posner 1993; Teasdale et al. 2004).

Despite these benefits, reservations exist with regard to planting hairy vetch since it has the potential to become weedy in subsequent crops, due to persistence of seeds in the soil or regrowth after incomplete termination (Snapp et al. 2005; Teasdale and Shirley 1998). Hairy vetch populations can have dimorphic seeds with hard or soft seed coats. The seeds with hard seed coats can persist and germinate in subsequent crops creating weed issues, which is often problematic in winter wheat and in perennial cropping systems (Aarssen et al. 1986). Additionally, termination methods such as mowing or using a roller crimper, often used in reduced tillage systems, can be ineffective in completely killing hairy vetch (Mischler et al. 2010).

If incomplete termination of hairy vetch occurs, it can regrow and compete with the cash crop causing yield reductions. Regrowth can also result in set seed, which only perpetuates its weediness (Boydston and Williams 2011; Curran et al. 2015; Snapp et al. 2005). Controlling hairy vetch in subsequent crops may require a herbicide application beyond that of the grower’s normal herbicide program. In winter wheat, herbicides like clopyralid, dicamba, or dicamba + 2,4-D are viable options for hairy vetch control (Curran et al. 2015; Mischler et al. 2010). Terminating with glyphosate is generally effective at all flowering stages (Hoffman et al. 1993).

For most mechanical control methods, such as rolling and mowing, the most effective termination timing is late-flowering to early-pod set (Hoffman et al. 1993; Mischler et al. 2010).

Seed dormancy, which is often blamed when hairy vetch becomes problematic in subsequent crops, is attributed to seed source or the maternal environment (Jannink et al. 1997). Jacobsen et al. (2010) tested hairy vetch from nine commercial seed sources available to growers in the northeastern United States and found that seed dormancy ranged from 1 to 21% among the sources. Scarification of seeds can eliminate the problems associated with seed dormancy (Jacobsen et al. 2010; Mirsky et al. 2015). Mirsky et al. (2015) reported that seed bank persistence of hairy vetch was eliminated 6 months after burial when seeds were scarified while 1 to 7% of seeds that hadn't been scarified continued to persist in the seed bank after 6 months.

Despite anecdotal and documented evidence (Snapp et al. 2005; Teasdale and Shirley 1998) of hairy vetch becoming weedy in subsequent crops, little research has evaluated this issue. The objective of this study is to compare the germination phenology of two popular hairy vetch cultivars: 'Groff' and 'Purple Bounty'. A companion study was conducted with the objective of evaluating when viable seed are set and the quantity of viable seed produced.

Materials and Methods

Study Sites. Field experiments were conducted in Blacksburg, Virginia at Kentland Farms, in the New River flood plain (37.192913, -80.573942) in a Ross Soil (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls), and Blackstone, Virginia at the Southern Piedmont Agricultural Research and Extension Center (37.082840, -77.972062) in an Appling coarse sandy loam (fine, kaolinitic, thermic, Typic Kanhapludults). Separate experiments were conducted to evaluate germination and seed set at these locations.

Germination Experiments. To evaluate germination phenology, two experiments were conducted: fall seeded hairy vetch and spring seeded hairy vetch. The fall experiment was used to assess germination phenology from the usual planting time for a hairy vetch cover crop while the spring experiment was used to assess seeds shattered after incomplete termination. Both studies were established as a randomized complete block design with six replications. Planting dates for the fall experiments were: October 20 and November 3, 2015 in Blackstone and Blacksburg, respectively. The spring experiment was planted May 19 and May 25, 2016 in Blackstone and Blacksburg, respectively.

The fall experiment was a 2 by 2 by 2 factorial of hairy vetch cultivar, burial depth, and vertebrate predation allowed or excluded. The spring experiment was a 2 by 2 factorial of hairy vetch cultivar and vertebrate predation allowed or excluded. Two cultivars of hairy vetch: Groff (United States Department of Agriculture (USDA) Agriculture Research Service, Beltsville, MD; T.A. Seeds, Jersey Shore, PA) and Purple Bounty (Seedway, Hall, NY and United States Department of Agriculture (USDA) Agriculture Research Service, Beltsville, MD) were used in this experiment. These cultivars were chosen for their flowering characteristics as Purple Bounty is an early flowering cultivar and Groff is a later flowering cultivar (Maul et al. 2011). Purple Bounty is a cultivar that was developed at the USDA-ARS Beltsville Agricultural Research Center from an early flowering parental line. Groff is a selection made from ‘AU Early Cover’ and bred over time to be more cold tolerant. The end result led to a flowering date that is about 20 days later than its ‘AU Early Cover’ parent (Maul et al. 2011).

In the fall experiment, seeds were either sown on the soil surface level to simulate overseeding of the cover crop into an existing crop or buried at a depth of 2.54 cm to simulate a drill depth. The spring experiment only included seeds sown on the soil surface, to simulate seed shattering into a no-tillage system. Vertebrate predation exclusion treatments had lids on boxes (described below) while predation allowed boxes did not have lids. Temperature, soil moisture, and photosynthetically active radiation data were collected in an uncovered box and a covered box over 6 months to determine the impact of the lids on the environment inside the boxes.

Each plot was a box constructed of hardware cloth lined with fiberglass window screening measuring 0.3m by 0.3m by 0.178m. In each box, 500 seeds were sown. The seed quantity was determined by weight using the average weight of 3 samples of 500 counted seed for each cultivar. Boxes were buried 10.2 cm into the ground and refilled with field soil to the level surrounding the box. Half of the boxes had lids to prevent vertebrate predation of the seeds, which were of the same construction and secured to the boxes.

For both fall and spring experiments, germinated seeds were counted every two weeks until the first flush of growth was complete, 8 weeks after seeding, and then on a monthly basis thereafter. Once a seed had germinated and was counted, it was removed from the box by pulling, taking care to limit disturbance to the soil as much as possible. Other weeds that germinated in the boxes were hand pulled to prevent competition.

Boxes were monitored for germination from their planting date until June 5 and June 6, 2017 in Blacksburg and Blackstone, respectively. Once a final count was completed, the boxes were removed and soil was collected from each box. Soil was collected from the top 5.08 cm of soil in boxes where the seed was planted at a drill depth and from the top 2.54 cm in boxes where seed was placed on the soil surface. Seeds were extracted from soil using elutriation. Viability of seed was tested using a 1% tetrazolium solution (ISTA 1996).

Data analysis was conducted using JMP (JMP Pro 12; SAS Institute, Inc., Cary, NC). For the fall experiment, the germination data were separated into three periods of time. The first period was the initial cover crop growing season, from October 2015 through the first week of May 2016, when germination is desirable. The second period was from May 2016 through the following December, representing germination occurring in the next cash crop growing season. The final period was from December 2016 until the termination of the experiment in the first week of June 2017. Data were also shown as overall seed fate expressed as percent germination, recovered and viable seed, seed recovered but not viable, (from the tetrazolium assay), and percent of seed lost. The lost seed are those that did not germinate and were not recovered at the end of the experiment. The spring experiment had two periods of interest for germination: from the initiation of the experiment in May 2015 through December 2016, which would be during a soybean or corn cash crop growing season, and the next period from December 2016 through July 2017. Final fate of the seed, which included seed germinated, recovered and viable seed, recovered but not viable seed, and seed that were lost was determined 13 months after the initiation of the experiment.

Main effects of cultivar, burial depth, predation allowed/excluded, location, block, and interactions of all other factors with cultivar were included in the model. For the spring experiment, burial depth and interactions with burial depth were excluded from the model as all seed were sown on the soil surface. If the overall ANOVA was significant, a means separation was used with Fisher's Protected $LSD_{\alpha=0.05}$ to compare across effects.

Seed Set Experiment. To determine the amount of viable seed added to the seed bank across multiple termination timings, replicated hairy vetch strips, measuring 1.6m by 8m, were planted in the fall of 2015 and 2016. The study sites were in Blacksburg and Blackstone, Virginia, as previously described. The same two cultivars, Groff and Purple Bounty, were drilled in a randomized complete block design with 4 replications at 28 kg ha^{-1}. Planting dates in 2015 were

October 20th in Blackstone and November 3rd in Blacksburg. In 2016, the studies were planted on September 28th and October 14th in Blacksburg and Blackstone, respectively.

The cover crops were allowed to grow through the winter and data collection started when the hairy vetch reached late-flowering or early-pod development. All seedpods were collected from random 0.09 m^2 subplots and counted. Collections took place every two weeks until the pods started shattering seed, for a total of five collections. In Blacksburg in 2017, only four collections took place due to early season flooding which delayed pod set. Seedpod subsamples were taken from new, undisturbed sites in the plot at each collection. From each collection, fifty pods were set aside and seeds were counted to determine the average number of seed per pod. When less than fifty pods were present in a sample, all the seeds were counted.

To test germinability, 50 seeds were collected from every plot at each sampling date, with the exception noted above, and placed into 100 by 15mm Petri dishes lined with filter paper (9 cm), with 7 ml of deionized water. Dishes were covered, sealed, and placed in darkness at ambient room temperature, approximately 22.7°C, which are adequate conditions for germination (Buhler and Hoffman 1999). Germination was counted every two weeks until germination ceased. Seeds were defined as germinated when a radical was visible, and seeds that had germinated were removed.

Data were analyzed using JMP (JMP Pro 12; SAS Institute, Inc., Cary, NC) with a model that included main effects of cultivar, location, year, collection date, block, and interactions between location, year, and collection date with cultivar. In the germination assay, cultivar, year, location, collection date, block, and interactions between location, year and collection date with cultivar were included in the model. If the overall ANOVA was significant, a means separation using Fisher's Protected $LSD_{\alpha=0.05}$ was used to detect further differences.

Results and Discussion

Germination Experiment. Data from the fall experiment indicate that during the initial (October 2015 to May 2016), following season (May 2016 to December 2016), and final (December 2016 to July 2017) germination periods, there was no significant interaction between cultivar with location, burial depth, or predation allowed or excluded ($p>0.05$), so data were pooled accordingly (Table 21).

In the initial germination period, main effects of location, predation allowed or excluded, and cultivar were significant ($p<0.001$), but burial depth was not significant ($p=0.05$). Groff had greater germination than Purple Bounty with 92.9% and 62.3% germination, respectively (Table 22). Blackstone had greater germination, 84%, than Blacksburg, 71%. The predation excluded boxes had greater germination than the predation allowed boxes, 81% to 74% respectively.

In the following season (May to December 2016) germination period, the main effects of burial depth, predation allowed or excluded, and cultivar were significant ($p=0.017$, $p=0.004$, and $p<0.001$, respectively). During this period, more Purple Bounty seed germinated than Groff seed, 1.05% and 0.43%, respectively. Seeds sown on the soil surface had less germination than those buried to 2.54 cm, 0.65 to 0.83%, respectively. Similar to the earlier initial germination period, boxes where predation was excluded had greater germination than the boxes where predation was allowed, 0.85 and 0.68%, respectively. In the final germination period (December 2016 to June 2017), the model was not significant ($p=0.615$).

Overall seed fate was expressed as germinated, recovered and viable, recovered but not viable, or lost. For overall seed fate, interactions between cultivar and predation as well as cultivar and location were not significant ($p>0.05$) (Table 23). The interaction between cultivar and burial depth was significant ($p=0.031$). Predation allowed or excluded, location, and cultivar were significant main effects ($p<0.001$). Groff had 90.3% of seed germinate over 20 months while Purple Bounty had 63.4% of seed germinate (Table 24). Overall, there was greater germination in Blackstone, 82%, than in Blacksburg, 72%. The predation excluded boxes had 81% of seed germinate and when predation was allowed, 72% of seed germinated. For seed that was recovered and tested positive for viability, both cultivars had <1% of seed deemed viable, 0.04% and 0.18% for Groff and Purple Bounty, respectively ($p<0.001$). Seeds that were recovered but tested negative for viability, cultivar was not significant but location was ($p=0.002$). Blackstone had more seeds found that were not viable, 0.47% than Blacksburg, 0.14%. For the lost seed, location, predation, and cultivar factors were significant ($p<0.001$). In contrast to the overall germination data, Blacksburg had a greater number of lost seed than Blackstone, 27.8% and 17.8%, respectively. Predation allowed boxes had losses of 27.3% while when predation was excluded, 18.2% of seeds were lost. Purple Bounty had a higher percentage of seed lost, 36.2%, as compared to Groff, 9.4%.

In the spring germination experiment for the initial May 2016 to December 2016 and following December 2016 to June 2017 germination periods, the interaction between location and cultivar was not significant ($p>0.05$) (Table 21). The interaction between cultivar and predation was significant for the initial germination period ($p=0.02$) but not in the final period ($p=0.20$). However, data were pooled across factors to allow for better analysis of the impact of cultivar on germination rather than predation. The interaction between cultivar and predation allowed or excluded was included in the model to account for this variation. In the initial germination period, both cultivar and predation were significant ($p<0.001$). Groff had greater germination than Purple Bounty, 69.7% as compared to 40.3% (Table 22). The predation excluded boxes also had greater germination than the predation allowed boxes, 79.3% and

30.6%, respectively. In the final germination period, predation allowed/excluded was significant ($p=0.004$) and cultivar was not significant ($p=0.20$). There was no germination in the predation excluded boxes and 0.06% germination in the predation allowed boxes.

In the overall seed fate data, there was a significant cultivar by predation allowed or excluded interaction for the percent germination ($p=0.02$) and percent seed lost ($p=0.03$) (Table 23). Data were pooled across all factors to allow for better analysis of the impact on germination from cultivar rather than predation. The interaction of cultivar and predation allowed/excluded was included in the model to account for this variation. Trends are similar in regards to cultivar with Groff having a greater germination and lesser viability and lost percentages than Purple Bounty (Table 24). For percent germination, the main effect of predation was significant ($p<0.001$) and predation excluded plots had 79.3% of seed germinate. When predation was allowed, 30.8% of seed germinated. Conversely, seed lost was greater for predation allowed boxes, 69% as compared to 20.3% for boxes in which predation was excluded. Location was significant in the recovered but not viable data set ($p<0.001$) with Blackstone having a greater percent of seed not viable as compared to Blacksburg, 0.3% and 0.01%, respectively.

The lids on the boxes created different environments between the predation allowed and predation excluded boxes. On average, predation excluded boxes (with lid) accumulated less moisture, 8.2% less volumetric water content on average compared to the predation allowed treatments. The predation excluded boxes also allowed less light to penetrate by 161 μM PAR $m^{-2} s^{-1}$ compared to predation allowed boxes (Table 25). However, a difference in temperature was not observed ($p=0.081$). Hairy vetch does not require light to germinate; therefore, this factor is unlikely to have impacted results (Buhler and Hoffman 1999). While moisture differences were observed, sufficient moisture was present for germination. Therefore, these differences are unlikely to have impacted results.

In the fall-initiated experiment, most germination occurred in the initial growing period with Groff having more seeds that germinated than Purple Bounty. In the subsequent cash crop growing season, there was still some germination occurring from both cultivars although the number was low, 0.43 to 1.05%; still, these seeds that germinate during this period could become weeds in the following cash crop.

There was also a small number of viable seed at the end of the experiments that could become weeds in future crops. This result is similar to that of Mirsky et al. (2015), who found that after 6 or 12 months of burial, 1 to 6% of seed were viable at a burial depth of 3 cm. The amount of viable seed and seed that germinated for both cultivars in the subsequent cash crop growing season was <1.1% which is less than the 1 to 21% viable seed reported by Jacobsen et al. (2010). This discrepancy could be attributed to cultivar; Jacobsen et al. (2010) tested different seed sources but did not report specific cultivar information.

The seed considered lost were seed that could not be accounted for at the end of the experiment. Vertebrate predation is suspected to be the primary cause losses in predation allowed boxes. However, loss in all boxes could be associated with predation from insects and pathogens. The amount of seed lost was comparable compared to the seed lost by Mirsky et al. (2015), which reported up to 40% loss in seeds that were buried to a depth of 3 cm.

These data indicate that while there was some germination in subsequent seasons and some viable seed found, seed dormancy is not the primary cause of weediness in these two cultivars of hairy vetch as the vast majority of germination occurred in the initial period, which for the fall-initiated experiment is when germination is desired. Choosing these cultivars could reduce the chance of hairy vetch becoming weedy based on this data. There are other tactics, rather than cultivar choice, that could reduce the number of hairy vetch seed that could become weeds, such as tillage and scarification, but these practices might not be practical for growers due to equipment needs, crop rotations, or lack of availability of seeds that have been pre-scarified (Mirsky et al. 2015).

In the spring-initiated experiment, a most of the germination occurred in the initial period from May 2016-December 2016 indicating that seed added to the soil seed bank at the end of the cover crop growing season will readily germinate in the subsequent cash crop growing season. This result is bolstered by findings that hairy vetch has the propensity to reseed itself in the following season, with >45% of seed shed germinating in the next season (Renzi et al. 2014). There is also evidence of shattered seed of hairy vetch being able to form a second stand, acceptable in a forage setting, without additional inputs (Renzi et al. 2017). There were greater losses of both cultivars in the spring-initiated experiment as compared to the fall-initiated experiment. These differences can be attributed to increased predation of the seed.

Seed Set Experiment. There were no significant interactions between location, year, and collection date with cultivar ($p>0.05$), so data were pooled accordingly (Table 26). Cultivar was not significant ($p=0.617$) but collection date was ($p<0.001$). Collections started when pods were first visible (collection date 1; late-May) and every two weeks after until seed was shattering (Table 27). Collection date 3 (late-June) was when amount of seeds collected peaked with 8,923 seeds m^{-2}. Seed quantity drops to 1718 seeds m^{-2} by collection date 5 (late-July). For both years and in both locations, collection date 3 occurred in the mid-June, ranging from June 16th to June 23rd, with the exception of Blacksburg in 2017 when collection date 3 fell on July 12th, due to early season flooding that delayed flower and pod set. Differences in reported flowering times between the two varieties did not have an impact on when viable seed were set between these varieties (Maul et al. 2011). Renzi et al. (2017) reported seed yield of up to 5,400 seeds m^{-2} regardless of seeding density at hairy vetch maturity, defined as directly prior to seed shattering. This is similar to the findings in this experiment, aligning with the time period between collection dates 3 and 4 (late-June to mid-July).

For the germination assay, only the main effects of year and collection date were significant ($p<0.001$). Germination was greater in 2017 than in 2016 with 24.9% germination as compared to 3.47% in 2016. This difference could be attributed to fungal growth in the petri dishes during the 2016 germination assay. The first collection date had the lowest germination with <1% of seed germinating. The cause of this is most likely due to seed not yet being viable. No difference in germination could be detected from any of the other collection dates, ranging from 13.4 to 20.8%.

Therefore, if growers have an effective termination prior to late-May, almost no viable seeds added to the seedbank. In organic production, effective termination by mechanical methods is best achieved during late-flowering to early-pod set. These data indicate this growth stage would not occur late-May or early-June, which is past the time when most growers would choose to terminate a cover crop to prepare for cash crop planting (Mischler et al. 2010). Alternatively, growers could attempt to terminate earlier, when an effective termination is less likely to occur, allowing for a greater chance of hairy vetch regrowth and subsequent seed set. If termination is incomplete, the subsequent seed added to the seedbank would likely contribute to hairy vetch being weedy in the following corn or soybean crop as seen in the spring-initiated germination experiment, when most of the germination occurring readily after seed is added to the seedbank.

Future research is needed to investigate alternative sources of weediness, more specifically seedbank additions and timing of those additions from incomplete termination.

Literature Cited

Aarssen LW, Hall IV, Jensen KIN (1986) The biology of Canadian weeds 76. *Vicia angustifolia* L., *V. cracca* L., *V. sativa* L., *V. tetrasperma* (L.) Schreb. and V. villosa Roth. Can J Plant Sci 66:711-737

Boydston RA, Williams MM (2011) Rye and vetch management for no-till snap bean production. Proc. Weed Sci. Soc. America 51:145

Buhler DD, Hoffman ML (1999) Andersen's guide to practical methods of propagating weeds & other plants. Lawrence, KS: Weed Sci Society of America. 150 p

Clark A, ed (2012) Managing cover crops profitably. 3rd edn. SARE Outreach: College Park, MD. 245 p

Curran WS, Wallace JM, Mirsky S, Crockett B (2015) Effectiveness of herbicides for control of hairy vetch (*Vicia villosa*) in winter wheat. Weed Technol 29:509-518

Frye WW, Blevins BL, Smith MS, Corak SJ, Varco JJ (1988) Role of annual legume cover crops in effieicent use of water and nitrogen. Cropping Strategies for Efficient Use of Water and Nitrogen: ASA Special Publication No.51 Pp 129-153

Hartwig NL, Ammon HU (2002) Cover crops and living mulches. Weed Sci 50:688-699

Hoffman ML, Regnier EE, Cardina J (1993) Weed and corn (*Zea mays*) responses to a hairy vetch (*Vicia villosa*) cover crop. Weed Technol 7:594-599

International Seed Testing Association (ISTA) (1996) International rules for seed testing. Seed Sci. Technol. 24:Supplement Pp 203-216

Jacobsen KL, Gallagher RS, Burnham M, Bradley BB, Larson ZM, Walker CW, Watson JE (2010) Mitigation of seed germination impediments in hairy vetch. Agron J 102:1346-1351

Jannink J, Merrick LC, Liebman M, Dyck EA, Corson S (1997) Management and winter hardiness of hairy vetch in Maine. University of Maine. Tech. Bull. 167

Maul J, Mirsky S, Emche S, Devine T (2011) Evaluating a germplasm collection of the cover crop hairy vetch for use in sustainable farming systems. Crop Sci 51:2615-2625.

Mirsky SB, Wallace JM, Curran WS, Crockett BC (2015) Hairy vetch seedbank persistence and implications for cover crop management. Agron J 107:2391-2400

Mischler R, Duiker SW, Curran WS, Wilson D (2010) Hairy vetch management for no-till organic corn production. Agron J 102:355-362.

Renzi JP, Chantre GR, Cantamutto MA (2014) Development of a thermal-time model for combinational dormancy release of hairy vetch (*Vicia villosa* spp. *villosa*). Crop Pasture Sci 65:470-478

Renzi JP, Chantre GR, Cantamutto MA (2017) Self-regineration of hairy vetch (*Vicia villosa* Roth) as affected by seedling density and soil tillage method in a semi-arid agroecosystem. Grass Forage Sci 72:524-533

Snapp SS, Swinton SM, Laharta R, Mutch D, Black JR, Leep R, Nyiraneza J, O'Neil K (2005) Evaluating cover crops for benefits, costs, and performance within cropping system niches. Agron J 97:322-332

Stute J, K, Posner JL (1993) Legume cover crop options for grain roatations in Wisconsin. Agron J 85:1128-1132

Teasdale JR, Devine TE, Mosjidis JA, Bellinder RR, Beste CE (2004) Growth and development of hairy vetch cultivars in the Northeastern United States as influenced by planting and harvesting date. Agron J 96:1266-1271

Teasdale JR, Shirley DW (1998) Influence of herbicide application timing on corn production in a hairy vetch cover crop. J Prod Agric 11:121–125

Undersander DJ, Ehlke NJ, Kaminski AR, Doll, JD, Kellin, KA (1990) Alt. Field Crops Manual. Univ. of Wisconsin-Madison Cooperative Extension, Madison. https://www.hort.purdue.edu/newcrop/afcm/vetch.html Accessed on: February 17, 2015

Table 21. Effects table for hairy vetch germination periods in the fall- and spring-initiated experiments in Blacksburg and Blackstone, Virginia.

	Fall Experiment			Spring Experiment	
Model Effects	October 2015 to May 2016	May 2016 to December 2016	December 2016 to June 2017	May 2016 to December 2016	December 2016 to June 2017
	----------------------------probability > F--------------------------				
Block	0.126	0.154	0.585	0.994	0.671
Location	**<0.001**	0.213	0.798	0.857	0.667
Cultivar	**<0.001**	**<0.001**	0.615	**<0.001**	0.201
Burial Depth	0.052	**0.019**	0.798	- [a]	-
Predation Allowed/Excluded	**0.001**	**0.004**	0.798	**<0.001**	**0.004**
Cultivar*Location [b]	ns [c]	ns	ns	ns	ns
Cultivar*Burial Depth	ns	ns	ns	-	-
Cultivar*Predation Allowed/Excluded	ns	ns	ns	**0.024**	ns

[a] - denotes a term not included in the model.

[b] * denotes an interaction.

[c] Abbreviation: ns, term not significant and removed from the model.

Table 22. Percentage of hairy vetch seed that germinated in the fall- and spring-initiated experiments over multiple time periods in Blacksburg and Blackstone, Virginia.

Cultivar	Fall Experiment [b]			Spring Experiment [c]	
	October 2015 to May 2016 [a]	May 2016 to December 2016	December 2016 to June 2017	May 2016 to December 2016	December 2016 to June 2017
	---------------------------------------%---------------------------------------				
Groff	92.9 a	0.43 b	0.02	69.7 a	0.02
Purple Bounty	62.3 b	1.05 a	0.05	40.3 b	0.04
p-value	<0.001	<0.001	0.615	<0.001	0.201

[a] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

[b] Data were pooled across location, burial depth, and predation allowed/excluded.

[c] Data were pooled across location and predation allowed/excluded.

Table 23. Effects test for overall seed fate for the fall- and spring-initiated experiments in Blacksburg and Blackstone, Virginia.

	Fall-initiated Experiment				Spring-initiated Experiment			
Model Effects	Germinated	Recovered and Viable	Recovered but not Viable	Lost	Germinated	Recovered and Viable	Recovered but not Viable	Lost
				---------------------------probability > F--------------------------				
Block	0.116	0.574	0.242	0.165	0.671	0.658	0.118	0.993
Location	**<0.001**	0.78	**0.002**	**<0.001**	0.667	0.248	**<0.001**	0.8
Cultivar	**<0.001**	**<0.001**	0.676	**<0.001**	**<0.001**	**<0.001**	0.806	**<0.001**
Burial Depth	0.449	0.129	0.248	0.398	- [a]	-	-	-
Predation Allowed/Excluded	**<0.001**	0.338	0.129	**<0.001**	**0.004**	0.248	1	**<0.001**
Cultivar*Burial Depth [b]	**0.031**	ns [c]	ns	**0.025**	-	-	-	-
Cultivar*Predation Allowed/Excluded	ns	ns	ns	ns	ns	**0.025**	ns	**0.028**

[a] - denotes a term not included in the model.

[b] * denotes an interaction.

[c] Abbreviation: ns, term not significant and removed from the model.

Table 24. Overall seed fate of the fall- and spring-initiated experiments in Blacksburg and Blackstone, Virginia.

Cultivar	Fall Experiment [a]				Spring Experiment [b]			
	Germinated [c]	Recovered and Viable	Recovered and Not Viable	Lost	Germinated	Recovered and Viable	Recovered and Not Viable	Lost
	---% ---							
Groff	90.32 a	0.05 b	0.28	9.36 b	69.73 a	0.05 b	0.15	30.08 b
Purple Bounty	63.35 b	0.18 a	0.33	36.15 a	40.31 b	0.28 a	0.17	59.25 a
p-value	<0.001	0.002	0.68	<0.001	<0.001	<0.001	0.81	<0.001

[a] Data were pooled across factors of location, burial depth, and predation allowed or excluded.

[b] Data were pooled across factors of location and predation allowed or excluded.

[c] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

Table 25. Average temperature, soil moisture, and photosynthetically active radiation in the vertebrate predation allowed and predation excluded boxes in Blacksburg, Virginia. Measurements were taken hourly over 6 months.

	Temperature	Moisture [a]	PAR [b]
	°C	%VWC [b]	μM PAR m^{-2} s^{-1}
Predation Allowed	14.6	19.7 a	239.4 a
Predation Excluded	15.1	11.5 b	78.4 b
p-value	0.081	<0.001	<0.001

[a] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.

[b] Abbreviation: PAR, photosynthetically active radiation; VWC, volumetric water content.

Table 26. Effects table for seed quantity and germination across collection date.

Model Effects	Seed Count	Germination
	-----probability > F-----	
Block	0.964	0.164
Location	0.091	0.23
Year	0.948	**<0.001**
Cultivar	0.951	0.328
Collection Week	**<0.001**	**<0.001**
Cultivar*Year [a]	ns [b]	ns
Cultivar*Location	ns	ns
Cultivar*Collection Week	ns	ns

[a] * denotes an interaction.

[b] Abbreviation: ns, term not significant and removed from the model.

Table 27. Seed quantity and germination from different collection dates across 2016 and 2017 in Blacksburg and Blackstone, Virginia.

Collection Date	Timing of Collection Date [a]	Seed Count [b]	Germination
		seeds m^{-2}	%
1	late-May	4161 bc	0.6 b
2	mid-June	5091 b	20.8 a
3	late-June	8923 a	17.4 a
4	mid-July	2863 bc	18.7 a
5	late-July	1719 c	13.4 a
p-value		<0.001	<0.001

[a] Due to flooding, the Blacksburg 2017 location was delayed by two weeks.

[b] Treatments within the same column followed by the same letter are not significantly different from one another by Fisher's protected $LSD_{\alpha=0.05}$.