Herbicide Carryover to Cover Crops and Evaluation of Cover Crops for Annual Weed Control in Corn and Soybeans

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Abstract

While cover crops are actively growing, they compete with winter annual weeds. Studies were conducted to determine the ability of early planted cover crop monocultures and mixtures and a fall applied residual herbicide to compete with winter annual weeds. Cereal rye containing cover crops provided the greatest control of winter weeds in May. Flumioxazin, as a fall applied herbicide, controlled winter weeds in December, but control did not persist until May. Once cover crops are terminated, their residue suppresses summer annual weeds. A greenhouse experiment studying the effects of cereal rye biomass on common ragweed and Palmer amaranth control and light penetration and two field experiments to determine the effects of cereal rye and wheat cover crop biomass terminated with a roller crimper or left standing on summer weed control and light penetration were conducted. For summer weed control, as cover crop biomass increased, weed control increased, light penetration decreased, soil temperature decreased, and soil moisture increased. Standing cover crop residue provided greater control of common ragweed compared to rolled residue until 8400 kg ha^{-1} of cover crop biomass. As cover crop biomass increased, rolled cover crop residue reduced light penetration compared to standing residue. Wheat cover crop residue increased soil moisture more compared to cereal rye residue. Cover crops must become established to produce adequate biomass to compete with weeds. Herbicide carryover has the potential to reduce cover crop establishment. A study was conducted to evaluate the potential for 30 different residual herbicides applied in the cash crop growing season to carryover to 10 different cover crops. While visible injury was observed, cover crop

biomass was similar to the nontreated check in all cases, indicating that herbicide carryover to cover crops is of little concern. Herbicide carryover has few biological effects on establishment of cover crops, under the conditions and herbicides evaluated, that are effective at competing with winter annual weeds and suppressing summer annual weeds.

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General Audience Abstract

Cover crops are grown after the cash crop has been harvested and terminated before another is planted. They are grown for environmental and agronomic benefits and not harvested. Cover crops improve soil health, reduce erosion, prevent nutrient loss, and control weeds. Cover crops can compete with weeds while they are actively growing. Their residue can create a mulch layer to reduce weed establishment and limit the amount of light reaching weed seed to reduce germination and establishment.

As winter cover crops are growing, they compete with winter weeds for sunlight, nutrients, and water. Fall applied herbicides that remain active in the soil are also utilized to control winter weeds in between cash crop growing seasons. Experiments evaluated the ability of cover crop monocultures and cover crop mixtures compared to a fall applied herbicide to compete with winter annual weeds. Monocultures and mixtures of cereal rye, crimson clover, hairy vetch, and forage radish were utilized. Cereal rye containing treatments provided the greatest control of winter weeds in the spring. The fall applied herbicide provided adequate control of winter weeds in December, but control did not persist until the May, indicating that a fall applied herbicide will not provide control of winter weeds from cash crop harvest to the next cash crop planting.

As cover crop biomass increases, summer annual weed control increases. Cover crops are usually terminated with herbicide and left standing in Virginia, but the use of a roller crimper lays down residue and creates a mulch layer. Experiments compared the effects of cereal rye and

wheat cover crops at different biomass rates terminated with herbicide only (left standing) or a roller crimper and herbicide on summer weed control, light penetrating the cover crop canopy and reaching the soil surface, soil moisture, and soil temperature. As cover crop biomass increased, weed control increased, light reaching the soil surface decreased, soil temperature decreased, and soil moisture increased. Standing cover crop residue provided greater weed control until 8400 kg ha^{-1} of cover crop biomass was reached. After 8400 kg ha^{-1} rolled cover crop residue provided greater control, but control from standing and rolled were both greater than 80% compared to the no cover control. Cereal rye intercepted more light than wheat cover crop residue at less than 6000 kg ha^{-1} of cover crop biomass was achieved. Rolled cover crop residue intercepted more light than standing residue.

Established cover crops most produce adequate biomass to effectively control weeds. Herbicides applied during the cash crop growing season to control weeds can remain active in the soil and reduce the establishment of subsequently planted cover crops. Experiments evaluated the potential for different herbicides applied during the cash crop, such as corn, cotton, or soybeans, to remain in the soil at high enough concentrations to injure cover crops commonly utilized in the Mid-Atlantic region. Cover crops utilized were wheat, barley, cereal rye, oats, annual ryegrass, forage radish, Austrian winter pea, crimson clover, hairy vetch, and rapeseed.

Results suggest that little potential exists for the herbicides utilized to persist in the soil to injure the five grass cover crop species utilized. There is the potential for some herbicides to injure forage radish, crimson clover, and rapeseed, but no reduction in cover crop biomass was observed, indicating there is little concern for herbicide carryover to cover crops. Residual herbicide carryover has little effect on establishment of cover crops and does not reduce cover crop biomass, under the conditions and herbicides tested in this study. Cover crops can effectively compete with winter weeds, and as cover crop biomass increases, summer annual weed control increases.

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*****Chapter 3: Herbicide Carryover to Various Fall Planted Cover Crop Species has been accepted for publication in Weed Technology.**

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Literature Review

Need for Integrated Weed Management. Uncontrolled weeds can cause a 50% yield loss in corn (*Zea mays* L.) which could result in an estimated loss of 26.7 billion U.S. dollars annually, and a 52% yield loss in soybeans (*Glycine max* (L.) Merr.), which could result in an estimated loss of 16.2 billion U.S. dollars annually (Soltani et al. 2016; Soltani et al. 2017). Weeds must be controlled to protect yields. Hand weeding and tillage methods have been a traditional approach of weed control in all countries. Now, developed countries, such as the United States, Japan, and Germany, rely more on herbicides for weed control as manual labor is less available and herbicides are more affordable. Herbicides are more effective at controlling weeds than hand weeding, increase yields compared to hand weeding, and improve soil health compared to tillage (Gianessi 2013).

Herbicide usage accounts for $5 billion annually in the United States and are the primary weed control method (Atwood and Paisley-Jones 2017; Brookes 2014). Increased reliance on one control method can lead to resistance development. Selection for herbicide resistant weed populations began in the 1940s (Shaner 2014). However, small herbicide resistance occurrences often went ignored until they became a major problem (Owen et al. 2014). In 1968, triazine-resistant common groundsel (*Senecio vulgaris* L.) was discovered. The triazine-resistant biotypes had reduced fitness and were easily controlled by alternative herbicides, which was presumed to be the case for future herbicide resistance cases (Shaner 2014). After weeds developed resistance to photosystem II (PSII) inhibiting herbicides, acetolactate synthase (ALS) inhibitors were seen as the solution, but resistance to ALS inhibiting herbicides rapidly developed in many weed species (Tranel and Wright 2002). New herbicide modes of action were often seen as the solution to herbicide resistant weeds. The introduction of glyphosate resistant crops in 1996 provided a brief recess from herbicide resistance development (Shaner 2014).

Before the introduction of herbicide resistant crops, weed control in soybeans consisted of multiple applications of selective herbicides, such as chlorimuron, imazamox, imazethapyr, pendimethalin, and trifluralin (Brookes 2014). The introduction of glyphosate resistant crops in 1996 led to a decrease use of different herbicide sight of actions (SOA) and glyphosate accounting for 80% of herbicide applied in glyphosate resistant soybeans (Duke 2012; Kniss 2018). Weed control in glyphosate resistant soybeans typically consisted of one or two in-crop applications of glyphosate alone. Simple, economic, and effective weed control afforded by glyphosate resistant crops led to decreased herbicide discovery and increased the selection pressure for glyphosate herbicide resistant weeds (Duke 2012).

No new herbicide SOA has been commercialized in over 20 years, so farmers have resorted back to applying multiple selective herbicides to control herbicide resistant weeds (Duke 2012). In 2012, 59% of herbicide tolerant soybeans received an additional herbicide treatment of 2,4-D pre-planting or a post-emergent (POST) application of chlorimuron, flumioxazin, or fomesafen, compared to 14% in 2006 (Brookes 2014). From 2002-2011, herbicide market value increased by 39% due to herbicide resistance and the need for alternative chemistries (Gianessi 2013). Over 200 species throughout the world have evolved resistance to one or multiple herbicides, and 41 have developed resistance to glyphosate. Palmer amaranth (*Amaranthus palmeri* S. Watson) has evolved resistance to six herbicide SOA, leaving few effective herbicide SOA for control, and is one of the most economically important glyphosate resistant weeds (Heap 2013, Heap 2019).

However, resistance development is not only seen with the use of herbicides. In Asia, hand pulling barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) selected for barnyardgrass that mimicked the appearance of rice (Barret 1983). To reduce selection on one control method, multiple control methods need to be implemented during the same growing season to control weeds and protect yields (Norsworthy et al. 2012; Thill et al. 1991).

Harker and O'Donovan (2013) discussed that any single weed control method repeated over time provides heavy selection pressure for weeds to develop resistance, so an integrated weed management (IWM) plan must be adopted. Rotation of herbicides and using multiple SOA herbicides with different, effective SOA is not considered IWM because only one control method is being utilized. Excluding herbicides is not part of an IWM plan, but diversifying control methods for an IWM plan by reducing reliance on herbicides is important (Harker and O'Donovan 2013). IWM reduces the selection pressure on herbicides and decreases the possibility of herbicide resistance development (Price et al. 2012; Snyder et al. 2016).

The importance of IWM strategies was discussed by weed scientists beginning in the 1960s, but they disagreed on what control methods an IWM plan should include (Shaw 1964; Walker and Buchanan 1982). Harker and O'Donovan in 2013 defined an IWM plan as the use of more than one weed management tactic (biological, chemical, cultural, or physical) during and surrounding a crop's life cycle in a given field. Biological control of weeds includes the use of living organisms, such as livestock, insects, bacteria, nematodes, and fungi. Chemical control of weeds is the use of herbicides. IWM includes rotating and applying multiple effective herbicide SOA along with an additional control tactic. Cultural methods include crop rotation, row spacing, planting timing, and the use of cover crops. Physical methods include tillage, hand-weeding, burning, and other methods (Harker and O'Donovan 2013).

Incorporating cultural practices into an IWM plan, such as cover crops has shown to reduce herbicide inputs and selection pressure for herbicide resistance (Price et al. 2012; Snyder et al. 2016). Combining a cereal rye (*Secale cereale* L.) cover crop with deep tillage for IWM reduced Palmer amaranth germination by 95% early in the growing season (DeVore et al. 2012). In the presence of a cereal rye cover crop, a herbicide application for weed control was not needed until four weeks after a cotton crop was planted (Korres and Norsworthy 2015). Cover crops provide an additional method of early season weed control to reduce pressure on herbicides alone.

Benefits of Cover Crops. A cover crop is a crop planted not for harvest but to achieve an environmental, agronomic, or soil health benefit. Harlan documented cover crops for their benefit as green manures that sequester nitrogen and increase soil organic matter in 1912. Research has shown the ability of cover crops to reduce nutrient loss, reduce soil erosion, increase soil organic matter (OM), increase soil structure, promote microbial activity, suppress disease and nematodes, and suppress weeds (Krutz et al. 2009; Snapp et al. 2005).

Cover crops provide benefits to increase soil health and soil fertility. Cover crops increased soil organic carbon 1.4 fold compared to cultivation with no cover crop (Steenwerth and Belina 2008). Increased organic matter from cover crops increased soil aggregate size and stability (Liu et al. 2005), which promotes root growth, increased water holding capacity, and soil structure (Danso et al. 1991). Increased organic matter correlates with increased microbial and soil fauna activity (Hartwig and Ammon 2002). Incorporating cover crops into a cropping system increased earthworm (*Lumbricus* spp.) biomass, which increased soil aeration and macropores (Hartwig and Ammon 2002). Mbuthia et al. (2015) showed increased microbial activity promotes soil health and increases nutrient availability.

Cover crops have been shown to reduce N leaching and scavenge residual N from previous crops to be used in subsequent cash crops (Burket et al. 1997; Dabney et al. 2001; Wayland et al. 1996). Legume cover crops fix atmospheric nitrogen (N) for cash crop utilization (Burket et al. 1997; Coombs et al. 2017). A hairy vetch (*Vicia villosa* Roth) cover crop provided 106 kg ha^{-1} of nitrogen to achieve a total maximum corn grain yield of 13.2 Mg ha^{-1} according to a ammonium nitrate fertilizer response curve (Spargo et al. 2016). A cereal rye cover crop integrated into a cropping system has shown to reduce erosion through decreased water and sediment loss and reduce residual herbicide loss in some instances (Krutz et al. 2009).

Crop yield is the main driver of profitability. Cover crops increased both yield and net returns in cotton (*Gossypium hirsutum* L.) when compared to fallow and conventional tillage systems (Price et al. 2012). However, cover crops have the potential to reduce yield. Clark et al. (1994) found that a cereal rye cover crop reduced corn grain yield by 1.3 Mg ha^{-1} compared to no cover crop unless additional nitrogen fertilizer was applied. Corn and soybean yields increased by 2.3 and 2.1 bushels, respectively, following a cover crop according to survey. Also, the survey of farmers on cover crops reported that those who do not use cover crops consider cost share/incentive programs the main influencing factor for adoption (Sustainable Agriculture Research & Education 2017).

Cover crops have many agronomic benefits, but many growers are reluctant to incorporate them into their cropping system because of cost and indecisiveness (Owen et al. 2014). Monetary incentives to adopt cover crops are offered through the Natural Resources Conservation Service (NRCS) and state agencies to protect water quality, reduce soil erosion, and reduce nutrient loss (Piedmont Environmental Council 2018; Natural Resources Conservation Service 2018). Pest management benefits of cover crops also play a role in farmer's economics. Incorporating cover crops, tillage, and reduced herbicide use into an IWM plan for weed control in corn resulted in a \$33.65 ha^{-1} increase in net returns when compared to a herbicide only weed management plan in Pennsylvania (Snyder et al. 2016). In the presence of heavy weed pressure, an oat (*Avena sativa* L.) cover crop increased sweet corn profit by \$590 ha^{-1} (O'Reilly et al. 2011).

Cover crops influence crop pests, including insects, pathogens, and weeds. Green cover and reduced tillage creates a favorable habitat for many insects and soil fauna (Hartwig and Ammon 2002). Cereal rye created a favorable habitat to increase beneficial insects for predation and competition on crop pests, such as aphids (*Aphis* spp.) (Hartwig and Ammon 2002). Hairy vetch (*Vicia villosa* Roth) and crimson clover (*Trifolium incarnatum* L.) in watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai) were shown to reduce Fusarium wilt (*Fusarium oxysporum* f. sp. *Niveum* Fon.) severity (Himmelstein 2013; Himmelstein et al. 2014). Bigler et al. (1995) showed green cereal rye cover was able to reduce the incidence of common smut (*Ustilago maydis* (DC.) Corda) in corn by providing a filter to keep spores from previous corn residue reaching growing corn. Brassica cover crop species produce toxic glucosinolates that provide control for nematodes (Monfort et al. 2007).

After termination, cover crop residue can suppress summer annual weeds while preserving yields (Ateh and Doll 1996). Greater cover crop biomass correlates with greater weed suppression (Teasdale et al. 1991). Mirsky et al. (2013) identified high biomass as greater than 8000 kg ha^{-1} and as a threshold for consistent suppression of annual weeds. Increased fertility, early planting date, and terminating cover crops later in the spring all increased cover crop biomass (Mirsky et al. 2011). Terminating cover crops later in the season could interfere with cash crop planting date, and increased fertility could increase weed competition. Mirsky et al.

(2011) saw an increase of over 2500 kg ha^{-1} of cover crop biomass when planted on September 5th compared to October 15th in Pennsylvania. Weed control was highest with cover crops planted early due to higher biomass production (Mirsky et al. 2011).

Cover crops suppressed summer annual weeds by as much as 56% (Reeves et al. 2005), reduced Palmer amaranth densities between cotton rows by 65% (Aulakh et al. 2012), and provided similar weed control when integrated with a pre-emergent (PRE) herbicide compared to a PRE followed by a post-emergent (POST) herbicide (Price et al. 2005). Cereal rye tends to provide the greater control of weeds compared to other cover crop species as it persists longer than legumes (Webster et al. 2013; Wiggins et al. 2016). A cereal rye cover crop reduced Palmer amaranth germination by 68% (DeVore et al. 2012) and increased the germination time of shepherd's-purse (*Capsella bursa-pastoris* (L.) Medik.) by 24% (Didon et al. 2014). In 2012, Nord et al. reported that greater cereal rye biomass resulted in less weed biomass.

Mixtures containing cereal rye can provide similar weed control as a monoculture of cereal rye while providing agronomic benefits of legumes or brassica cover crops. A cover crop mixture of cereal rye and hairy vetch provided 95% control of summer annual weeds that was similar to a monoculture of cereal while receiving the nitrogen fixation benefits of the hairy vetch (Hayden et al. 2012). However, hairy vetch has the potential to become a weed if not terminated properly (Pittman et al. 2019). Mischler et al. (2010b) reported incomplete control of hairy vetch when terminated with a roller crimper alone.

Terminating cover crops with a roller crimper breaks the vascular tissue to kill the cover crop while creating a mulch layer of residue for weed suppression (Ashford and Reeves 2003). Cover crops have traditionally been terminated by glyphosate or other herbicides in row crop agriculture in the United States (Anderson 1996). When comparing terminating a cereal rye cover crop with a roller crimper compared to herbicides alone, Davis (2010) reported no difference in weed populations, but did report less weed biomass from the roller crimper terminated cover crop compared to the herbicide terminated cover crop. Cover crop terminated by a roller crimper + glyphosate compared to cover crop terminated by glyphosate and left standing had lower redroot pigweed (*Amaranthus retroflexus* L.) densities (Moyer et al. 1999). A cover crop terminated later in the growing season had increased biomass, which allowed the roller crimper to create a thicker mulch layer to contribute to greater weed control (Mirsky et al. 2011).

Cover crops interact with weeds at many stages of the weed's life cycle and through multiple pathways, such as nitrogen immobilization, blocking germination cues, and providing a physical barrier. Cover crops with high carbon to nitrogen (N) ratios often reduce soil available N during cover crop decomposition, which reduces nutrient availability for weeds and cash crops. Soil microbes scavenge N from the soil needed to decompose the cover crop residue, which leads to low amounts of inorganic N available in the top portion of the soil for uptake by weeds (Mirsky et al. 2013). Some cover crops also have the potential to suppress weeds through the release of allelopathic chemicals (Mirsky et al. 2013). However, research has shown little effects in terms of weed control from allelopathy (Lou et al. 2015). The physical mulch layer from cover crops acts as a barrier that weeds must grow around or through to reach sunlight. This barrier requires weed seeds to exhaust their carbohydrate reserves stored in the endosperm for growth until they can perform photosynthesis. This barrier also intercepts light and prevents it from reaching weed seeds in or on the soil.

Light Effects on Weed Seeds. Light interactions in plants are regulated by photoreceptors called phytochromes. Five phytochromes have been identified in mouse-ear cress (*Arabidopsis thaliana*

(L.) Heynh.): A, B, C, D, and E. Only A, B, and E are involved in germination. C and D are involved in shade avoidance and plant growth (Baskin and Baskin 2014). In seeds, most often, germination is inhibited by far-red light with a median wavelength of 730 nm and promoted by red light with a median wavelength of 660 nm. In some cases, far-red light has shown to promote germination. This interaction occurs because phytochrome A is very sensitive to light and can be activated to promote germination by a sudden or short burst of light. Phytochrome B and E are involved in the detection of the red to far-red light ratio (R:Fr). Phytochrome B detects differences in R:Fr to promote or prevent germination. There are two forms of phytochrome B present in plants: one that inhibits germination and absorbs red light (Pr) and one that promotes germination and absorbs far-red light (Pfr). In the presence of red light, Pr is turned into Pfr and germination is initiated. In the presence of far-red light, Pfr is turned into Pr and the seed remains dormant (Baskin and Baskin 2014). Sunlight has a 1.1:1 R:Fr, which promotes germination when other requirements for germination are met, such as temperature, moisture, and nutrients (Ballare and Casal 2000). The effect of light was found to be reversible with red light followed by far-red light inhibiting germination and far-red light followed by red light promoting germination (Leon and Owen 2003).

Light is a requirement for many small seeded weeds to germinate, but not most crop seeds (Ballare and Casal 2000). Annual ryegrass (*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot), redroot pigweed, smooth pigweed (*Amaranthus hybridus* L.), common ragweed (*Ambrosia artemisiifolia* L.), and Palmer amaranth germination has all been documented to be affected by light in some way (Deregibus et al. 1994; Gallagher and Cardina 1998; Jha et al. 2010; Pickett and Baskin 1973). Small seeded weeds have less energy stored for growth in their endosperm to reach light to begin photosynthesis. Germination of some weed species is more influence by temperature than by light and often cold stratification can make weed seeds more sensitive to light (Leon and Owen 2003).

Shade from crop canopy and cover crops can be used to manage phytochrome mediated weeds. Jha and Norsworthy (2009) showed that as the soybean canopy closed, Palmer amaranth germination declined, indicating light penetrating through green cover has the potential to reduce weed pressure. Shading and light interception from cover crops can also suppress weeds (Liebert et al. 2017). Cover crops reduced the quantity of photosynthetically active radiation that reached the soil surface to reduce weed germination (Wayman et al. 2015). Teasdale and Mohler (1993) found that as cover crop biomass increased, the amount of light penetrating the canopy and reaching the soil surface decreased. Light interception in cereal rye lasted longer than hairy vetch as it degraded slower due to a higher C:N ratio, indicating it to be a good candidate for weed control. A slightly lower R:Fr was observed under a terminated cover crop canopy than unfiltered sunlight (Teasdale and Mohler 1993).

Herbicide Carryover to Cover Crops. Establishment is essential to maximize cover crop biomass and therefore weed control; however, there is the potential for herbicide carryover to cover crops (Cornelius and Bradley 2017). Cornelius and Bradley (2017) saw cover crop stand reduction from carryover of thirteen herbicides used in soybean and nine herbicides used in corn. Carryover from pyroxasulfone reduced Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot) and winter oats (*Avena sativa* L.) biomass by 67%. Treatments containing imazethapyr, fomesafen, and flumetsulam resulted in the greatest herbicide carryover symptoms across all cover crop species (Cornelius and Bradley 2017). Other research indicates that atrazine and metasulfuron injured wheat a year after it was applied (Moyer et al. 2010). Pendimethalin and imazethapyr reduced stand and biomass of cover crops after being applied in the previous cash crop (Tharp and

Kells 2000, Hanson and Thill 2001). Mirksy et al. (2017) observed reduced annual ryegrass biomass from carryover of *S*-metolachlor, pyroxasulfone, pendimethalin, and dimethenamid-*P*; and 80% reduction of red clover *(Trifolium pretense)* biomass by mesotrione. Herbicide carryover is determined by the interaction of many factors, including specific herbicide properties, soil physical and chemical properties, weather, and cover crop species sensitivity.

Herbicide persistence in the soil depends on its ability to be physically or chemically removed or degraded, which is determined by soil factors, climate, and herbicide properties (Blasioli et al. 2011). Soil texture, cation exchange capacity (CEC), pH, and organic matter (OM) content affect herbicide persistence in soil. The more herbicide adsorbed to soil, the more likely it is to persist in the soil because less of the herbicide is in soil solution to be taken up by plants, leached, or degraded (Anderson 1983). Generally, higher clay content, increased soil OM, and higher CEC increases the amount of herbicide bound to soil particles and decreases herbicide loss to volatilization, leaching, microbial degradation, and plant uptake (Blasioli et al. 2011; Loux and Reese 1993). Soils with a higher clay content increase the half-life of some herbicides. Pyroxasulfone's half-life ranged from 104 to 134 days in finer textured clay loam soils compared to 46 to 48 days in a sandy loam soil (Westra et al. 2014). Fomesafen and imazethapyr carryover is correlated with extended half-life in clay soils (Mueller et al. 2014). Sulfentrazone applied to soils with higher CEC showed less damage when applied before sunflower planting. The CEC of soil is increased by soil OM and higher in finer textured soils (Kerr et al. 2004). Organic matter has the greatest adsorption strength for agrochemicals (Blasioli et al. 2011).

Depending on the herbicide, changes in soil pH can extend the half-life and persistence of herbicides. As pH decreases, chemical and microbial breakdown of herbicides are slower, so some herbicides will persist longer (Blasioli et al. 2011). However, triazine herbicides degrade quicker in lower pH soils most likely due to a chemical process (Chen et al. 2018; Chan-Cupul et al. 2015). Conversely, imidazolinone herbicides, such as imazaquin and imazethapyr, persistence in the soil increases as soil pH decreases (Loux and Reese 1993). At neutral pH, cloransulam has a 200 day half-life (Shaner et al. 2014).

Climatic conditions such as moisture and temperature can affect herbicide persistence in the soil. Herbicide degradation is faster in warm temperatures and with adequate moisture because of increased microbial activity (Zimdahl 2007). However, too much soil moisture can decrease soil microbial activity. As soil moisture increases above 41% of absolute moisture, microbial activity decreases (Prado and Airoldi 1999). Pendimethalin degraded faster with higher rainfall (Zimdahl et al. 1984). The degradation rate of simazine, atrazine, and diuron increases as soil moisture increases (Bauer and Calvet 1999). Herbicides degrade quicker in moist soils because they are more readily available for plant uptake and microbial degradation. Soil colloids are hydrophilic, so water displaces the herbicide molecules and reduces the amount of herbicide adsorbed to the soil (Anderson 1983). Thus indicating that herbicide persistence in the soil could increase in drought conditions because more herbicide is bound to soil colloids and less would be leached through the soil profile. The interaction between herbicide degradation and climatic conditions is also affected by the herbicide structure and chemical properties.

A herbicide’s water solubility, volatility, ability to bind to soil and organic matter, and soil half-life affect its persistence in the soil. Herbicides that are readily water soluble remain in soil solution and are more likely to be leached out of the soil profile or taken up by plants. However, herbicides that are strongly adsorbed to soil may not be displaced by water and some herbicides can react with chemicals in the soil to form water-insoluble compounds (Anderson 1983; Braschi et al. 2011). The soil sorption index is the KOC. This unit is used to express the sorption of herbicide to soil and soil organic matter. The higher the KOC the more likely the herbicide will be absorbed to the soil, the longer it will persist in the soil, and less likely the herbicide will be lost to leaching (Monaco et al. 2002). Cantwell et al. (1989) found that imidazoline degradation depends on the amount in soil solution. Less herbicide adsorbed to the soil, means more will be available for degradation in soil solution. The amount of herbicide in soil solution also determines the amount at risk for volatilization.

The vapor pressures of herbicides affect their ability to volatilize and be lost to the atmosphere. Herbicides with higher vapor pressures are more likely to volatilize and less likely to persist in soil (Blasioli et al. 2011). Volatility of herbicides can be minimized by incorporating them into the soil or using granules. The energy needed to cause volatilization is called the latent heat of vaporization. This energy can be increased to reduce the ability of a herbicide to volatilize by altering the herbicides molecular structure. For example, the volatility of 2,4-D can be decreased by increasing the length and mass of its side chains (Anderson 1983). Decreased vapor pressure reduces the possibility of volatilization and increases the amount of herbicide that remains in the soil. The duration that the herbicide remains in the soil is defined as the herbicides half-life. Herbicide soil half-life is the loss of herbicide through all possible pathways that act on herbicide in the soil environment. The longer the soil half-life, the longer the herbicide remains active and the higher potential for carryover to future crops (Monaco et al. 2002).

The risk of herbicide carryover onto cover crops is influenced by soil and herbicidal properties, but the susceptibility of the cover crop to a specific herbicide also determines the potential risk of herbicide carryover. Susceptibility is the level of a certain herbicide that injures the target plant. If a plant has a higher degree of susceptibility, then it will show a greater response to the herbicide (Anderson 1983). Cover crop susceptibility is influenced by all the factors previously discussed in regard to herbicide persistence, the toxicity of the herbicide to the plant, and the biological factors of the cover crop.

The physiology, morphology, and herbicide metabolism of the cover crop influences its susceptibility. In grass species, the coleoptile node is a major site of herbicide entry into the plant. This node remains under the soil surface, but its location under the soil surface varies by species. Depending on the location of the herbicide in the soil and the location of the coleoptile node, the herbicide may cause injury or the plant may avoid the herbicide. For example, barley's coleoptile node remains 1.3 cm above the seed, so the coleoptile depth in the soil depends on the seeding depth (Anderson 1983). The seed size also contributes to the ability of the seedling's roots to outgrow the layer of herbicide treated soil. Large seeded species can elongate unexpanded cells in their radicles for roots to outgrow the herbicide treated layer of soil before significant injury occurs to the plant (Anderson 1983). Cover crops can outgrow and avoid herbicide injury, but once the herbicide enters the plant, the cover crop can be damaged or metabolize the herbicide to reduce its toxicity.

When the herbicide enters the cover crop, the herbicide must translocate to its site of action to be effective. Translocation of herbicides varies between species. After the herbicide enters a plant cell, the herbicide can be metabolized, react with chemicals to form immobile or insoluble conjugates, be transported to a herbicide insensitive sink, be secreted from the plant, or translocate to the active site to affect the plant (Anderson 1983). For example, pyroxsulam is used as a selective herbicide to control blackgrass in wheat because wheat shows less translocation of the herbicide compared to blackgrass, which can be attributed to the increased metabolism of pyroxsulam (deBoer et al. 2010), and florasulam is selectively used in wheat to control broadleaf weeds because wheat metabolizes the herbicide (deBoer et al. 2006).

In summary, herbicide persistence in soil depends on climate, herbicide properties, and soil properties. Herbicides applied during the cash crop growing season has shown the potential to persist in the soil and injure cover crops. Based on the complex interactions and variation in herbicide degradation among climate and soil conditions, research is needed to corroborate previous research and evaluate herbicide carryover potential to reduce establishment of cover crops commonly used in the Mid-Atlantic region of the United States of America. The interaction between herbicide persistence and cover crop injury is complex and site specific, so additional localized research is needed.

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Winter Annual Weed Control of Early Planted Cover Crops and Soil Applied Residual Herbicides

Abstract

Winter annual weeds can interfere with cash crop planting. Cover crops produce residue that suppresses summer annual weeds, but little research exists on their ability to suppress winter annual weeds while actively growing and how that compares to a fall applied residual herbicide. Field studies were conducted in Blacksburg, Virginia in 2017 and 2018, Christiansburg, Virginia in 2017, and West Point, Virginia in 2018 to determine the ability of early planted cover crops to suppress winter annual weeds prior to cash crop planting and compare that to a fall-applied residual herbicide, flumioxazin. Cover crops were planted in September and fertilized to maximize cover crop biomass. Cover crop treatments consisted of monocultures, two-way, and three-way mixtures of cereal rye, crimson clover, hairy vetch, and forage radish. Cover crop mixtures produced greater biomass compared to monocultures as a group, due to the lower biomass of the legume monocultures. Flumioxazin provided similar control as the average of all cover crops across all weed species rated in December. Flumioxazin provided less Persian speedwell control and similar control of purple deadnettle, and yellow woodsorrel compared to the average of all cover crops at cover crop termination in May. Cereal rye containing treatments provided greater than 85% control of all weed species at cover crop termination. As cover crop biomass increased to 6000 kg ha^{-1}, winter weed biomass decreased at cover crop termination in May to less than 200 kg ha^{-1}. Cereal rye containing treatments were more effective at reducing winter annual weed density in mid-March compared to legume monocultures and forage radish. No difference was observed in winter annual weed control between cereal rye alone or in a

mixture. Cereal rye can be used in a mixture to receive the additional agronomic benefits of a legume or brassica cover crop species without compromising winter annual weed control, and cereal rye is more effective at controlling winter weeds compared to a fall applied residual herbicide.

Introduction

The use of herbicide resistant crops caused a reduction in the use of residual herbicides and tillage as a weed control tactic, which led to an increase in winter annual weed populations (Banerjee et al. 2009, Gueli and Smeda 2002; Hasty et al. 2002; Krausz et al. 2003).Winter annual weeds cause difficulty planting, increase competition with cash crops, and provide a potential host for plant pathogens (Buhler 1995; Creech et al. 2005; Dahlke et al. 2001; Kremer 2005; Venkatesh et al. 2000).

Typically, a herbicide preplant application is made to control all weeds prior to cash crop planting in the spring. However, weed control prior to cash crop planting has become more difficult as herbicide resistance has developed in winter annual weeds, such as horseweed (*Conyza canadensis* L.) (Heap 2019). Fall applied residual herbicides and cover crops have been shown to provide an alternative method to control winter weeds to provide relatively weed free conditions prior to cash crop planting in the subsequent spring (Cornelius and Bradley 2017; Krausz et al. 2003; Monnig and Bradley 2008). Krausz et al. (2003) documented greater than 90% control of at least one winter annual weed species by fall-applied atrazine, simazine, rimsulfuron plus thifensulfuron, flumetsulam, and metribuzin. A fall application of 2,4-D plus simazine, rimsulfuron plus thifensulfuron plus 2,4-D, and glyphosate plus 2,4-D also provided at least 90% control of winter weeds prior to cash crop planting (Monnig and Bradley 2008). Cornelius and Bradley (2017) saw greater winter weed control from a fall applied herbicide when compared to a cereal rye and cereal rye plus hairy vetch cover crop.

Fall planted cover crops affect winter weeds throughout their entire life cycle. While winter annual cover crops are actively growing, they compete with and suppress winter annual weeds. A cereal rye cover crop suppressed winter annual weeds by at least 90% (Hayden et al.

2012; Werle et al. 2018). Pittman et al. (2019) reported 88% to 96% suppression of horseweed from winter annual cover crops in the spring, prior to cover crop termination. Forage radish provided 100% control of winter annual weeds in the fall (Lawley et al. 2011).

Growers need additional tools to combat herbicide resistant weeds and control winter annual weeds prior to cash crop planting. Research has shown that cover crops can compete with winter annual weeds; greater cover crop biomass, which can be achieved through fertility and early planting date, results in greater weed control (Mirsky et al. 2011). Furthermore, cover crop mixtures tend to be more efficient in using resources than monocultures (Liebman and Dyck 1993), which suggest that mixtures may be more competitive with winter weeds. However, little research exists on the effects of early planted cover crops and cover crop mixtures to compete with winter annual weeds. The objective of this study is to evaluate the ability of early planted cover crop monocultures and mixtures to control winter annual weeds in early spring, compared to a fall applied residual herbicide.

Materials and Methods

Study Sites. Locations were Blacksburg, Virginia at Kentland Farm (37.192913, -80.573942), which is located in the New River flood plain with a Ross soil (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls) in 2017 and 2018, Christiansburg, Virginia (37.093837, -90.447115) in the New River Valley with a Berks-Groseclose complex (loamy-skeletal, mixed, active, mesic Typic Dystrudepts; fine, mixed, semiactive, mesic Typic Hapludults) in 2017, and West Point, Virginia (37.544890, -76.907342) in 2018. The West Point location was located in the coastal plain region of Virginia on a Pamunkey fine sandy loam (fine-loamy, mixed, semiactive, thermic Ultic Hapludalfs). The Blacksburg location was previously fallow in both years, and the Christiansburg location was in no-till planted winter wheat (*Triticum aestivum* L.) the previous year. The West Point location was previously in corn (*Zea mays* L.). Paraquat (Helmquat 3SL; Helm Agro US, Inc; Tampa, FL) was applied at 0.56 kg ai ha^{-1} with COC at 1% v v^{-1} directly before cover crop planting at all locations and years.

Experimental Design. The experiments utilized a randomized complete block design with 4 replications. Plots were 3 by 39.6 meters. There were 10 treatments in addition to a no-cover control. Treatments were monocultures of cereal rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth), and forage radish (*Raphanus raphanistrum* subsp. *sativus* (L.) Domin.); mixtures of cereal rye + crimson clover, cereal rye + hairy vetch, cereal rye + forage radish, cereal rye + crimson clover + forage radish, and cereal rye + hairy vetch + forage radish; and flumioxazin at 0.11 kg ai ha^{-1}. Seeding rates are presented in Table 1.

Field Management and Data Collection. Cover crops were planted with a Tye drill (AGCO Corporation Headquarters, Duluth, GA) on 16.5 cm rows and flumioxazin (Valor; 0.11 kg ai ha^{-}

^{1}; Valent U.S.A. Corporation; Walnut Creek, CA) was applied with a CO_2 pressurized backpack sprayer delivering 140 L ha^{-1} with a hand boom equipped with 6 XR 11002 nozzles (TeeJet®, Spraying Systems Co., Wheaton, IL) on 46 cm spacing on September 1, 2018 in Blacksburg, September 4, 2018 in Christiansburg, September 6, 2019 in Blacksburg, and September 9, 2019 in West Point. The whole experiment was fertilized with 44.8 kg ha^{-1} of nitrogen and 22.4 kg ha^{-1} of phosphorus as P_2O_5 and potassium as K_2O 4 weeks after planting to increase biomass. The whole experiment was terminated on May 2, 2018 and May 1, 2019 at Blacksburg and May 3, 2018 at Christiansburg.

Data collected included visible winter annual weed control, cover crop biomass, a spring weed survey, and biomass of winter annual weeds. Cover crop biomass was taken both immediately after the first killing frost, which occurred around December 5th each year, and prior to cover crop termination, which occurred in early May each year. Above ground biomass was measured from the middle of each plot in a 0.25 m^2 quadrat. Biomass was taken after the first killing frost to document the effects of forage radish prior to winter kill. After collection, biomass was dried at 65.5ºC for 3 days and weighed. Visible weed control was taken on a 0 to 100% scale compared to the no cover control, with 0 being no control and 100 being complete weed control. Visible control data were taken mid-November and at cover crop termination. Visible weed control data were collected on the most abundant weed species present at each location. A spring weed survey consisted of quantifying the number of weeds present by species in a random 0.25 m^2 quadrat in mid-March. All weeds were counted by species in a 0.25 m^2 quadrat and then summed for weed density. Counts were converted to weeds m^{-2} for presentation. For weed diversity, the total number of weed species present were summed.

Biomass of winter annual weeds was collected at cover crop termination as previously described. All data were collected randomly in a uniform representative area of each plot.

Data Analyses. Data analyses were conducted using JMP Pro 13 (SAS Institute, Inc., Cary, NC). Treatment, location, and interactions of location and treatment were considered fixed effects and block and year were considered random effects for the cover crop and weed biomass and spring weed survey (species diversity and density) analyses. For the visible weed control analyses, the full model was used for Persian speedwell (*Veronica persica* Poir.). Purple deadnettle (*Lamium purpureum* L.) was only present at Christiansburg and Blacksburg in 2017, so year was not included in these models. Yellow woodsorrel (*Oxalis stricta* L.) was only present at Christiansburg and henbit (*Lamium amplexicaule* L.) was only present at West Point, so year and location were excluded from those models.

Data were subject to ANOVA (α=0.05) to determine if there were significant effects and interactions. If no significant interactions were detected between treatment and location and if location was considered in the model, then data were pooled across location. Subsequently, contrast statements were used at α=0.05 to address the study objectives. An exponential regression was utilized to relate weed biomass with cover crop biomass at cover crop termination.

The flumioxazin containing treatment was excluded from all analysis involving cover crop biomass as there was no cover crop. Forage radish as a monoculture was excluded from the analysis for cover crop biomass at cover crop termination and the regression for winter weed biomass at cover crop termination by cover crop biomass as the forage radish winter killed and there was no living cover crop to compete with weeds. The West Point location was not included in the visible control analysis at cover crop termination due to early cover crop termination.

Results and Discussion

Cover Crop Biomass. There was not a significant interaction of treatment by location (p=0.139) for cover crop biomass taken at the first killing frost, so data were pooled over locations. Forage radish alone produced the greatest biomass at this time with 2228 kg ha^{-1}, and crimson clover produced the least with 342 kg ha^{-1}. Cereal rye biomass more than doubled the biomass of the average of legume monocultures in the fall. Forage radish produced more biomass at the first killing frost than the average of cover crop mixtures with 2228 and 1487 kg ha^{-1}, respectively (Figure 1). Forage radish grows more rapidly in the fall to accumulate biomass and compete with weeds compared to the other cover crops utilized in this study. Baraibar et al. (2018) saw similar forage radish biomass in the fall prior to winter kill ranging from 1643 to 2094 kg ha^{-1} across three years in Pennsylvania.

West Point was excluded from the cover crop biomass at termination analysis due to early termination of the cover crop. A significant interaction was not detected for treatment by location (p=0.508) for cover crop biomass at cover crop termination, so data were pooled across location. Cover crop biomass ranged from 3656 to 8936 kg ha^{-1} (Figure 2). Cereal rye alone produced over 3500 kg ha^{-1} more than the legume monocultures, on average. The average biomass of cover crop mixtures, two-way mixtures, and three-way mixtures was greater than the average biomass of cover crop monocultures, which was driven by the legume monocultures. There was no difference observed between cereal rye biomass and the average of cover crop mixtures. There was no difference in biomass between two-way and three-way cover crop mixtures (Figure 2).

Pittman et al. (2019) saw similar results with legume monocultures being out produced by cereal rye and cereal rye producing similar biomass as the average of cover crop mixtures. Pittman et al. (2019) also saw a difference between the biomass of cover crop monocultures and cover crop mixtures taken at termination, which was attributed to the lower biomass of the legume monocultures. Cereal rye alone produced similar biomass as document by Mirsky et al. (2013), and cover crop mixtures produced similar biomass as documented by Finney et al. (2016).

Winter Annual Weed Control at First Killing Frost. Persian speedwell data were collected at all locations and years except West Point. Purple deadnettle data were collected at Christiansburg and Blacksburg in 2017. Henbit data were only collected at West Point, and yellow woodsorrel data were only collected at Christiansburg. A difference was not detected in treatment by location (p=0.999) for Persian speedwell control at the first killing frost, so data were pooled across Blacksburg and Christiansburg. Persian speedwell control ranged from 43 to 81%. The average of the monocultures and the average of the two-way cover crop mixtures provided less Persian speedwell control compared to the three-way mixtures with 59, 52, and 77% control, respectively (Figure 3 and Table 2). No other differences were detected indicating that most cover crops and flumioxazin performed similarly for Persian speedwell.

Purple deadnettle data were pooled across Christiansburg and Blacksburg in 2017 as treatment by location (p=0.999) was not significant. Purple deadnettle control ranged from 44 to 84% (Figure 3). The three-way mixtures provided more control than the two-way mixtures with 79 and 53% control, respectively (Table 2). Flumioxazin and hairy vetch + forage radish + cereal rye provided greater than 80% control (Figure 3).

Yellow woodsorrel was only rated at Christiansburg in 2017-2018. There were no differences observed by our contrast statements (Table 2.) The three-way mixtures of hairy vetch + forage radish + cereal rye and crimson clover + forage radish + cereal rye provided greater than 80% yellow wood sorrel control. Henbit was only rated at West Point in 2018, and there were also no differences observed in our contrast statements, most likely due to uneven henbit populations throughout the field. Cereal rye alone provided the greatest henbit control with 83%. Forage radish provided the least control with 20%.

Flumioxazin provided similar weed control as the average of all cover crops across all weed species, suggesting a fall applied residual herbicide can be as effective at controlling winter annual weeds in the early winter (Table 2). In two of the four weeds rated, the three-way mixtures were more effective at controlling winter annual weeds compared to the two-way mixtures, suggesting a cover crop mixture containing forage radish provides greater competition with winter annual weeds early in their life cycle. We did not observe 100% weed control from forage radish as documented by Lawley et al. (2011) most likely due to differences in soil and climate in eastern Maryland. Forage radish grows quickly to produce its biomass in the fall before winter killing, so it will grow quick to be more competitive with winter weeds in the fall compared to grass and legume cover crop species.

Spring Weed Survey. Weeds present in at least one location were purple deadnettle, Persian speedwell, common chickweed (*Stellaria media* (L.) Vill), hairy bittercress (*Cardamine hirsute* L.), downy brome (*Bromus tectorum* L.), dandelion (*Taraxacum officinale* F.H. Wigg.), Carolina geranium (*Geranium carolinianum* L.), purslane speedwell (*Veronica peregrina* L.), cutleaf evening-primrose (*Oenothera laciniata* Hill), mouseear chickweed (*Cerastium fontanum* Baumg. ssp. *vulgare* (Hartm.) Greuter & Burdet), horseweed (*Conyza canadensis* L.), henbit (*Lamium* *amplexicaule* L.), prickly lettuce (*Lactuca virosa* L.), corn gromwell (*Buglossoides arvensis* (L.) I.M. Johnson), annual bluegrass (*Poa annua* L.), catchweed bedstraw (*Galium aparine* L.), and poison-hemlock (*Conium maculatum* L.).

There was not a significant treatment by location interaction (p=0.184) for the total number of weedy plants m^{-2}, so data were pooled across location. The average of all cover crop treatments and flumioxazin alone reduced spring weed density compared to the no cover control (Figure 4). There was not a difference in the number of weedy plants between the average of cover crop treatments or cover crop mixtures compared to flumioxazin with 111, 90, and 72 weedy plants m^{-2}, respectively. Cereal rye-containing treatments had a lower weed density compared to both legume monocultures and forage radish. The average weed density of cover crop monocultures (138 weedy plants m^{-2}) was greater than the average of two-way cover crop mixtures (84 weedy plants m^{-2}), which was due to the large number of weedy plants in the legume monocultures and forage radish (Figure 4).

Overall, cover crops containing cereal rye were more effective at reducing weed density in the spring compared to legumes or forage radish in monoculture. Flumioxazin was able to reduce weed density similar to those of cover crops suggesting that a fall-applied residual herbicide can aid in winter weed control. Cornelius and Bradley (2017) observed greater reduction in weed density of a fall-applied residual herbicide compared to a cereal rye or cereal rye + hairy vetch cover crop, but they saw similar results from a cereal rye cover crop with 68 to 72% reduction in weed density. Pittman et al. (2019) also saw a reduction in winter weed density between cover crop treatments and the no cover control, but they did not observe differences in cereal rye-containing treatments compared to legumes or forage radish in monoculture.

A significant treatment by location interaction was detected (p=0.013) for number of weed species in each plot recorded in mid-March, so data were separated by location. At Blacksburg, cereal rye-containing treatments had fewer weed species 0.25 m^{-2} compared to the average of legume monocultures (Table 3). Two-way and three-way mixtures had fewer weed species present when compared to cover crop monocultures with 2.46, 2.69, and 3.94 species, respectively. Cover crop mixtures also reduced the number of weed species compared to flumioxazin.

At Christiansburg, the only differences observed in contrast statements were between cover crops and cover crop mixtures compared to flumioxazin. Flumioxazin had fewer weed species 0.25 m^{-2} (0.5) compared to cover crop mixtures (1.5) and the average of all cover crops (1.42) (Table 3). At West Point, cereal rye reduced the number of weed species present compared to cover crop mixtures. The only location with a difference in the number of weed species between cover crops and the no cover control was West Point with 2.48 and 4 weed species 0.25 m^{-2}, respectively.

There were no differences observed in weed species 0.25 m^{-2} at any location between flumioxazin and the no-cover control (Table 3). Cover crops resulted in a decrease in the number of weed species 0.25 m^{-2} at only one location. Results indicate that flumioxazin and cover crops have little impact on the amount of weed species present.

Winter Weed Biomass at Cover Crop Termination. The West Point location was omitted from this analysis due to early cover crop termination. Winter weed biomass was collected together and not separated by species. There was not a significant interaction in treatment by location (p=0.128), so data were pooled across Blacksburg 2017 and 2018 and Christiansburg 2017. Forage radish was excluded from contrasts involving cover crop monocultures due to winter killing. Winter weed biomass ranged from 2 to 1929 kg ha^{-1} with forage radish having the most and cereal rye having the least.

Cover crop mixtures led to lower winter weed biomass compared to flumioxazin (Figure 5). Flumioxazin only reduced winter weed biomass by 51% compared to the no cover control. Flumioxazin did reduce winter weed biomass compared to forage radish. Cereal rye containing treatments reduced winter weed biomass compared to legume monocultures and forage radish. Forage radish led to an increase in winter weed biomass compared to the no cover control, due to the fact that the forage radish winter killed and there was nothing present subsequently to compete with weeds. There was not a difference in winter weed biomass between cover crop monocultures compared to two-way or three-way cover crop mixtures.

Cover crop mixtures were more effective at reducing winter weed biomass than flumioxazin as the cover crop mixtures can actively compete with winter weeds, throughout the season while flumioxazin dissipates over the course of the season. The average of all cover crops did not reduce winter weed biomass to the level of flumioxazin due to the poor control by forage radish. Hayden et al. (2012) saw similar results with a 98% reduction in winter weed biomass from a cereal rye monoculture. Pittman et al. (2019) saw similar results with 50% more horseweed biomass reduction following a cereal rye-containing cover crop compared to legumes in monoculture. Overall, cereal rye and cover crop mixtures effectively reduced winter weed biomass by at least 90%, and thus cereal rye can be used in mixtures to control winter weeds while receiving additional benefits from legume and/or brassica cover crops. Baraibar et al. (2017) observed lower winter weed biomass in radish with 81 kg ha^{-1} in the spring compared to our results, most likely due to differences in weed species and growing conditions.

Winter Annual Weed Control at Cover Crop Termination. The West Point location was omitted from this analysis due to early cover crop termination. Weeds rated were Persian speedwell at Christiansburg and Blacksburg in all years, purple deadnettle at Blacksburg in 2017 and Christiansburg, and yellow woodsorrel at Christiansburg. A significant interaction for treatment by location was detected for Persian speedwell ($p<0.001$), so data were separated by location. A significant interaction was not detected for purple deadnettle ($p=0.149$) control, so data were pooled across location. Forage radish was again excluded from contrasts involving cover crop monocultures due to winter killing.

Forage radish was the only cover crop treatment to provide less than 80% Persian speedwell control at Blacksburg with 30% control (Figure 6). Cover crops (86%) and cover crop mixtures (95%) provided greater control than flumioxazin (66%) at Blacksburg, but there was no difference at Christiansburg. Flumioxazin did provide greater Persian speedwell control compared to forage radish at Blacksburg with 66 and 30% control, respectively but not at Christiansburg (Table 4). Legume monocultures provided similar Persian speedwell control as cereal rye-containing treatments at Blacksburg (87 and 95%, respectively), but cereal rye-containing treatments provided greater control at Christiansburg (87 versus 53%). Similar Persian speedwell control observed between cereal rye and cover crop mixtures at both locations. Two-way cover crop mixtures provided greater Persian speedwell control than cover crop monocultures at Christiansburg but not at Blacksburg, most likely due to the poor control from legume monocultures at Christiansburg (Figure 6 and Table 4).

Flumioxazin provided similar purple deadnettle control as the average of all cover crops and cover crop mixtures with 79, 83, and 92% control, respectively. Cereal rye-containing treatments provided greater control (92%) than legume monocultures (66%) and a forage radish monoculture (63%). Two-way and three-way mixtures provided greater purple deadnettle control compared to cover crop monocultures, but three-way mixtures did not provide greater control compared to two-way mixtures (Table 4).

Flumioxazin provided similar yellow woodsorrel control as cover crops, but provided less control compared to cover crop mixtures (Table 4). Hairy vetch and crimson clover provided the least yellow woodsorrel control with 47 and 53%, respectively (Figure 6). Cereal rye-containing treatments provided greater yellow woodsorrel control (87%) compared to legume monocultures (50%). Cover crop monocultures controlled yellow woodsorrel less than two-way mixtures likely due to the low control from crimson clover and hairy vetch (Figure 6 and Table 4).

Forage radish, crimson clover, hairy vetch, and flumioxazin never provided greater than 80% control of any weed species, except for crimson clover and hairy vetch at Blacksburg on Persian speedwell (Figure 6). All winter annual weed species were controlled more by cereal-rye containing treatments compared to legume monocultures, except for Persian speedwell in Blacksburg (Table 4), which reinforces the importance of using cereal rye in a mixture or as a monoculture to increase winter annual weed control. Pittman et al. (2019) observed similar results with 88 to 97% reduction in winter annual weed control by all cover crop treatments, including those containing cereal rye, but they did not observe differences between cereal rye-containing treatments and legume monocultures, most likely due to differences in weed species evaluated. Creech et al. (2008) saw different results with greater winter weed control from a fall applied herbicide compared to a fall seeded cover crop. Werle et al. (2018) also saw at least 85% control of winter annual weeds by a cereal rye cover crop.

We did not observe a difference between cereal rye as a monoculture compared to all cover crop mixtures or between two-way and three-way mixtures (Table 4). Cereal rye can be used in a mixture to receive the additional agronomic benefits of a legume or a forage radish cover crop without sacrificing winter annual weed control. Baraibar et al. (2018) reported similar results with greater winter weed control when incorporating a grass species into a cover crop mixtures or using grass species as a monoculture compared to without a grass species.

There was a negative correlation with weed biomass as cover crop biomass increased. Winter weed biomass decreased to less than 200 kg ha^{-1} at 6000 kg ha^{-1} of cover crop biomass (Figure 7). Cover crop biomass was able to account for only 32% of the variation in winter weed biomass. Variability may be explained in that cover crop biomass was used to measure winter weed biomass, which is not necessarily a complete measure of cover crop competition, especially across four different cover crop species.

Management Implications. Cereal rye is needed in a cover crop to maximize biomass and maximize winter weed suppression compared to the cover crops utilized in this study. Flumioxazin applied in the fall controlled winter weeds compared to the no cover control, but in most cases, flumioxazin provided less control compared to cover crop mixtures at cover crop termination in May. Cover crop mixtures that contain cereal rye can control winter weeds greater than cover crop monocultures in most cases while still providing the agronomic benefits of a legume or forage radish. Incorporating a cereal rye containing cover crop into a cropping system can reduce winter annual weed populations, likely making preplant burndown herbicide applications more successful and allowing for easier cash crop planting and establishment.

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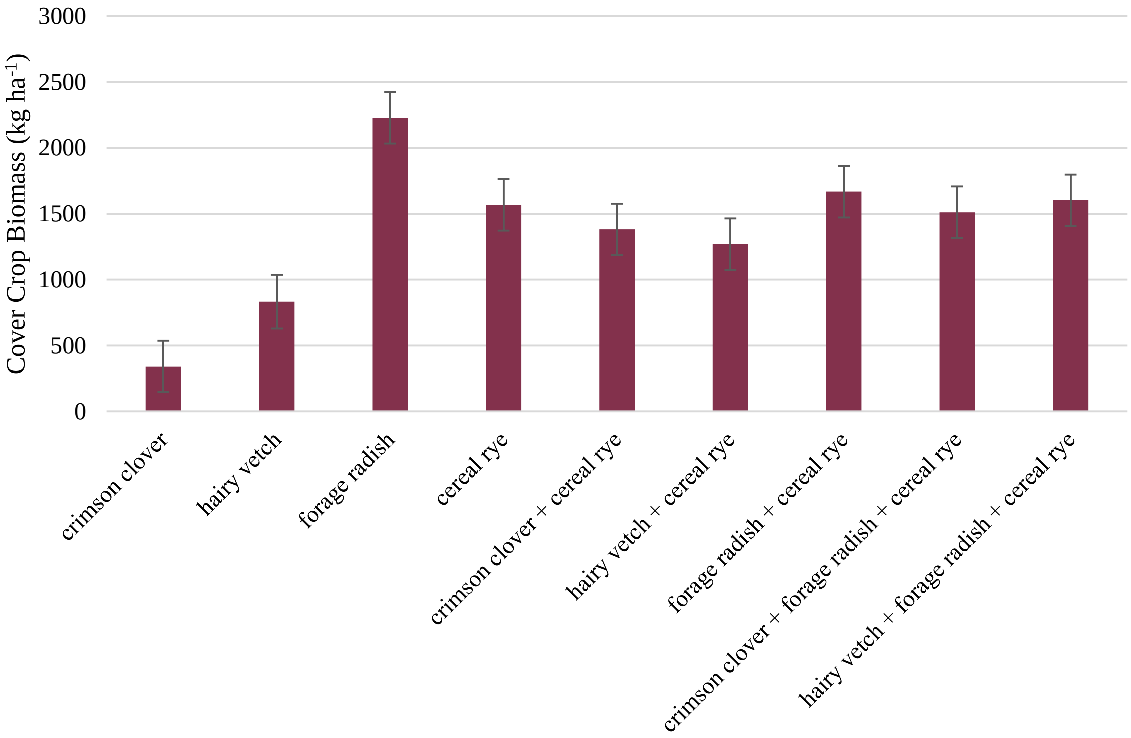
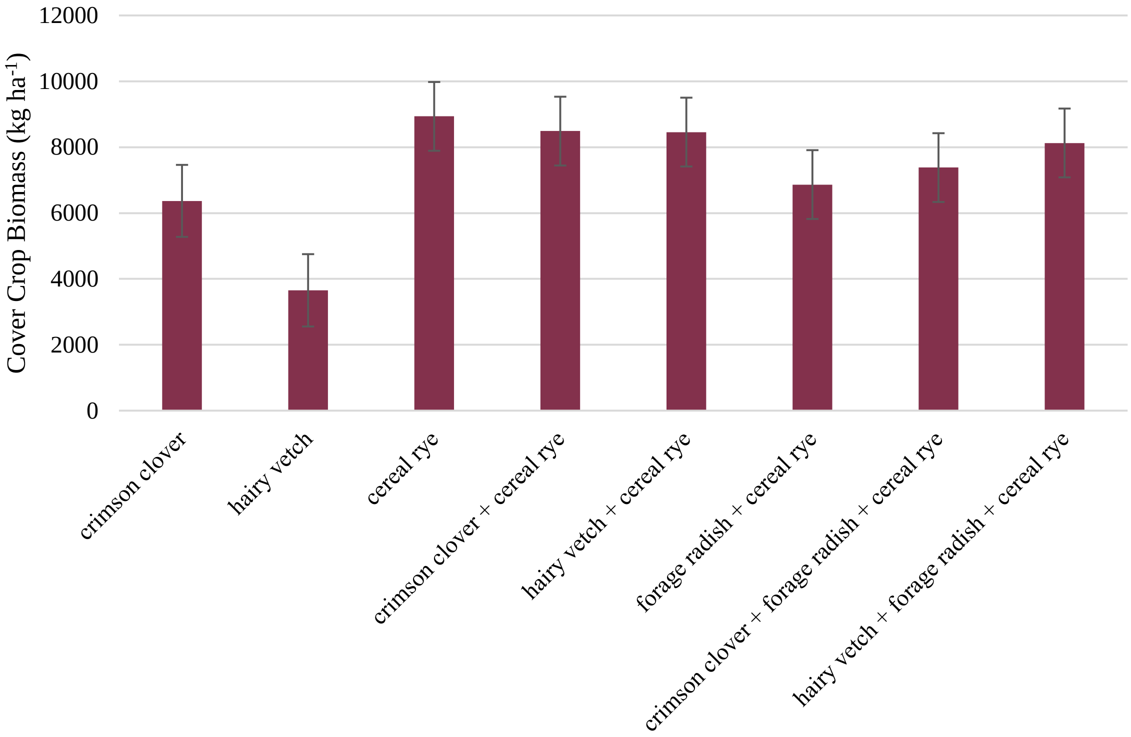
Table 1. Treatments evaluated for winter annual weed suppression in field experiments in Blacksburg (2017 and 2018), Christiansburg (2017), and West Point (2018), VA.

	Cover Crop							
Treatments	Species 1	Seeding Rate	Species 2	Seeding Rate	Species 3	Seeding Rate	Herbicide	Rate
		kg ha^{-1}		kg ha^{-1}		kg ha^{-1}		kg ai ha^{-1}
1	Crimson clover	22	---	---	---	---	---	---
2	Hairy Vetch	28	---	---	---	---	---	---
3	Forage radish	9	---	---	---	---	---	---
4	Cereal rye	125	---	---	---	---	---	---
5	Crimson clover	16	Cereal rye	50	---	---	---	---
6	Hairy Vetch	20	Cereal rye	50	---	---	---	---
7	Forage radish	5	Cereal rye	69	---	---	---	---
8	Crimson clover	13	Cereal rye	38	Forage radish	2	---	---
9	Hairy Vetch	17	Cereal rye	38	Forage radish	2	---	---
10	---	---	---	---	---	---	Flumioxazin	0.12
11	---	---	---	---	---	---	---	---



Contrasts	Mean of 1st term	Mean of 2nd term	p-value
	-------kg ha^{-1}-------		
Cereal rye vs. legume monocultures	1568	588	**<0.001**
Cereal rye vs. forage radish	1568	2228	**0.023**
Cereal rye vs. mixtures	1568	1487	0.526
Forage radish vs. mixtures	2228	1487	**0.0028**
Monocultures vs. mixtures	1242	1487	0.126
Monocultures vs. two-way mixtures	1242	1440	0.225
Monocultures vs. three-way mixtures	1242	1557	0.169
Two-way mixtures vs. three-way mixtures	1440	1557	0.770

Figure 1. Cover crop biomass at the first killing frost with contrast statements comparing treatments in field experiments in Blacksburg (2017 and 2018), Christiansburg (2017), and West Point (2018), VA. Bars are means and lines are standard errors.



Contrasts[a]	Mean of 1st term	Mean of 2nd term	p-value
	-------kg ha^{-1}-------		
Cereal rye vs. legume monocultures	8937	5013	**<0.001**
Cereal rye vs. mixtures	8937	7862	0.289
Monocultures vs. mixtures	6321	7862	**0.005**
Monocultures vs. two-way mixtures	6321	7936	**0.009**
Monocultures vs. three-way mixtures	6321	7752	**0.023**
Two-way mixtures vs. three-way mixtures	7936	7752	0.902

[a] Forage radish was excluded from this analysis.

Figure 2. Cover crop biomass at cover crop termination with contrast statements comparing treatments in field experiments in Blacksburg (2017 and 2018) and Christiansburg (2017), VA. Bars are means and lines are standard errors.

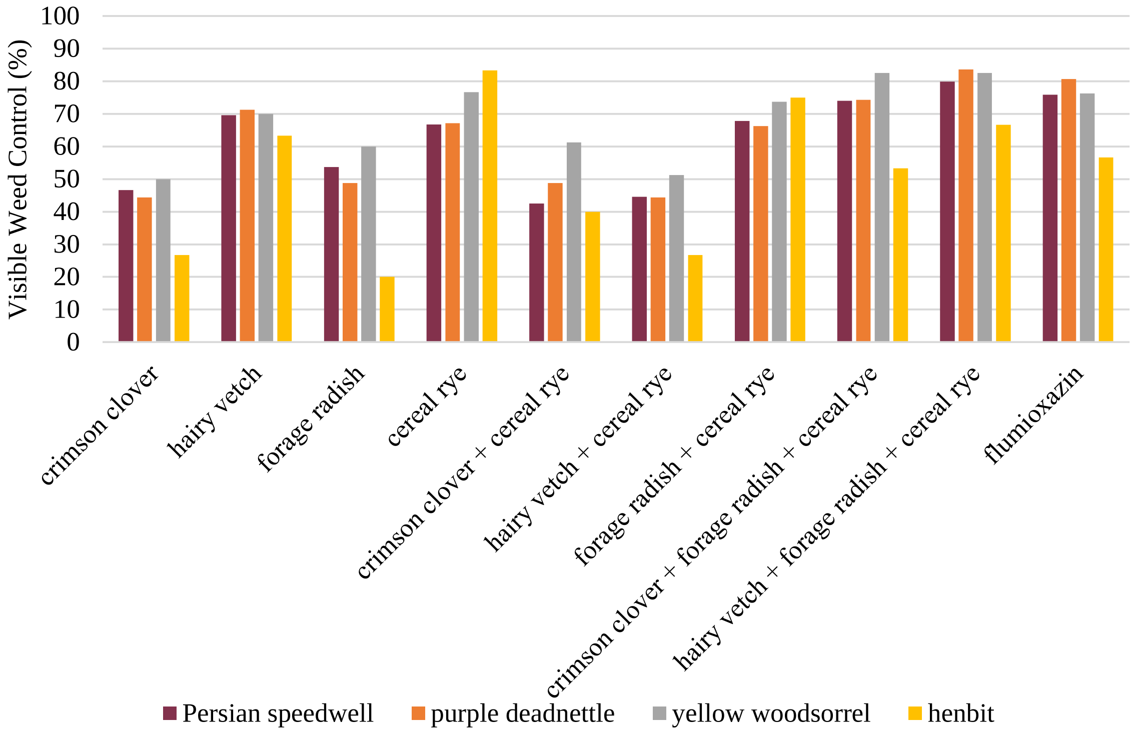


Figure 3. Winter weed control by species at the first killing frost in field experiments in Blacksburg (2017 and 2018), Christiansburg (2017), and West Point (2018), VA. Contrasts comparing treatments are presented in Table 2.

Table 2. Visible winter weed control at the first killing frost by species compared using contrast statements (α=0.05) in field experiments in Blacksburg (2017 and 2018), Christiansburg (2017), and West Point (2018), VA.

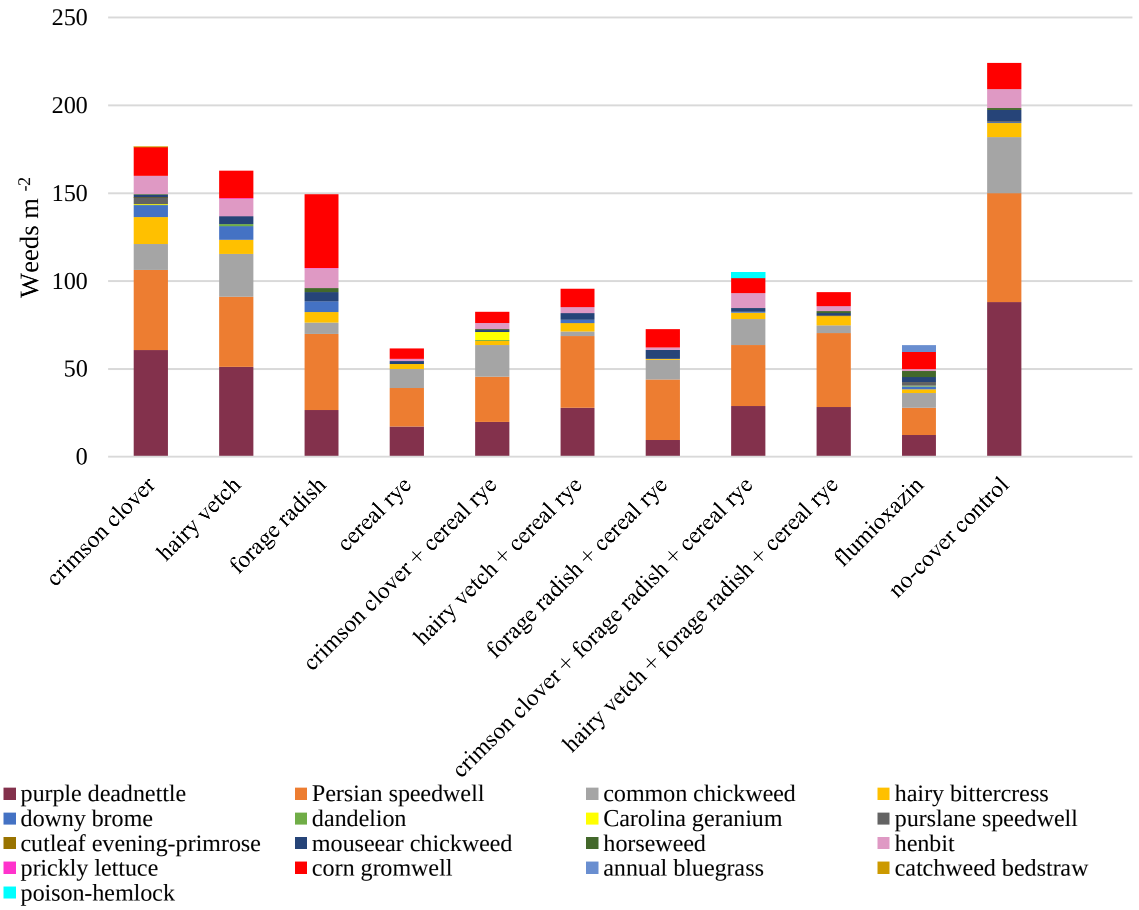
	Persian Speedwell[a]			Purple Deadnettle[b]			Yellow Woodsorrel[c]			Henbit[d]		
Contrasts	Mean of 1st term	Mean of 2nd term	p-value	Mean of 1st term	Mean of 2nd term	p-value	Mean of 1st term	Mean of 2nd term	p-value	Mean of 1st term	Mean of 2nd term	p-value
	----Control (%)----			----Control (%)----			----Control (%)----			----Control (%)----		
Cereal rye-containing treatments vs. legume monocultures	63	58	0.509	64	58	0.525	71	60	0.438	58	45	0.412
Cereal rye-containing treatments vs. forage radish	63	54	0.385	64	49	0.252	71	60	0.555	58	20	0.072
Forage radish vs. legume monocultures	54	58	0.744	49	58	0.554	60	60	1	20	45	0.278
Monocultures vs. two-way mixtures	59	52	0.323	58	53	0.593	64	62	0.879	48	47	0.937
Monocultures vs. three-way mixtures	59	77	**0.046**	58	79	0.062	64	83	0.242	48	60	0.470
Two-way mixtures vs. three-way mixtures	52	77	**0.007**	53	79	**0.027**	62	83	0.211	47	60	0.453
Cover crops vs. flumioxazin	61	76	0.241	61	81	0.143	68	76	0.641	51	57	0.755
Cover crop mixtures vs. flumioxazin	62	76	0.302	63	81	0.213	70	76	0.756	52	57	0.831

[a] Persian speedwell was only rated at Blacksburg in 2017 and 2018 and at Christiansburg in 2017.

[b] Purple deadnettle was only rated at Blacksburg in 2017 and at Christiansburg in 2017.

[c] Yellow woodsorrel was only rated at Christiansburg in 2017.

[d] Henbit was only rated at West Point in 2018.

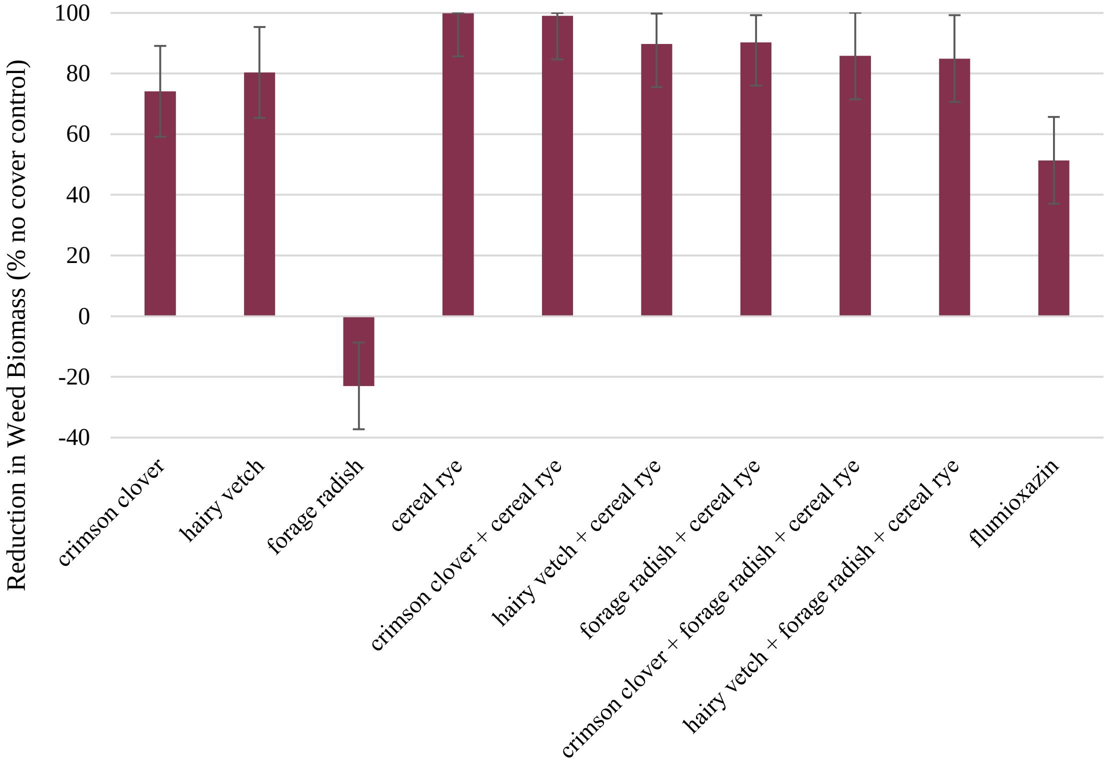


Contrasts	Mean of 1st term	Mean of 2nd term	p-value
	------weeds m^2------		
Cover crops vs. no cover control	111	225	**0.004**
Cereal rye-containing treatments vs. legume monocultures	85	170	**<0.001**
Cereal rye-containing treatments vs. forage radish	85	151	**0.002**
Cereal rye vs. mixtures	61	90	0.333
Monocultures vs. two-way mixtures	138	84	**0.007**
Monocultures vs. three-way mixtures	138	99	0.095
Two-way mixtures vs. three-way mixtures	84	99	0.495
Cover crops vs. flumioxazin	111	72	0.288
Cover crop mixtures vs. flumioxazin	90	72	0.777
Flumioxazin vs. no cover control	72	225	**0.003**

Figure 4. Spring weed density by treatment taken in mid-March with contrast statements comparing treatments in field experiments in Blacksburg (2017 and 2018), Christiansburg (2017), and West Point (2018), VA.

Table 3. Spring weed diversity by treatment taken in mid-March compared using contrast statements in field experiments in Blacksburg (2017 and 2018), Christiansburg (2017), and West Point (2018), VA.

Contrasts	Blacksburg			Christiansburg			West Point		
	Mean of 1st term	Mean of 2nd term	p-value	Mean of 1st term	Mean of 2nd term	p-value	Mean of 1st term	Mean of 2nd term	p-value
	--Species 0.25 m^{-2}--			--Species 0.25 m^{-2}--			--Species 0.25 m^{-2}--		
Cover crops vs. no cover control	3.17	3.63	0.376	1.42	1.00	0.268	2.48	4.00	**0.016**
Cereal rye-containing treatments vs. legume monocultures	2.60	4.63	**<0.001**	1.42	1.50	0.773	2.39	2.33	0.903
Cereal rye-containing treatments vs. forage radish	2.60	3.63	0.057	1.42	1.25	0.663	2.39	3.33	0.127
Cereal rye vs. mixtures	2.88	2.55	0.546	1.00	1.50	0.202	1.33	2.60	**0.047**
Monocultures vs. two-way mixtures	3.94	2.46	**<0.001**	1.31	1.50	0.489	2.33	2.22	0.794
Monocultures vs. three-way mixtures	3.94	2.69	**0.004**	1.31	1.50	0.541	2.33	3.17	0.094
Two-way mixtures vs. three-way mixtures	2.46	2.69	0.609	1.75	1.50	1.000	2.22	3.17	0.386
Cover crops vs. flumioxazin	3.17	4.00	0.110	1.42	0.50	**0.019**	2.48	2.67	0.753
Cover crop mixtures vs. flumioxazin	2.55	4.00	**0.008**	1.50	0.50	**0.014**	2.60	2.67	0.913
Flumioxazin vs. no cover control	4.00	3.63	0.589	0.5	1	0.321	2.67	4.00	0.101



Contrasts	Mean of 1st term	Mean of 2nd term	p-value
	------% reduction[a]------		
Cereal rye-containing treatments vs. forage radish	92	-23	**<0.001**
Cereal rye-containing treatments vs. legume monocultures	92	77	**0.045**
Cereal rye vs. mixtures	99	90	0.404
Monocultures vs. two-way mixtures[b]	85	93	0.490
Monocultures vs. three-way mixtures	85	85	0.966
Two-way mixtures vs. three-way mixtures	93	85	0.310
Cover crops vs. flumioxazin	76	51	0.100
Cover crop mixtures vs. flumioxazin	90	51	**0.015**
Forage radish vs. flumioxazin	-23	51	**<0.001**

[a] Data are presented as a percent reduction relative to the no cover control.

[b] Forage radish was excluded from contrasts containing monocultures.

Figure 5. Winter weed biomass at cover crop termination with contrast statements comparing treatments in field experiments in Blacksburg (2017 and 2018) and Christiansburg (2017), VA. Bars are means and lines are standard errors.

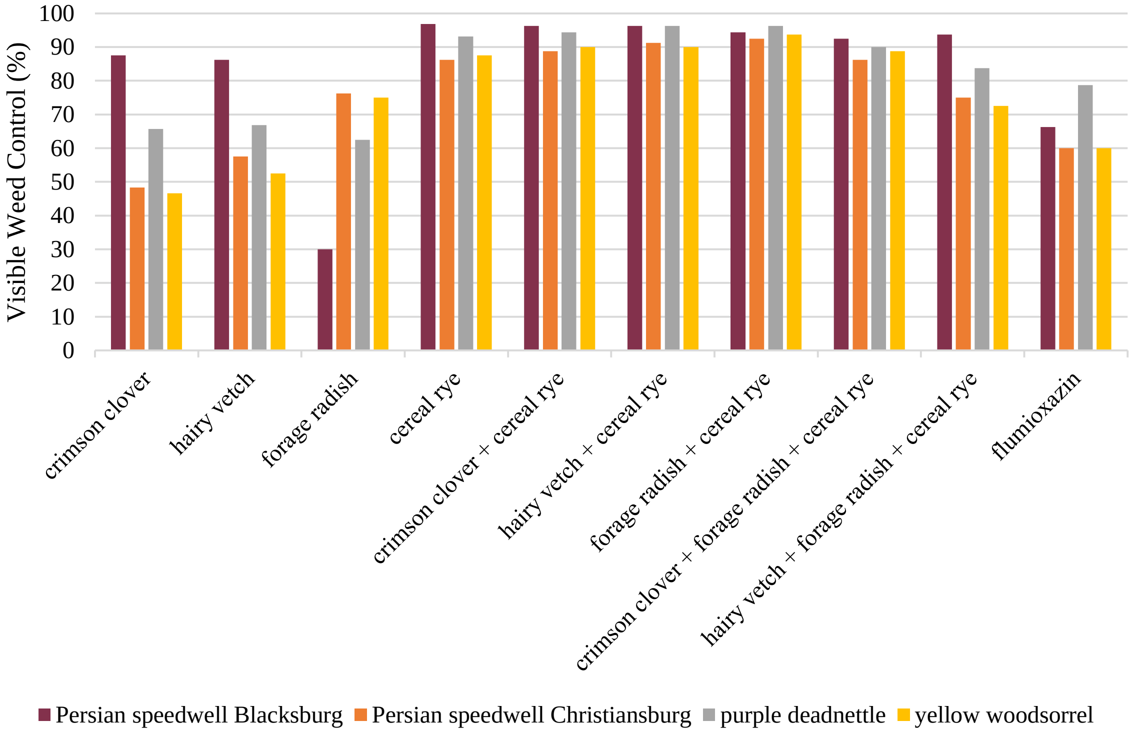


Figure 6. Visible winter weed control at cover crop termination in field experiments in Blacksburg (2017 and 2018) and Christiansburg (2017), VA. Contrasts comparing treatments are presented in Table 4.

Table 4. Winter weed control at cover crop termination by species compared using contrast statements in field experiments in Blacksburg (2017 and 2018) and Christiansburg (2017), VA.

	Persian speedwell											
	Blacksburg			Christiansburg			purple deadnettle			yellow woodsorrel		
Contrasts	Mean of 1st term	Mean of 2nd term	p-value	Mean of 1st term	Mean of 2nd term	p-value	Mean of 1st term	Mean of 2nd term	p-value	Mean of 1st term	Mean of 2nd term	p-value
	----Control (%)----			----Control (%)----			----Control (%)----			----Control (%)----		
Cereal rye-containing treatments vs. forage radish	95	30	**<0.001**	87	76	0.397	92	63	**<0.001**	87	75	0.330
Cereal rye-containing treatments vs. legume monocultures	95	87	0.054	87	53	**0.002**	92	66	**<0.001**	87	50	**<0.001**
Cereal rye vs. mixtures	97	95	0.687	86	87	0.968	93	92	0.889	88	87	0.968
Monocultures vs. two-way mixtures[a]	90	96	0.196	64	91	**0.008**	75	96	**<0.001**	62	91	**0.005**
Monocultures vs. three-way mixtures	90	93	0.532	64	81	0.124	75	87	**0.009**	62	81	0.091
Two-way mixtures vs. three-way mixtures	96	93	0.592	91	81	0.327	96	87	0.146	91	81	0.311
Cover crops vs. flumioxazin	86	66	**<0.001**	78	60	0.140	83	79	0.544	77	60	0.155
Cover crop mixtures vs. flumioxazin	95	66	**<0.001**	87	60	**0.038**	92	79	0.065	87	60	**0.037**
Flumioxazin vs. forage radish	66	30	**<0.001**	60	76	0.314	79	63	0.108	60	75	0.355

[a] Forage radish was excluded from contrasts containing monocultures.

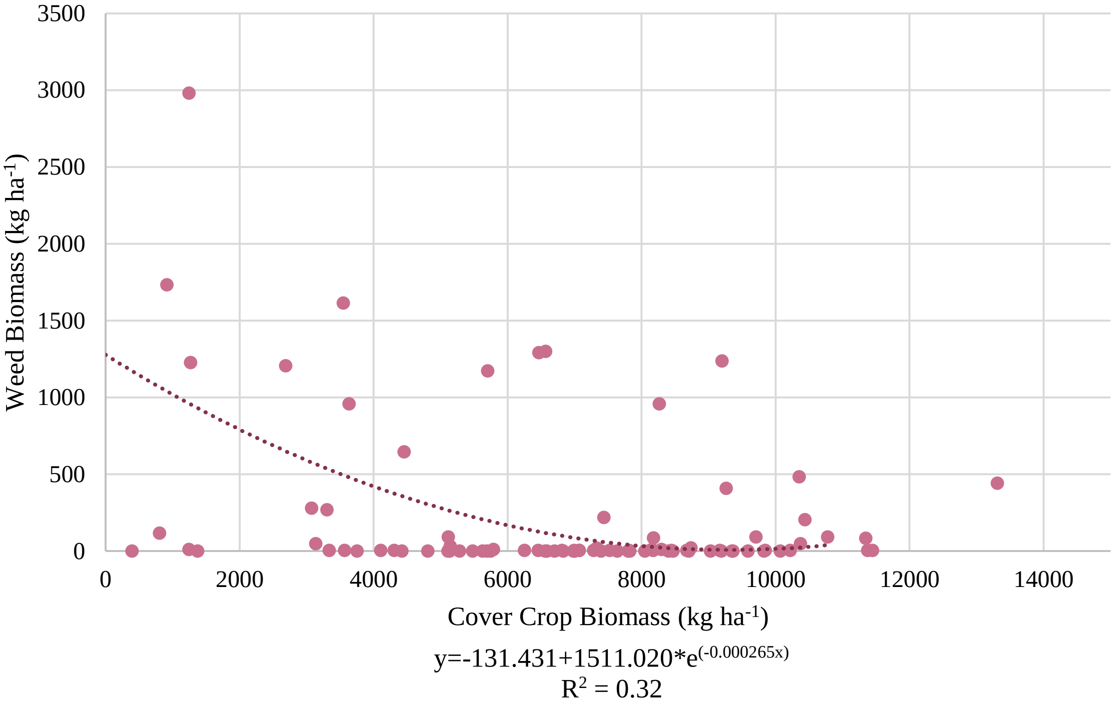


Figure 7. Relationship between cover crop biomass and winter weed biomass at cover crop termination in field experiments in Blacksburg (2017 and 2018) and Christiansburg (2017), VA.

Weed Suppression and Light Penetration at Various Biomass Levels in Standing and Rolled Cereal Rye and Wheat

Abstract

Greater cover crop biomass has been associated with greater summer annual weed suppression, especially small seeded weeds that require light for germination. Both rolling cover crop residue and leaving residue standing are common practices, but little research exists comparing these termination methods. Therefore, we evaluated the effects of cover crop biomass level, cover crop species (wheat or cereal rye), and cover crop termination method (roller crimper and herbicide or herbicide alone) on weed control and light penetrating the cover crop canopy. A greenhouse study was conducted to compare cereal rye biomass rate with common ragweed and Palmer amaranth establishment and light interception. Additionally, two field studies were conducted further comparing cover crop species, termination method, and various biomass levels effects on weed control, light penetration, soil moisture, and soil temperature. Across experiments, as cover crop biomass increased, weed control and light penetration decreased. Cover crop species had no effect on common ragweed control, but standing residue provided greater weed control than rolled residue up to 8400 kg ha^{-1} for the small plot field study. Cereal rye intercepted more light compared to wheat in both field studies but in the small plot study, there was no difference in light interception after 6000 kg ha^{-1} of cover crop biomass. Rolled cover crop residue intercepted more light than standing residue, even though differences never exceeded 10%. Increased cover crop biomass led to at least a 20% reduction in soil temperature and 40% increase in soil moisture at 10000 kg ha^{-1} of cover crop biomass compared to no cover crop. In the small plot field study, rolled cereal rye provided a greater reduction in soil temperature than standing cereal rye, rolled wheat, or standing wheat. In the small plot field study, wheat led to a greater increase

in soil moisture compared to cereal rye. Obtaining maximum cover crop biomass will lead to greater weed control through greater light interception to prevent weed establishment, reduce soil temperature to delay weed establishment, and increase soil moisture, which could have adverse effects on weed establishment.

Introduction

Since the adoption of glyphosate resistant crops, decreased herbicide discovery has led no new mode of action being discovered in over 25 years and an increase in use of glyphosate, causing weeds to develop herbicide resistance (Duke 2012). Over 200 weed species have developed resistance to at least one herbicide mode of action and 41 species have developed resistance to glyphosate. Palmer amaranth (*Amaranthus palmeri* S. Watson) has developed resistance to six herbicide mode of actions, leaving few effective herbicides available for control (Heap 2013, Heap 2019). Increased herbicide resistance has been the result of relying solely on herbicides for weed control.

An integrated weed management (IWM) approach is needed to use multiple methods, including herbicides, to control weeds (Harker and O'Donovan 2013). Using cover crops as a component of an IWM has shown to be effective at controlling weeds and reducing selection pressure for herbicide resistance (Price et al. 2012; Snyder et al. 2016). As cover crop biomass increases, weed control increases (Teasdale et al. 1991). In order to achieve consistent summer annual weed suppression, at least 8000 kg ha-1 of cover crop biomass is needed (Mirsky et al. 2013). Cereal rye (*Secale cereale* L.) has shown to reduce Palmer amaranth growth rate, facilitating timely herbicide application (DeVore et al. 2012; Korres and Norsworthy 2015).

Terminated cover crop residue can suppress weeds through multiple mechanisms, such as blocking or altering germination cues like light and moisture. Cover crop residue acts as a barrier that requires weed seed to deplete their carbohydrate reserves in order to grow through the mulch layer and reach sunlight. This mulch layer can also intercept light, reducing the amount reaching seeds or seedlings, which require light for germination and establishment (Ballare and Casal 2000). Germination of common ragweed (*Ambrosia artemisiifolia* L.) and multiple *Amaranthus* species has been shown to be adversely affected by reduced light (Gallagher and Cardina 1998; Jha et al. 2010; Pickett and Baskin 1973). Wayman et al. (2015) and Teadale and Mohler (1993) both observed cover crops reducing the amount of photosynthetically active radiation (PAR) reaching the soil surface. But the relationship between cover crop biomass and the light quantity penetrating the cover crop canopy is not well characterized.

Terminating cover crops is usually performed with herbicide alone, but a roller crimper has the potential to aid in weed control (Anderson 1996; Ashford and Reeves 2003). Davis (2010) saw a reduction in weed biomass from cover crops terminated with a roller crimper instead of herbicide alone. This finding indicates a roller crimper may assist in weed control, but the relationship between a rolled versus non-rolled cover crop, weed emergence, and the quantity of light penetrating a cover crop canopy is still unknown. The quantity of cover crop residue that a seedling can emerge through before exhaustion is also unknown.

The objective of this study was to optimize cover crop management for control of Palmer amaranth and common ragweed by evaluating the relationship between termination method, cover crop biomass, and light penetration.

Materials and Methods

Greenhouse Study. Studies were initiated in 2018 and 2019 to determine the optimal biomass of a cereal rye (*Secale cereale* L.) cover crop needed to suppress Palmer amaranth (*Amaranthus palmeri* S. Watson) and common ragweed (*Ambrosia artemisiifolia* L.) and to assess the relationship between cover crop biomass, weed control, and light penetrating the cover crop canopy. Separate studies were conducted for each weed species. The studies were conducted in a greenhouse in Blacksburg, Virginia (37.231967, -80.434754).

The experiments utilized a randomized complete block design with four replications. Plots were 25.4 cm by 52.1 cm trays filled with potting mix (Vigoro, Swiss Farms Products Inc., Las Vegas, NV) to a depth of 2.5 cm. 100 weed seeds of either Palmer amaranth or common ragweed were spread on top of the potting mix to simulate weed seed shed in a no-tillage setting. Cereal rye biomass (stem, leaf, and flower tissue) was harvested from the field and allowed to dry for two weeks prior to use. Cover crop biomass was laid directly on top of the potting mix after the weed seeds were spread. Treatments were 0, 2000, 4000, 6000, 8000, and 10000 kg ha^{-1} of cereal rye biomass. Directly after the weed seed was sown, the cereal rye was cut to fit the trays, weighed, and laid on top of the soil, and then the trial was initiated.

To monitor light penetration through cereal rye residue, 59.7 by 12.7 cm boxes were constructed with wood and topped with Plexiglas. Cereal rye residue was placed on the top of each box at the rates previously mentioned. Boxes excluded light except the light that penetrated through the cereal rye residue. There was a hole on the side of the light box for a quantum light bar (LI-191R Line Quantum Sensor, Li-Cor Inc., Lincoln, NE) to be inserted. The light box was used in addition to the trays so not to disturb the cover directly over the weed seed in trays. Just like the trays, boxes were replicated 4 times per treatments in a randomized complete block deisgn.

The common ragweed experiment was initiated on May 9th, 2018 and May 13th, 2019 and the Palmer amaranth experiment was initiated on June 15th, 2018 and June 12th, 2019. The plots were watered on an automatic schedule twice a day for three minutes, which maintained field capacity. Light readings were taken once a week at or close to solar noon with clear sky with a quantum light bar that measured the amount of photosynthetically active radiation (PAR) (400-700 nm) in µmol s^{-1} m^{-2} penetrating the cover crop residue for four weeks. Weed stand counts and weed biomass were collected four weeks after each trial was initiated.

Data were analyzed using JMP Pro 13 (SAS Institute, Inc., Cary, NC). Cover crop biomass was considered a fixed effect. Block and year were considered random effects. Data were subject to ANOVA (α=0.1). An exponential regression was utilized to determine the relationship between cereal rye biomass compared to Palmer amaranth and common ragweed weed control and biomass, respectively. An exponential regression was also utilized to determine the relationship between cover crop biomass and the percent of PAR reaching the soil surface. For statistical analyses, weed control was determined by converting weed stand counts to a percent of the no cover control and light penetration data were converted to a percent of the no cover control.

Small Plot Field Study. Studies were initiated in 2017 and 2018 to determine the optimal biomass of a cereal rye and a wheat (*Triticum aestivum* L.) cover crop to suppress Palmer amaranth and common ragweed and to assess the relationship between cover crop biomass, weed control, light penetrating the cover crop and reaching the soil surface, and standing or rolled cover crop residue. Locations were Blacksburg, Virginia at Kentland Farm (37.192913, -

80.573942) in the New River flood plain on a Ross soil (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls) and in Shawsville, Virginia (37.180773, -80.240059) in the New River Valley on a Hayter soil (fine-loamy, mixed, active, mesic Ultic Hapludalfs). The Blacksburg location was previously left fallow, and the Shawsville location was previously in no-till planted sweet corn (*Zea mays* L.). At both locations, paraquat at 0.56 kg ai ha^{-1} and COC at 1% v v^{-1} was applied to control any weeds prior to no-till planting of cover crops.

The experiments utilized a factorial design arranged as a randomized complete block with four replications of a treatment and plot size of 3.05 by 7.62 m. Factors were cover crop species, cover crop biomass rate, and termination method. Each experiment consisted of a total of 12 treatments plus a no cover check (Table 5) and 4 replications. Cover crop species were cereal rye (Elbon South; Green Cover Seeds, Bladen, NE) or wheat (Gore Soft Red; Green Cover Seeds). In order to obtain a gradient of biomass levels (i.e. low, medium and high), planting date and seeding rate were altered as indicated in Table 5. Cereal rye and wheat were drilled no-till on 16.5 cm rows to a depth of 2 to 3 cm. Cover crops were terminated on April 27th, 2018 for the first year and April 29th, 2019 for the second year with either glyphosate (Roundup PowerMAX; Monsanto Company; St. Louis, Missouri) at 1.5 kg ai ha^{-1} for the standing biomass or glyphosate + a roller crimper for the rolled biomass. The roller crimper was a roller with chevron pattern crimpers mounted to the 3-point hitch of a tractor.

Weed microplots of Palmer amaranth and common ragweed seeds were sown the day of cover crop termination, directly after glyphosate application, but before the use of the roller crimper. Each weed species were sown in separate 1 by 1 m microplots randomly located within each plot. Weed microplots of 100 Palmer amaranth and 100 common ragweed seeds were spread on the soil surface separately in each plot in 2017. However, poor weed germination occurred during the first year of the study. For 2018, 500 Palmer amaranth and 500 common ragweed seeds were cold stratified in moist sand and then sown in each plot. Weed seeds were spread on top of the soil surface simulate weed seed shed in a no-tillage cropping system. Cover crops were terminated with glyphosate or glyphosate + roller crimper.

Light penetration evaluated the amount of PAR reaching the soil surface in all plots, including the no cover, were taken twice a week in the middle of each plot starting April 16th for the first year and April 18th for the second year for the Blacksburg location and April 17th for the first year and April 19th for the second year for the Shawsville location and ending on June 8th for the first year and June 10th for the second year. Light readings were taken at or close to solar noon with a quantum light bar that averages the amount of PAR in µmol s^{-1} m^{-2} penetrating the cover crop canopy across a meter of the plot to reduce variability in data from potential in plot variations in cover. Soil temperature data were taken in the middle of the plot on the same day as light penetration data. Soil moisture data were also taken the same day, but three samples were taken in each plot and then averaged. Soil temperature data were recorded with a thermometer, and soil moisture data were recorded with a time-domain reflectometry (TDR) moisture meter (Field Scout TDR 300 Soil Moisture Meter, Spectrum Technologies Inc., Aurora, IL). Soil temperature and moisture probes were inserted approximately 5 cm deep in the soil profile to capture the conditions to which weed seeds were exposed. Cover crop biomass from a 0.25 m^2 area was taken at cover crop termination. Weed counts and biomass were taken in each plot at six weeks after cover crop termination of common ragweed in the 1 m^2 microplot for the second year of the study. Weed counts and biomass were taken six weeks after cover crop termination, because cash crops are typically planted 2 weeks after terminating and a postemergence herbicide application is applied 4 weeks after cash crop planting. Palmer amaranth did not germinate consistently at either location in either year, and common ragweed did not germinate consistently at either location in the first year. Data were not collected on those weeds at those respective locations and years but other data types were collected.

Data were analyzed using JMP Pro 13. Cover crop biomass, cover crop species, cover crop termination method and all possible interactions were considered fixed effects. Site year and block were considered random effects. Data were subject to ANOVA (α=0.1) and a stepwise model selection was conducted to remove any interactions that were not significant. Data were separated by cover crop species or termination method prior to running an exponential regression as determined by significant interactions detected by ANOVA. An exponential regression was utilized to compare cover crop biomass with common ragweed stand counts, common ragweed biomass, soil temperature, soil moisture, and light penetration. Common ragweed stand counts were converted to a percent of the no cover control for statistical analysis. Soil temperature data were converted to a percent reduction relative to the no cover control, soil moisture data were converted to a percent increase relative to the no cover control, and light penetration data were converted to a percent of PAR reaching the soil surface relative to the no cover control within each replication. PAR, soil temperature, and soil moisture data were then averaged across time from cover crop termination to six weeks after cover crop termination for each plot for statistical analyses.

On-Farm Field Study. Studies were initiated in 2019 to evaluate the effectiveness of a rolled and standing cereal rye and wheat cover crop to suppress weeds in soybeans (*Glycine max* (L.) Mer.) and to assess the relationship between weed control, cover crop biomass, termination method, and light penetration. Studies were conducted in Brodnax (36.655288, -77.896834), Suffolk (36.663245, -76.733975), and West Point (37.539548, -76.902218), Virginia. The

Broadnax location was in the piedmont region of Virginia on an Appling-Mattaponi complex (fine, kaolinitic, thermic Typic Kanhapludults; fine, mixed, subactive, thermic Oxyaquic Hapludults). The Suffolk and West Point location were in the coastal plain region of Virginia on a Kenansville loamy sand (loamy, siliceous, subactive, thermic Arenic Hapludults) and Pamunkey fine sandy loam (fine-loamy, mixed, semiactive, thermic Ultic Hapludalfs), respectively. The Brodnax location was previously in soybeans. The Suffolk location was previously left fallow, and the West Point location was previously in corn.

A factorial study with a randomized complete block design with four replications was used. Factors were cover crop type and termination method. Cover crop species were cereal rye (Elbon South; Green Cover Seeds), wheat (Gore Soft Red; Green Cover Seeds), and hairy vetch (TNT; Green cover Seeds). The Suffolk and West Point location consisted of four treatments and a no cover control. Treatments at Suffolk and West Point consisted of cereal rye terminated with glyphosate at 1.5 kg ae ha^{-1} only, cereal rye terminated with glyphosate + a roller crimper, wheat terminated with glyphosate only, and wheat terminated with glyphosate + a roller crimper. The Brodnax location included the treatments just listed and two additional treatments: cereal rye + hairy vetch terminated with glyphosate and cereal rye + hairy vetch terminated with glyphosate + a roller crimper. This study was designed as a collaboration with growers in Virginia, so plot size varied based off of grower equipment. In Brodnax, plots were 7.6 by 45.7 m. In Suffolk, plots were 4.6 by 6.1 m, and in West Point, plots were 9.1 by 30.5 m.

Cover crops were planted on 16.5 cm rows. Cover crops were planted at Suffolk and West Point on October 10, 2018 at a rate of 135 kg ha^{-1} for wheat and 123 kg ha^{-1} for cereal rye. Brodnax was planted on November 11, 2018 at 67 kg ha^{-1} for cereal rye, 112 kg ha^{-1} for wheat, and 34 kg ha^{-1} for hairy vetch. Cover Crops were terminated on May 10, 2019 at Brodnax and

Suffolk and at West Point on April 24, 2019. Soybeans were planted at Suffolk on 76.2 cm rows and Brodnax on 38.1 cm rows on May 22, 2019 and at West Point on May 8, 2019 on 76.2 cm rows.

Data collected included cover crop biomass, light penetration measured in PAR, soil moisture, soil temperature, visible weed control, and weed biomass. Cover crop biomass was collected prior to cover crop termination in a random 0.25 m^2 quadrat. Light penetration was collected using a quantum light bar and methods previously described. Soil temperature and moisture were measured as previously described. Light penetration, soil moisture, and soil temperature were recorded at cover crop termination, at soybean planting, and two and four weeks after planting (WAP) soybeans. The three sets of PAR, soil temperature, and soil moisture data were collected in each plot and then averaged. Visible weed control was recorded two and four WAP on a 0 to 100% scale, with 0 being no control and 100 being complete weed suppression. Weed biomass was recorded in a 1 m^2 quadrat in the middle of each plot 4 WAP.

Data were analyzed using JMP Pro 13. Data were subject to ANOVA and then subsequent means separating using Fisher's Protected LSD (α=0.1). Cover crop termination method, cover crop species, and cover crop termination method by species were considered fixed effects. Location and block were considered random effects. The no cover control data were excluded from all analyses of visible weed control. Light penetration data were converted to a percent of the no cover control. The soil moisture and temperature data were converted to a percent change relative to the no cover control. No weeds were present at Brodnax so data weed control data were not included from that location.

Results and Discussion

Greenhouse Study. Cover crop biomass was significant ($p<0.001$) for Palmer amaranth and common ragweed control (as determined by stand count reductions relative to the no cover control). There was a positive correlation between weed control and cover crop (Figure 8). Cereal rye at 10000 kg ha^{-1} of biomass provided 58% common ragweed control and 84% Palmer amaranth control. Palmer amaranth control was greater than that reported by DeVore et al. (2012), who saw a 68% decrease in germination. Cereal rye biomass was able to account for 49% of the variation in common ragweed control and 81% of the variation in Palmer amaranth control (Figure 8). Cereal rye residue provided 85% Palmer amaranth control and 60% common ragweed control at 10000 kg ha^{-1} of biomass.

There was not a significant interaction between cover crop biomass and common ragweed biomass ($p=0.551$) or for Palmer amaranth biomass ($p=0.175$). Common ragweed and Palmer amaranth biomass were not very responsive to cover crop biomass, because cover crop biomass was able to reduce weed density, but weeds that established had less intraspecific competition and were able to grow larger.

Cover crop biomass was significant for light penetration ($p<0.001$). There was a negative correlation with cover crop biomass and light penetration (Figure 9). Less PAR penetrated the cereal rye residue at greater cover crop biomass. Cover crop biomass was able to account for 86% of the variation in PAR reaching the soil surface. Greater cover crop biomass has the potential to suppress weed establishment and germination as it intercepts more light that is a requirement of small seeded weeds to germinate. Jha and Norsworthy (2009) also saw evidence that light is important for Palmer amaranth germination and establishment as germination was higher in the presence of light compared to complete darkness.

Small Plot Field Study.

Cover Crop Biomass Effects on Common Ragweed Control. Cover crop termination method (p=0.073) was significant for cover crop biomass effects on common ragweed control, so cover crop biomass was separated by cover crop termination method for the regression. There was no difference detected between cover crop species (p=0.660), so data were pooled accordingly. As cover crop biomass increased, common ragweed control increased for both standing and rolled cover crop residue (Figure 10). Teasdale et al. (1991) also saw greater weed control as cover crop biomass increased. Standing cover crop residue provided greater weed control than rolled cover crop residue until around 8200 kg ha^{-1} of cover crop biomass, above which rolled cover crop residue provided greater common ragweed control. Moyer et al. (1999) saw greater weed suppression of redroot pigweed from cover crops terminated with a roller crimper + glyphosate compared to cover crops terminated only with glyphosate most likely due to difference species and redroot pigweed seed size. At 10000 kg ha^{-1}, both standing and rolled cover crop residue provided greater than 80% common ragweed control (Figure 10). Standing residue likely provided greater control at lower biomass because the standing cover crop appeared to have fewer gaps in cover compared to the rolled residue. However, at greater biomass rates, the rolled cover crop residue developed a thicker mulch layer with less gaps. This thicker mulch layer could prevent weed establishment as weeds must grow through the layer to reach sunlight and become established.

Cover crop biomass (p<0.001), cover crop termination method (p=0.003), and cover crop species by cover crop biomass (p=0.038) were significant for cover crop biomass effects on common ragweed biomass, so two regressions were utilized with one separating cover crop biomass by cover crop species and one separating cover crop biomass by cover crop termination method. Common ragweed biomass was greater in wheat cover crop residue compared to cereal rye cover crop residue until around 4000 kg ha^{-1} of cover crop biomass. After 4000 kg ha^{-1} of cover crop biomass, little differences existed between common ragweed biomass between cover crop species (Figure 11). Rolled cover crop residue resulted in more common ragweed biomass compared to standing cover crop biomass (Figure 11). Davis (2010) saw different results with less weed biomass accumulation in a cover crop terminated with a roller crimper compared to a cover crop left standing most likely due to differences in weed species. Common ragweed biomass was greater in rolled cover crop residue because after the common ragweed emerged and grew through the thick mulch layer, it was not shaded. In the standing residue, the common ragweed was shaded for the length of the study.

Overall, standing cover crop residue provided greater common ragweed control compared to rolled cover crop residue until 8400 kg ha^{-1} of cover crop biomass. The species of cover crop did not affect common ragweed control from stand counts, but did affect common ragweed biomass. Cereal rye resulted in less common ragweed biomass compared to wheat at cover crop biomass less than 4000 kg ha^{-1}. We observed different results from Mischler et al. (2010) who did not see a reduction in common ragweed density following a cereal rye cover crop compared to the no cover control most likely due to climate and soil differences in Pennsylvania.

Cover Crop Biomass Effects on PAR. Cover crop biomass ($p<0.001$), cover crop biomass by termination method ($p=0.030$), and cover crop biomass by species ($p<0.001$) were significant for cover crop biomass effects on PAR penetrating the cover crop residue, so data were separated by cover crop termination and by cover crop species for the regressions comparing cover crop biomass and PAR. As cover crop biomass increased, the amount of PAR reaching the soil surface decreased in all cases. Teasdale and Mohler (1993) and Liebert et al. (2017) also observed greater PAR interception as cover crop biomass increased.

Cereal rye residue intercepted more PAR compared to wheat residue at less than 6000 kg ha^{-1} of cover crop biomass, even though differences were less than 5%. After 6000 kg ha^{-1} of cover crop biomass, little differences existed between cereal rye and wheat cover crop residue effects on PAR reaching the soil surface (Figure 12). Cereal rye most likely caused a greater reduction in the amount of PAR reaching the soil surface compared to wheat because at lower biomass, cereal rye created a more uniform mulch layer when rolled and its height most likely allowed it intercept more PAR when left standing compared to wheat. Liebert et al. (2017) also saw similar results with a greater reduction in PAR reaching the soil surface from cereal rye (64%) compared to barley (*Hordeum vulgare* L.) (41%).

At greater than 2000 kg ha^{-1} of cover crop biomass, rolled cover crop residue had a greater reduction in PAR (~5%) reaching the soil surface compared to standing cover crop residue, most likely due to the standing residue canopy allowing more PAR to penetrate compared to the thick mulch layer of the rolled residue (Figure 12). Davis et al. (2010) also observed less PAR reaching the soil surface in a rolled cover crop compared to a standing cover crop.

Cover Crop Biomass Effects on Soil Temperature. Cover crop biomass by species by termination method interaction (p=0.047) was significant, so data were separated by species by termination method for the regression comparing cover crop biomass with soil temperature reduction relative of the no cover control. As cover crop biomass increased, the reduction in soil temperature relative to the no cover control increased (Figure 13). At greater than 6000 kg ha^{-1} of cover crop biomass, rolled cereal rye residue reduced soil temperature more compared to standing cereal rye, standing wheat, and rolled wheat residue. Standing cereal rye and rolled wheat had resulted in similar soil temperature reductions, regardless of cover crop biomass.

Rolled cereal rye residue most likely resulted in a greater soil temperature reduction at greater cover crop biomass because of the thicker mulch layer that reduced solar warming from the sun. Regardless of species or termination method, the cover crop residue reduced soil temperature compared to no cover, which could delay weed germination and decrease growth rate of germinated weeds (Teasdale 1993; Teasdale and Mohler 1993), thus allowing for a longer duration before a postemergence herbicide application or other control tactic is needed.

Cover Crop Biomass Effects on Soil Moisture. Cover crop biomass by cover crop species (p=0.037) was significant, so data were separated by cover crop species for the regression comparing cover crop biomass with the increase in soil moisture relative of the no cover control. Termination method was not significant (p=0.864). There was a positive relationship between cover crop biomass and the percent increase in soil moisture. Wheat cover crop residue resulted in a greater increase in soil moisture compared to cereal rye residue until almost 10000 kg ha^{-1} of cover crop biomass (Figure 14). At 10000 kg ha^{-1} of cover crop biomass, both cereal rye and wheat residue resulted in over a 40% increase in soil moisture compared to the no cover control. Wheat cover crop has the potential to conserve more moisture in the soil than cereal rye. An increase in soil moisture has the potential to conserve water in times of drought for crops but also for weeds. However, when soils are saturated, cover crops, especially a wheat cover crop, can inhibit soil drying and prevent germination or establishment of weed species that are intolerant of saturated soils (Teasdale and Mohler 1993).

Large Plot Field Study.

Cover Crop Biomass. Species (p=0.009) was significant, so cover crop biomass was separated by species. Cereal rye accumulated over 1000 kg ha^{-1} more of biomass than wheat with 3755 and 4874 kg ha^{-1}, respectively, which is average for Virginia. Cereal rye biomass was similar to that reported in the Great Lakes region (Hayden et al. 2012), but lower than that reported in Pennsylvania and Alabama (Mischler et al. 2010; Price et al. 2012, 2016).

Weed Control. Weeds rated were large crabgrass (*Digitaria sanguinalis* (L.) Scop.) at Suffolk and West Point, redroot pigweed (*Amaranthus retroflexus* L.) at Suffolk, and carpetweed (*Mollugo verticillata* L.) at West Point. Weeds were not present at Brodnax due to an extended drought period after cover crop burndown until four WAP soybeans, therefore these data were not included in the analyses. Cover crop species was significant for control of all individual weed species, but termination and termination by species was not two and four WAP. Data were separated by cover crop species. Termination method was not significant most likely due to low cover crop biomass accumulation and to most of the standing cover crop residue was essentially rolled by equipment at soybean planting.

Cereal rye provided greater control of all weeds at both two and four WAP. Cereal rye has been shown to be more effective at controlling summer annual weeds compared to other cover crops as it accumulates greater cover crop biomass (Webster et al. 2013; Wiggins et al. 2016). Wheat did not provide greater than 60% control of any weed species at two or four WAP. Cereal rye provided greater than 75% control of all weed species two WAP, but did not provide adequate control of large crabgrass or redroot pigweed four WAP with 61 and 23% control, respectively. Cereal rye provided 88% carpetweed control four WAP (Table 6). Poor weed control from wheat and cereal rye can be attributed to low cover crop biomass accumulation

(<5000 kg ha^{-1}). Mirsky et al. (2013) reported that at least 8000 kg ha^{-1} of cereal rye biomass is need for adequate weed suppression.

Species, treatment, and species by treatment were not significant for weed biomass. No differences were observed most likely due to low accumulation of cover crop biomass providing a thin mulch layer that weeds were able to grow through and become established and due to weed populations being low.

Cover Crop Residue Effect on PAR. There was a significant effect of cover crop species (p<0.001), so data were separated by cover crop species. Termination method or termination method by cover crop species was not significant. Less PAR reached the soil under cereal rye residue (37%) compared to under wheat residue (49%) (Table 7). Cereal rye was better at intercepting PAR most likely due to it accumulating more biomass compared to wheat, with an average of 4874 and 3755 kg ha^{-1}, respectively. However, the amount of PAR intercepted by cereal rye was low compared to that reported by Liebert et al. (2017) and Teasdale and Mohler (1993), likely due to less cover crop biomass.

Cover Crop Residue Effect on Soil Temperature and Moisture. There was a significant effect of cover crop species (p=0.026) for soil temperature. Cover crop species and cover crop species by termination method were not significant. Cereal rye residue resulted in a greater reduction in soil temperature compared to the no cover control than wheat residue with 4.1 and 2.1% reduction, respectively (Table 7). The reduction in soil temperature was small, but it does have the potential to delay germination of weed species that require warmer temperatures to break dormancy.

Cover crop species and cover crop termination method were not significant for soil moisture (Table 7). There was no difference in soil moisture by termination method or cover crop species most likely due to the low cover crop biomass accumulated in this study and the rolling effect of planting equipment on standing residue.

Research Implications. Cover crop residue at the highest biomass has the potential to affect weed establishment and germination. However, very low levels or even a short flash of light can break weed seed dormancy (Baskin and Basking 2014). If weed seed germination is initiated under cover crop residue, the cover crop residue still provides a physical mulch layer that weeds must grow through to reach full sunlight and become established (Mirsky et al. 2013). After germination, weeds require light for photosynthesis to grow through cover crop residue to become established (Teasdale and Mohler 1993). Most weed species have a photosynthetic light compensation point, the amount of PAR where photosynthesis equals respiration, in the range of 20 to 50 µmol s^{-1} m^{-2} (Smith 1986). Under our highest cover crop biomass (>10000 kg ha^{-1}), this much quantity of PAR could not reach the soil surface, which could cause germinated weeds to die before becoming established (Teasdale and Mohler 1993).

In summary, greater cover crop biomass was associated with greater weed control, greater light interception, increased soil moisture, and reduced soil temperature. Therefore, the primary goal of cover crop management should be to maximize biomass at termination. Standing cover crop residue provided greater common ragweed control and reduced common ragweed biomass compared to rolled cover crop residue, but rolled residue provided greater light interception compared to standing residue. For common ragweed, managers should leave residue standing when cover crop biomass levels are less than 8400 kg ha^{-1}. Results indicate that roller crimper terminated cover crop residue does not improve control relative to standing residue. However, rolling may have the potential to assist in control of weeds that are more dependent on light for establishment than common ragweed through increased light interception. Further research is needed in this area.

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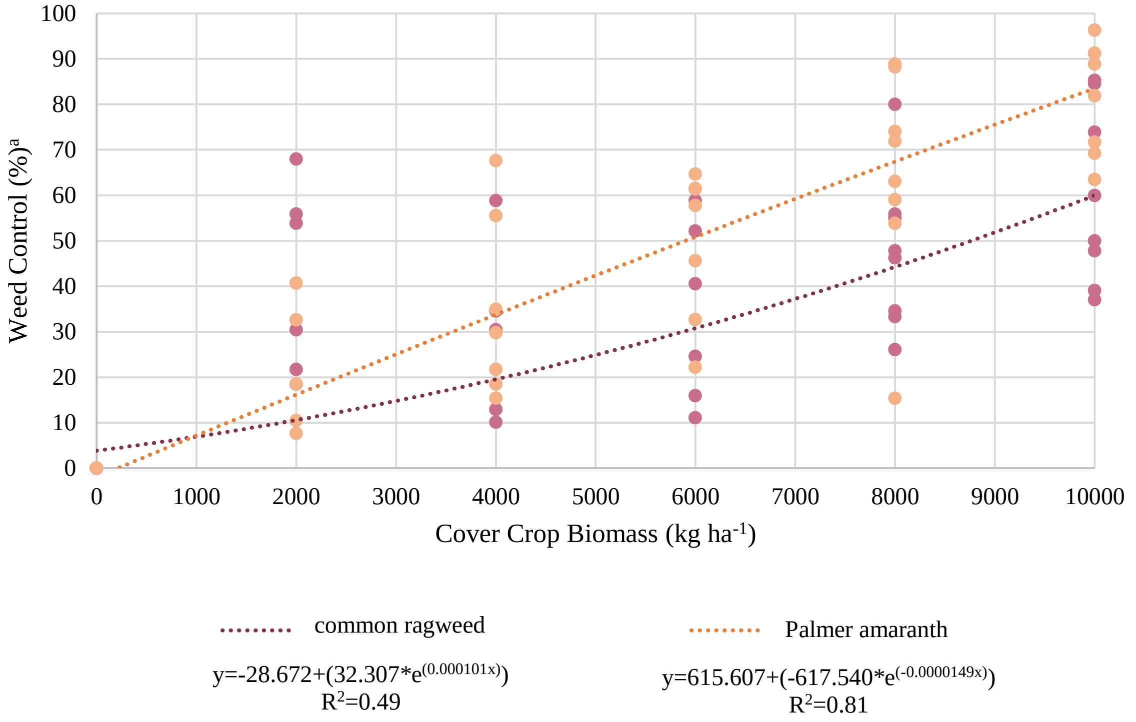
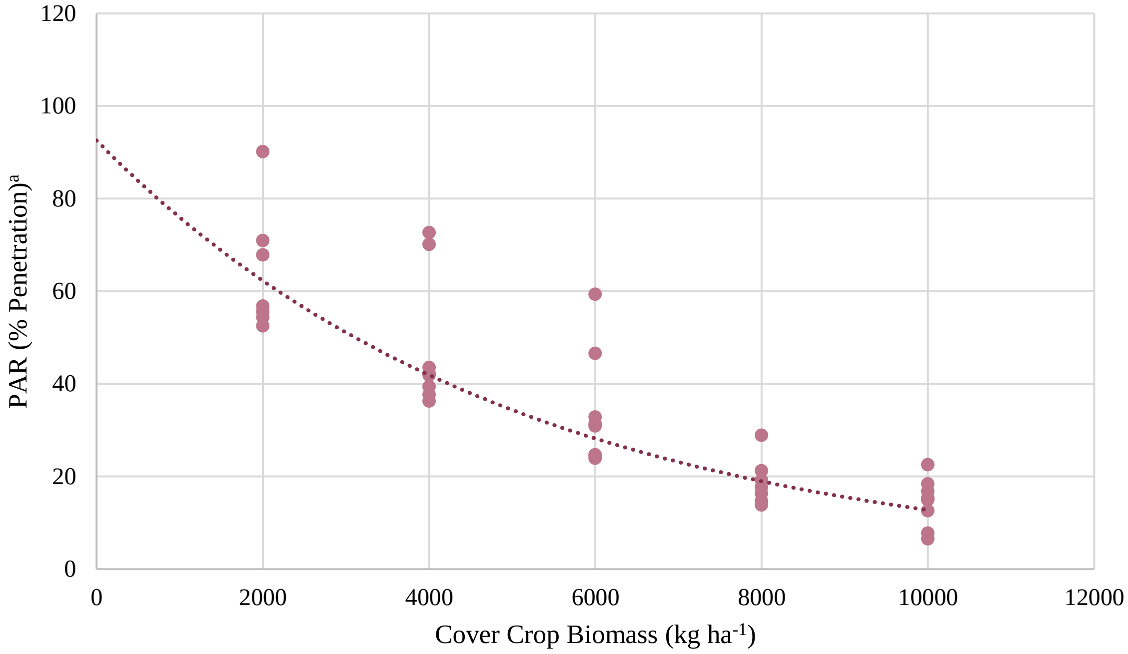
Table 5. Species, planting date, and seeding rate of rolled versus standing cover crop treatments in small plot field experiments in Blacksburg and Shawsville (2018 and 2019).

No.	Cover crop species	Planting date	Seeding rate	Type of cover
			kg ha^{-1}	
1	---	---	---	---
2	cereal rye	Nov. 15	56	standing
3	cereal rye	Oct. 15	84	standing
4	cereal rye	Sept. 15	112	standing
5	cereal rye	Nov. 15	56	rolled
6	cereal rye	Oct. 15	84	rolled
7	cereal rye	Sept. 15	112	rolled
8	wheat	Nov. 15	56	standing
9	wheat	Oct. 15	95	standing
10	wheat	Sept. 15	134	standing
11	wheat	Nov. 15	56	rolled
12	wheat	Oct. 15	95	rolled
13	wheat	Sept. 15	134	rolled



[a] Weed control was converted to % control by comparing weed stand counts to the no cover control.

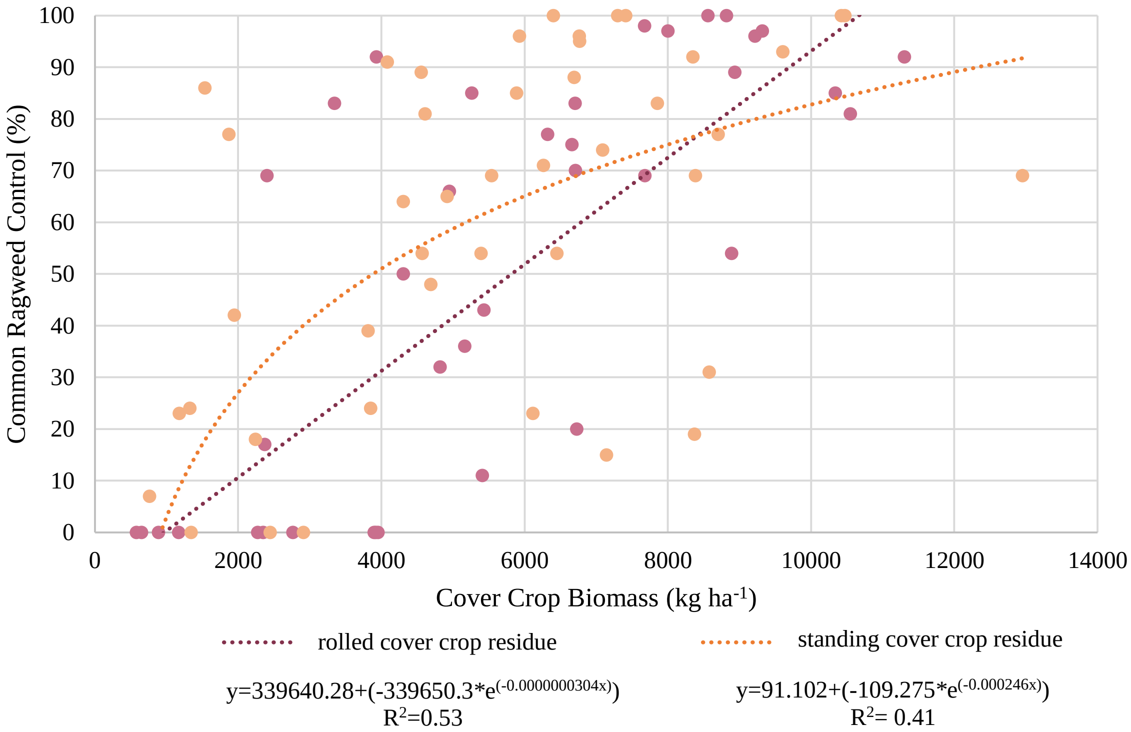
Figure 8. Effects of cereal rye biomass on common ragweed and Palmer amaranth control four weeks after trial initiation in the greenhouse in Blacksburg (2018 and 2019).



$y=5.807+(92.340*e^{(-0.000247x)})$
$R^2=0.86$

[a] PAR is calculated as a % of PAR that penetrated the cover crop canopy in μmol s^{-1} m^{-2} relative to the no cover control over the duration of the experiment.

Figure 9. Effects of cover crop biomass on PAR penetration in the greenhouse experiments in Blacksburg (2018 and 2019).



[a] Common ragweed control was converted to % control by comparing weed stand counts to the no cover control.

Figure 10. Effects of cover crop biomass on common ragweed control separated by termination method in small plot experiments six weeks after cover crop termination at Blacksburg and Shawsville (2019).

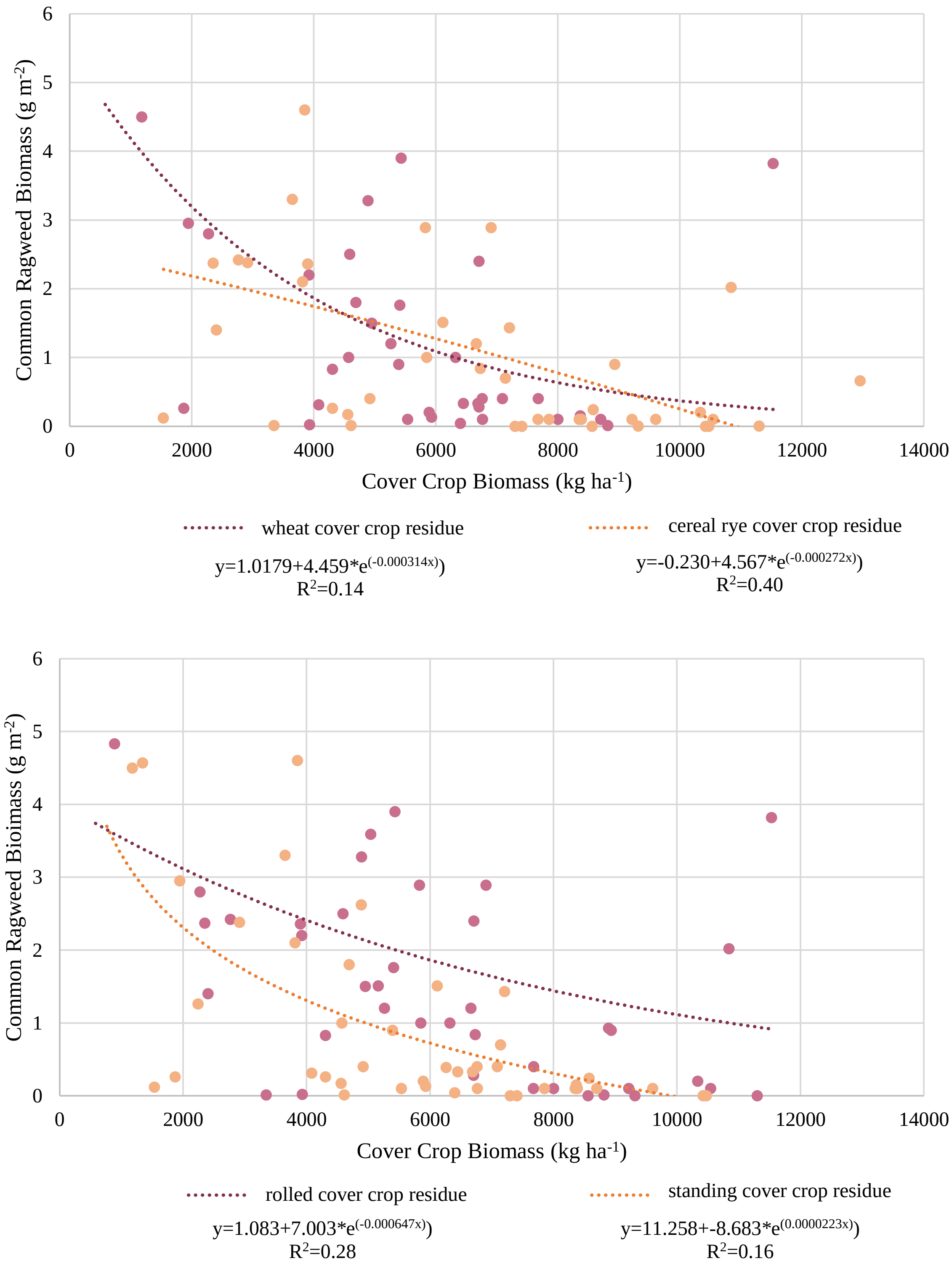
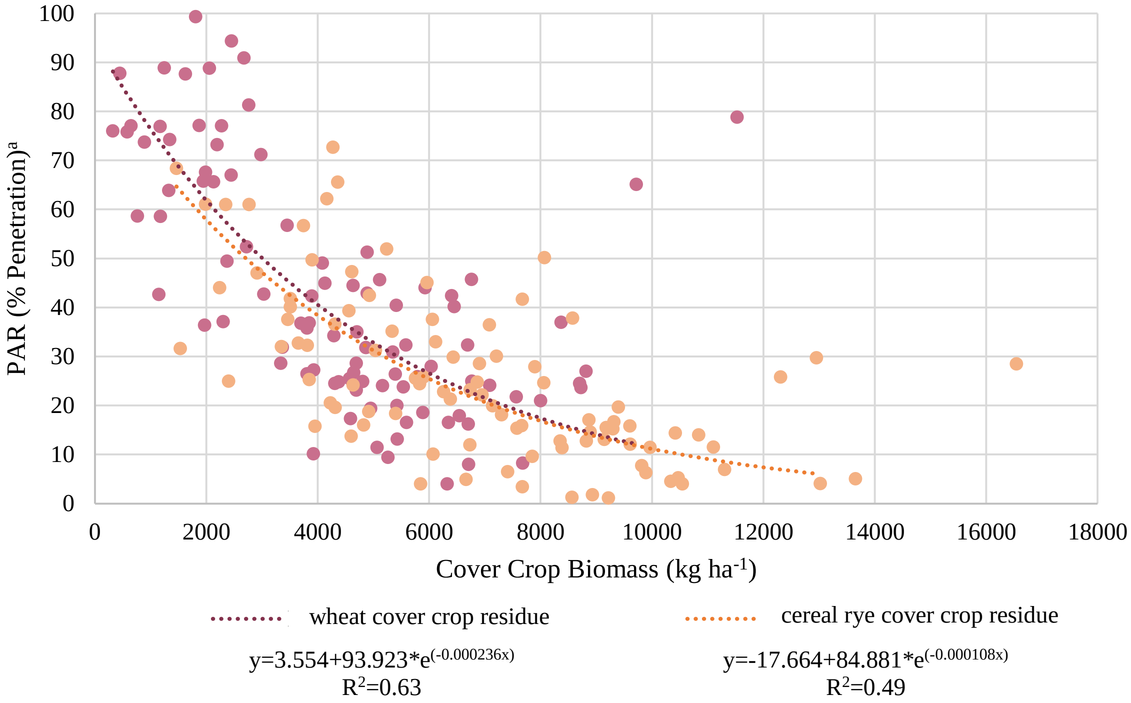
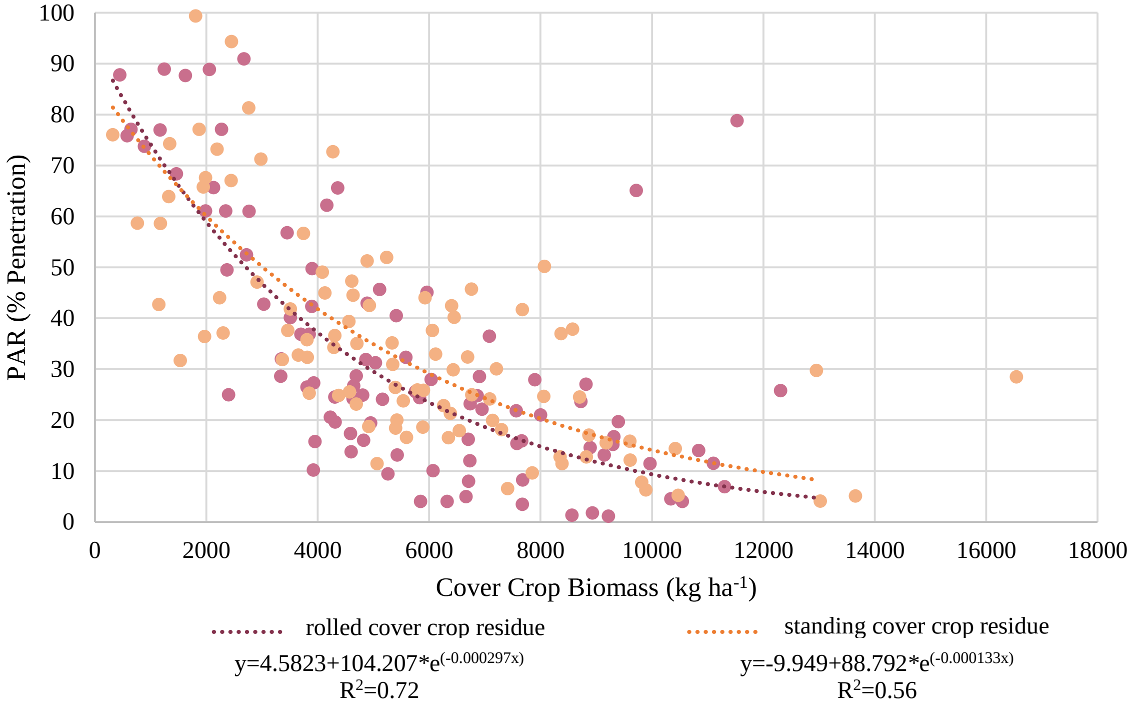


Figure 11. Effects of cover crop biomass on common ragweed biomass separated by cover crop species and termination method six weeks after cover crop termination in small plot experiments

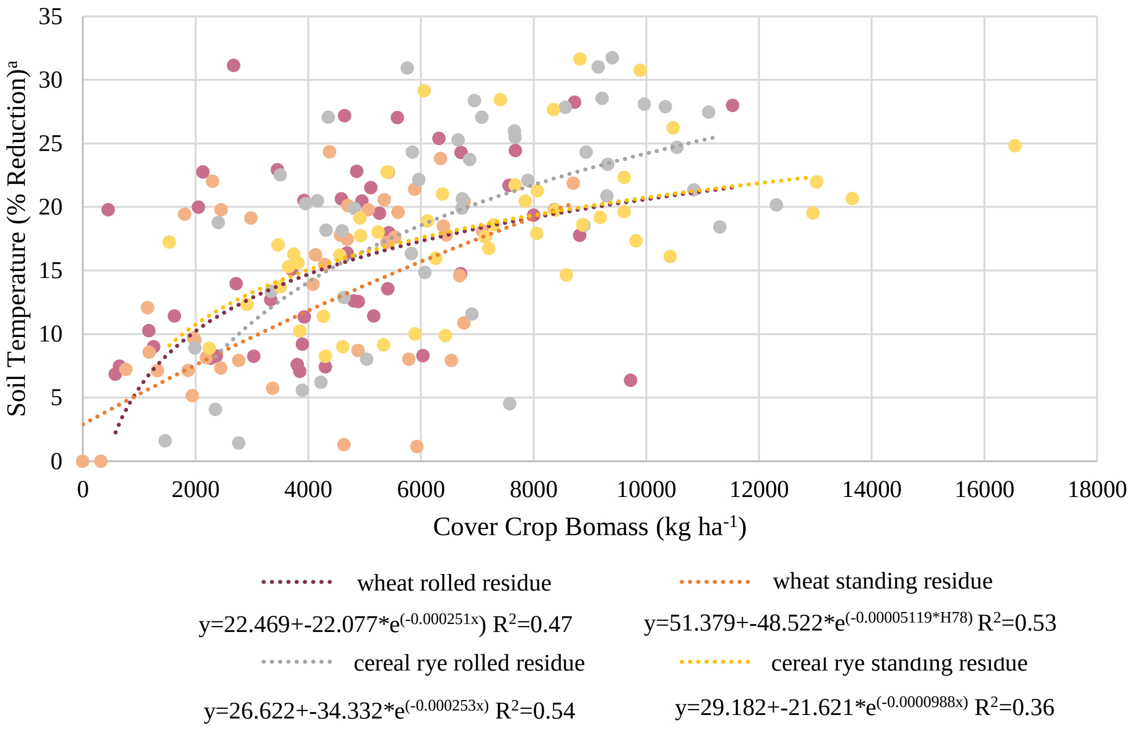
at Blacksburg and Shawsville (2019).





[a] PAR is calculated based off the amount of PAR that penetrated the cover crop canopy in µmol s^{-1} m^{-2} compared to the no cover control over the duration of the experiment.

Figure 12. Effects of cover crop biomass on PAR penetration separated by termination method in small plot experiments at Blacksburg and Shawsville (2018 and 2019).



[a] Soil temperature is calculated as the average % reduction in soil temperature of the no cover control over the duration of the experiment.

Figure 13. Effects of cover crop biomass on soil moisture separated by cover crop species by termination method in small plot experiments in Blacksburg and Shawsville (2018 and 2019).

[a] Soil moisture is calculated as the average percent increase compared to the no cover control over the duration of the experiment.

Figure 14. Effects of cover crop biomass on soil moisture separated by cover crop species in small plot experiments at Blacksburg and Shawsville (2018 and 2019).

Table 6. Summer weed control of cover crop residue by cover crop and weed species two and four WAP in large plot experiments at Suffolk and West Point (2019).

	2 WAP[a]			4 WAP		
Species	wheat	cereal rye	p-value	wheat	cereal rye	p-value
	---% control---			---% control---		
large crabgrass[b]	42b	77a	0.058	24b	61a	0.002
redroot pigweed[c]	38b	76a	0.005	6b	23a	0.003
carpetweed[d]	58b	96a	0.040	47b	88a	0.034

[a] Abbreviation: WAP; weeks after planting.

[b] Large crabgrass data were collected at Suffolk and West Point.

[c] Redroot pigweed data were collected at Suffolk.

[d] Carpetweed data were collected at West Point.

Table 7. Effects of cover crop residue by species on PAR penetration, soil moisture, and soil temperature in large plot experiments in Brodnax, Suffolk, and West Point (2019).

	Cover Crop Species		
	wheat	cereal rye	p-value
	---% of no cover---		
PAR[a]	49a	37b	**<0.001**
	---% reduction---		
Temperature[b]	2.1b	4.1a	**0.026**
	---% increase---		
Moisture[c]	0.85	0.43	0.927

[a] PAR is calculated based off the amount of PAR that penetrated the cover crop canopy in µmol s^{-1} m^{-2} compared to the no cover control.

[b] Soil temperature is calculated as a % reduction in soil temperature of the no cover control.

[c] Soil moisture is calculated as a percent increase compared to the no cover control.

Herbicide Carryover to Various Fall Planted Cover Crop Species

Abstract

Residual herbicides applied in summer cash crops have the potential to injure subsequent winter annual cover crops, yet little information is available to guide grower's choices. Field studies were conducted in 2016 and 2017 in Blacksburg and Suffolk, Virginia to determine carryover of 30 herbicides commonly used in corn, soybean, or cotton on wheat, barley, cereal rye, oats, annual ryegrass, forage radish, Austrian winter pea, crimson clover, hairy vetch, and rapeseed cover crops. Herbicides were applied to bare ground either 14 weeks before cover crop planting for a preemergence timing or 10 weeks for a postemergence timing. Visible injury was recorded 3 and 6 weeks after planting (WAP), and cover crop biomass was collected 6 WAP. There were no differences observed in cover crop biomass among herbicide treatments, despite visual injury that suggest some residual herbicides have the potential to effect cover crop establishment. Visible injury on grass cover crop species did not exceed 20% from any herbicide. Fomesafen resulted in the greatest injury recorded on forage radish with >50% injury in one site year. Trifloxysulfuron and atrazine resulted in >20% visible injury on forage radish. Trifloxysulfuron resulted in the greatest injury (30%) observed on crimson clover in one site year. Prosulfuron and isoxaflutole significantly injured rapeseed by 17 to 21%. Results indicate that commonly used residual herbicides applied in the previous cash crop growing season result in little injury on grass cover crop species, and only a few residual herbicides could potentially effect the establishment of a forage radish, crimson clover, or rapeseed cover crop.

Introduction

Cover crop hectares planted almost doubled from 2012 to 2017 (CTIC 2017), with most cover crop users residing in the mid-Atlantic and southeastern areas of the United States (USDA ERS 2012). Cover crops have many benefits including nitrogen fixation, erosion mitigation, protecting water quality, increasing soil health, and weed suppression (Hayden et al. 2012; Krutz et al. 2009; Pittman et al. 2019; Snapp et al. 2005). In a survey of farmers that utilize cover crops, 69% of farmers said they sometimes or always see increased control of herbicide resistant weeds following a cereal rye cover crop (CTIC 2017).

Incorporating cover crops into an integrated weed management (IWM) plan has shown to reduce herbicide inputs and selection for further herbicide resistance development (Price et al 2012; Snyder et al. 2016). Combining a cereal rye (*Secale cereale* L.) cover crop with deep tillage reduced Palmer amaranth (*Amaranthus palmeri* S. Watson) germination by as much as 98% in soybeans (*Glycine maxx* (L.) Merr.) (DeVore et al. 2013). Wiggins et al. (2015) found incorporating a legume cover crop into an IWM system in corn reduced Palmer amaranth height, allowing greater grower flexibility in herbicide application timing. Cover crops provide an additional method of early season weed control to reduce pressure on herbicides alone to create an effective IWM plan.

To achieve these benefits, successful cover crop establishment is critical. Weed suppression in particular relies on successful establishment leading to greater cover crop biomass, which can be achieved through an earlier planting date and delayed termination (Mirsky et al. 2011; Mohler and Teasdale 1993). However, herbicides applied during the preceding cash crop may persist in the soil and injure subsequent cover crops (Cornelius and Bradley 2017, Palhano et al. 2018) thus reducing establishment and mitigating these benefits.

Research on herbicide carryover to cover crops is limited, particularly in parts of the United States with greatest adoption.

Herbicide persistence in the soil depends on the herbicide's interactions with the soil and climate to be physically or chemically removed or degraded (Braschi et al. 2011). Soil texture, cation exchange capacity (CEC), pH, and organic matter (OM) content affect herbicide persistence in soil. The more herbicide adsorbed to soil, the more likely it is to persist because less of the herbicide is in soil solution to be taken up by plants, leached, or degraded (Anderson 1983). Generally, greater clay content and CEC increases the amount of herbicide bound to soil particles and decreases herbicide loss to volatilization and other mechanisms (Braschi et al. 2011; Loux and Reese 1993; Ranie et al. 2018). For example, pyroxasulfone's half-life ranged from 104 to 134 days in finer textured clay loam soils compared to 46 to 48 days in a sandy loam soil in Colorado (Westra et al. 2014). Fomesafen and imazethapyr carryover is correlated with extended half-life in clay soils (Mueller et al. 2014). The CEC of soil is increased by soil OM and greater in finer textured soils (Kerr et al. 2004). Agrochemicals are strongly adsorbed to OM (Braschi et al. 2011). However, increased OM, is associated with increased microbial activity, which can increase herbicide degradation (Gunapala and Scow 1998; Kramer et al 2002).

Depending on the herbicide, changes in soil pH can increase its persistence. As pH decreases, chemical and microbial breakdown of herbicides are slower, so some herbicides will persist longer (Ball et al. 2003; Braschi et al. 2011). The net charge of the herbicide molecules and herbicide degradation mechanism can affect how they react in soils of varying pH (Monaco et al. 2002). For example, imidazolinones have a net negative charge at higher pH values, but as the pH decreases, the charge becomes neutral. At a neutral charge, the herbicide is less water soluble (hydrophobic) and more likely to associate with soil organic matter, which causes the herbicide to be less available for microbial degradation and persist in the soil longer. Sulfonylurea herbicides are mainly degraded through non-microbial processes that are more active at lower soil pH, so as the soil pH increases, the degradation process of sulfonylurea herbicides slows (Monaco et al. 2002; Snader 2014).

Environmental conditions, such as moisture and temperature, can affect herbicide persistence in the soil. Herbicide degradation is faster in warm temperatures and with adequate moisture because of increased microbial activity and chemical processes (Ball et al. 2003; Cobucci et al. 1998; Kotoula-Syka et al. 1997; Zimdahl 2007). However, as soil moisture increases above 41%, microbial activity decreases (Prado and Airoldi 1999). Herbicide persistence in the soil can increase in drought conditions because more herbicide is bound to soil particles and less is leached through the soil profile. The interaction between herbicide degradation and environmental conditions is also affected by the herbicide structure and chemical properties.

Herbicide physiochemical properties, such as water solubility, volatility, and binding affinity to soil and OM, affect herbicide persistence in soil. Herbicides that are readily water soluble remain in soil solution and are more likely to be leached or taken up by plants. However, herbicides that are strongly adsorbed to soil may not be displaced by water and some herbicides can react with chemicals in the soil to form water-insoluble compounds (Anderson 1983; Braschi et al. 2011). The amount of herbicide in soil solution also determines the amount at risk for volatilization. Herbicides with higher vapor pressures are more likely to volatilize and less likely to persist in soil (Braschi et al. 2011). Increased soil moisture at the soil surface also increases herbicide volatilization losses (Beestman and Deming 1974).

The duration that the herbicide remains in the soil is described by the herbicide’s half-life. Herbicide soil half-life is a statistic used to measure the average time it takes to lose half of the herbicide through all possible pathways that act on herbicide in the soil environment (Anderson 1983). The longer the soil half-life, the longer the herbicide has the potential to remain at concentrations high enough to impact plant growth and the greater potential for carryover to future crops (Monaco et al. 2002).

The risk of herbicide carryover onto cover crops is influenced by soil, weather, and herbicidal properties, but the sensitivity of cover crop species to a specific herbicide also determines the potential risk of injury from a herbicide. Anderson (1983) stated that the extent to which a plant responds to herbicide is a measure of its susceptibility to that herbicide. If a plant is more susceptible to the herbicide, then it will show a greater response to the herbicide. The susceptibility of the plant is a factor of the selectivity of the herbicide on that plant species. Herbicides are selective in their ability to affect and control plants (Anderson 1983). Selectivity of herbicides on plants is complex, and differences in herbicide selectivity can be due to, but not limited to, plant morphology, herbicide dose, plant uptake of the herbicide, translocation within the plant, metabolism within the plant, and the herbicide’s mode of action (Cobb 1992).

Previous research by Cornelius and Bradley (2017) in Missouri reported cover crop stand reduction from carryover of 13 herbicides used in soybean and nine herbicides used in corn. Carryover from pyroxasulfone reduced Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot) and winter oats (*Avena sativa* L.) biomass by 67%. Treatments containing imazethapyr, fomesafen, and flumetsulam resulted in the greatest herbicide carryover symptoms across all cover crop species evaluated (Cornelius and Bradley 2017). In Arkansas, Palhano et al. (2018) observed carryover injury on crimson clover (*Trifolium incarnatum* L.) from atrazine, pendimethalin, pyroxasulfone, and S-metolachlor, and on cereal rye (*Secale cereale* L.) and wheat (*Triticum aestivum* L.) from pyroxasulfone. Other research indicates that atrazine and metsulfuron injured wheat a year after it was applied (Moyer et al. 2010).

Herbicides applied during the cash crop growing season have shown the potential to persist in the soil and injure cover crops (Cornelius and Bradley 2017; Palhano et al. 2018). Based on the complex interactions and variation in herbicide degradation among climate and soil conditions, research is needed to corroborate previous research and evaluate herbicide carryover potential to reduce establishment of cover crops commonly used in the mid-Atlantic region of the United States. The objective of this study was to determine the potential for 30 different residual herbicides commonly used in summer cash crops in Virginia to persist in the soil and injure subsequent cover crops.

Materials and Methods

Study site. Studies were conducted in 2016 and 2017 to determine the carryover potential of various herbicides to fall planted cover crops. Locations were Blacksburg, Virginia at Kentland Farm (37.19ºN, 80.57ºW) and Suffolk, Virginia at the Tidewater Agriculture Research and Extension Center (36.66ºN, 76.73ºW). Studies were repeated at both locations in both years, for a total of four site-years. The Blacksburg location is located in the New River flood plain with a Ross silt loam (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls) containing 33.3% sand, 49.1% silt, and 17.6% clay with a pH of 6.5, 4.4% OM, and a CEC of 10.1 cmol kg-1. The Suffolk location was on a Kenansville loamy sand (loamy, siliceous, subactive, thermic Arenic Hapludults) with 84% sand, 9% silt, and 7% clay with a pH of 6.3, 0.5% OM, and a CEC of 4.5 cmol kg-1. Both sites were tilled with a disc to prepare the seed bed, and after, glyphosate (Roundup PowerMAX; Monsanto Company; St. Louis, Missouri) was applied at 1.26 kg ae ha-1 to control weeds before application of the residual herbicides utilized in this study.

Experimental Design. The experiments utilized a randomized complete block design with a split-plot treatment structure with four replications. The main plot was herbicide treatment and the split-plot was cover crop species. Plots were 3 by 9.1 m. Each of the 10 different cover crop species (Table 8) were planted in two rows spaced 16.5 cm apart using a Tye drill (AGCO Corporation Headquarters, Duluth, Georgia). There were 30 residual herbicide treatments: 12 were applied at a “preemergence timing,” 14 weeks prior to cover crop planting, (Table 9) and 18 were applied at a “postemergence timing,” 10 weeks prior to cover crop planting (Table 10). A non-treated check was included. Herbicides were applied at a preemergence timing if their label prevents a postemergence application or based on when growers usually apply them.

Timings were selected to be the shortest—yet realistic—time between application and cover crop planting, representing a realistic, maximum potential for carryover.

Field Management and Data Collection. Preemergence treatments were applied on June 1st in 2016 and June 2nd in 2017 in Suffolk and June 13th in 2016 and June 12th in 2017 in Blacksburg. Postemergence treatments were applied on June 27th in 2016 and July 6th in 2017 in Suffolk and July 11th in 2016 and 2017 in Blacksburg. These timings were late compared to traditional timings in Virginia, but not unrealistic for a late planting or double cropping behind a winter annual cereal or brassica crop. Herbicide treatments were applied using a CO2 pressurized backpack sprayer delivering 140 L ha-1 with a hand boom equipped with 4 XR 11002 nozzles (TeeJet®, Spraying Systems Co., Wheaton, IL) on 46 cm spacing. Cover crops were planted in Suffolk on September 2nd in 2016 and on September 13th in 2017 and on September 19th in 2016 and 2017 in Blacksburg. Cover crop seeding dates were early, but still realistic, for the area to simulate the maximum potential for the herbicides utilized in this trial to affect cover crop establishment.

Cover crops were assessed for visible injury 3 and 6 weeks after planting on a scale of 0 to 100, where 0 is no visible injury and 100 is complete plant necrosis (Frans et al. 1986). Aboveground cover crop biomass for 0.6 row m was collected 6 weeks after planting (WAP). Cover crop biomass was then dried at 65.5ºC for 3 days and weighed.

Data Analyses. Data were analyzed using JMP Pro 14 (JMP Pro 14; SAS Institute, Inc., Cary, NC). Herbicide treatment, year, and interaction in treatment by year were considered fixed effects and block was considered a random effect for both the visible injury and biomass data analyses. Data were subjected to ANOVA. In many but not all instances, treatment by location or year and treatment by species interactions were detected. Herbicide carryover is known to vary by location (i.e. soil and weather factors) (Braschi et al. 2011; Loux and Reese 1993; Ranie et al. 2018) and individual cover crop species (Anderson 1983). Therefore all data were analyzed by species and by location and when necessary by year, when a significant interaction in treatment by year existed, including biomass data. Biomass data were subjected to ANOVA followed by a Dunnett's Test at $\alpha=0.1$ using the non-treated check as the control group.

The non-treated check was excluded from the visible injury analysis. Many treatments resulted in no (0%) visible injury leading to a non-normal, zero-inflated data set. Therefore, a 0, no injury, or 1, any injury, was assigned to all visible injury rating data points and analyzed using a generalized linear model with a binomial distribution and logit link to determine which herbicide treatments resulted in injury to each cover crop species. Based on this analysis, data from treatments that did not cause visible injury were excluded from further analysis. Data from treatments that did cause visible injury were subjected to ANOVA followed by means separation using Tukey's HSD at $\alpha=0.1$.

Results and Discussion

Cover Crop Biomass Response. Cover crop biomass was positively correlated with precipitation between the two years (Table 11). No differences were detected in cover crop biomass regardless of treatment for all cover crop species relative to the non-treated. The lack of difference can be explained by the observed injury being more in the form of discoloration and irregular growth and less as stunting. Cornelius and Bradley (2017) saw biomass reductions from herbicide carryover onto wheat, forage radish, cereal rye, crimson clover, oats, Austrian winter pea, annual ryegrass, and hairy vetch. Palhano et al. (2018) saw similar results to our study with no biomass reduction of Austrian winter pea, cereal rye, wheat, hairy vetch, or rapeseed, but they did observe a biomass reduction of crimson clover from atrazine, pendimethalin, pyroxasulfone, and S-metolachlor. Differences between our findings and the results of previous research is most likely due to differences in the weather and soil in Virginia compared to Arkansas and Missouri.

Visible Herbicide Carryover to Grass Species. According to the generalized linear model, many treatments resulted in no (0%) visible injury. Of the treatments that did result in visible injury, less injury was generally observed on grass cover crop species when compared to broadleaf species. There were no differences among treatments that caused injury on all grass species and injury was < 20% (Tables 12 and 13).

In general, herbicide visible injury was greater in 2016 than 2017. Wheat was injured by 27 out of the 30 herbicides evaluated in this study; however, only saflufenacil, isoxaflutole, and imazethapyr resulted in >15 % injury 3 WAP, but no herbicide resulted in >10% injury 6 WAP (Tables 12 and 13). Dimethanamid-P, rimsulfuron + thifensulfuron-methyl, and flumioxazin resulted in 0% injury on wheat at both locations and rating timings. Injury from isoxaflutole and imazethapyr was expected due to 4 month rotation restrictions to wheat according to their labels (Anonymous 2019; Anonymous 2017a).

Saflufenacil resulted in 18% injury on wheat in Blacksburg 3 WAP (Table 12). Saflufenacil is registered for use preplant in wheat, but injury can occur to some sensitive varieties (Anonymous 2017b). Results were similar to those reported by Cornelius and Bradley (2017) with injury from atrazine, imazethapyr, and isoxaflutole. However, unlike Cornelius and Bradley (2017) and Palhano et al. (2018), wheat was not injured by pyroxasulfone, topramezone, or rimsulfuron + thifensufluron-methyl.

Acetochlor, chlorimuron ethyl, and imazamox did not result in injury on barley at either location, regardless of rating timing. All other herbicides resulted in significant injury on barley in Suffolk 3 WAP, but only cloransulam-methyl resulted in >15% injury (Table 12). Cloransulam-methyl has a 12 month rotational interval to barley (Anonymous 2017c). There were no herbicides that injured barley more than 10% 3 WAP (Table 12), and no injury was observed on barley 6 WAP in Blacksburg. However, isoxaflutole injured barley >15% in Suffolk 6 WAP in 2016. Only fomesafen resulted in injury (19%) on barley in Suffolk 6 WAP in 2017 (Table 13).

No herbicide treatment resulted in significant cereal rye injury in Blacksburg. Pyroxasulfone (10%), isoxaflutole (14%), prosulfuron (12%), cloransulam-methyl (17%), and fluometuron (14%) resulted in cereal rye injury in Suffolk 3 WAP (Table 12). Prosulfuron injury can be explained by its average half-life of 118 days when the soil pH is between 6.1 and 6.6 (Shaner 2014). Cereal rye injury was observed from 14 herbicides 6 WAP in Suffolk, but injury was <10% (Table 13). Palhano et al. (2018) reported similar results with carryover observed to cereal rye from pyroxasulfone. Similarly, Cornelius and Bradley (2017) observed carryover to cereal rye from cloransulam-methyl and isoxaflutole. Cereal rye was not injured to the level observed from atrazine (81-90%) by Ivany et al. (1985), likely due to warmer and wetter conditions in Virginia compared to Canada.

Greater injury in Suffolk compared to Blacksburg on barley from cloransulam-methyl and isoxaflutole and on cereal rye from cloransulam-methyl, fluometuron, isoxaflutole, and pyroxasulfone can be attributed to greater organic matter in Blacksburg promoting more microbial activity to degrade the herbicides in the soil (Gunapala and Scow 1998; Kramer et al 2002). Cloransulam-methyl, fluometuron, isoxaflutole, and pyroxasulfone persistence in the soil is heavily influenced by microbial activity (Shaner 2014).

Injury on oats was only observed in Blacksburg 3 WAP from 7 of 30 herbicides, but none of the herbicides resulted in >10% injury (Table 12). No visible injury was observed in Suffolk 3 WAP or 6 WAP at either location.

Annual ryegrass was injured by 17 herbicides in Suffolk 3 WAP and 5 herbicides in Blacksburg 3 WAP, but none of the herbicides resulted in >15% visible injury (Table 12). Annual ryegrass was not injured 6 WAP in Blacksburg and no herbicide resulted in >10% injury in Suffolk 6 WAP.

Visible Herbicide Carryover to Broadleaf Species. Hairy vetch was not rated in Suffolk in 2016 and Austrian winter pea and rapeseed were not rated in Blacksburg in 2017 due to a poor stand in the non-treated. For these species, data were only analyzed from the locations where 2 years of data existed. Stand establishment challenges also highlight real world issues growers face in conservation tillage systems.

Fomesafen resulted in the most injury on forage radish of all herbicides tested in Suffolk 3 WAP, Suffolk 6 WAP in 2017, and Blacksburg 6 WAP in 2017 with 24, 24, and 58% injury, respectively (Tables 14 and 15). Fomesafen also resulted in 10% injury on forage radish 3 WAP in Blacksburg (Table 14). Forage radish injury from fomesafen was greater in 2017 than 2016 most likely due less total rainfall in 2017 at both locations (Table 11). Fomesafen degrades much slower under aerobic conditions compared to anaerobic conditions, so lower soil moisture can increase herbicide persistence (Cobucci et al 1998; Shaner 2014). Cornelius and Bradley (2017) also saw the greatest amount of injury on radish from fomesafen. Greater injury from fomesafen onto forage radish in Blacksburg compared to Suffolk can be attributed to fomesafen's longer half-life in clay soils as the soil at Blacksburg has a greater clay content (Mueller et al 2014).

Trifloxysulfuron resulted in >15% injury in Suffolk (23%) and Blacksburg (18%) 3 WAP and in Blacksburg 6 WAP (19%) on forage radish (Tables 14 and 15). Sulfonylurea persistence is determined mainly by soil pH, which determines the degradation rate by chemical hydrolysis and by soil microbes. As soil pH increases to 7.0, sulfonylurea persistence increases due to increased anionic forms of the herbicide resulting in decreased microbial degradation and dissipation (Grey and McCullough 2012, Shaner 2014). Even though our soil pH was below 7, our results suggest the higher soil pH in Blacksburg compared to Suffolk led to decreased degradation of trifloxysulfuron and thus greater injury in Blacksburg. Trifloxysulfuron can control wild radish (*Raphanus raphanistrum* L.), and it has a 12 month rotational restriction to radish following an application in cotton (*Gossypium* spp.) (Anonymous 2015).

Atrazine resulted in >10% injury on forage radish in Blacksburg 6 WAP in 2016 and in Suffolk 6 WAP in 2016 with 20 and 13% injury, respectively (Table 15). Burnside et al. (1971) reported atrazine can persist in the soil over a year, which explains the injury on forage radish and multiple other cover crop species (Tables 12, 13, 14, and 15), but Cornelius and Bradley (2017) did not observe atrazine carryover to forage radish. Similar forage radish injury was observed from isoxaflutole (up to 13%) and rimsulfuron + thifensulfuron-methyl (up to 12%) as Cornelius and Bradley (2017) (Table 14 and 15).

Austrian winter pea was injured by 15 herbicides, but only bicyclopyrone + mesotrione + S-metolachlor resulted in >10% injury in Suffolk 3 WAP (Table 14). No herbicides resulted in significant visible injury 6 WAP. Of all broadleaf cover crop species evaluated, Austrian winter pea was generally injured less across all herbicides in Suffolk.

Trifloxysulfuron resulted in the greatest crimson clover injury (30%) 6 WAP in Suffolk in 2017 followed by linuron and cloransulam-methyl at 10% injury (Table 8). Trifloxysulfuron also resulted in 26% injury in Suffolk 3 WAP, 13% in Blacksburg 3 WAP, 13% in Suffolk 6 WAP in 2016, and 15% in Blacksburg 6 WAP in 2016 (Tables 14 and 15). Results were different compared to Palhano et al. (2018), who saw no trifloxysulfuron carryover injury to crimson clover.

Bicyclopyrone + mesotrione + S-metolachlor resulted in >10% injury on crimson clover in Suffolk 6 WAP in 2016 (11%) and in Blacksburg 6 WAP in 2017 (13%) (Table 15). Flumioxazin resulted in injury in Suffolk 3 WAP and in Suffolk 6 WAP in 2016 with 11 and 18% injury, respectively (Tables 14 and 15). Flumioxazin is primarily degraded in the soil by microbes, and soil OM increases microbial activity, which explains why injury was observed in Suffolk and not Blacksburg as Suffolk has much lower soil OM (Gunapala and Scow 1998; Kramer et al 2002; Shaner 2014)

There was no significant injury on hairy vetch in Blacksburg 3 WAP. There was no injury >10% on hairy vetch 6 WAP in Blacksburg, and only 7 herbicides caused significant injury (Table 15).

Rapeseed was injured by 27 herbicides and 7 of those herbicides resulted in ≥15% injury 3 WAP in Suffolk: simazine, bicyclopyrone + mesotrione + S-metolachlor, mesotrione, isoxaflutole, prosulfuron, rimsulfuron + thifensulfuron-methyl, and sulfentrazone, (Table 14). Only isoxaflutole and prosulfuron resulted in >15% injury on rapeseed 6 WAP in Suffolk with 19 and 17% visible injury, respectively (Table 15). Low soil organic matter in Suffolk can explain injury from isoxaflutole. Isoxaflutole degradation is dependent on microbial activity, which is influenced by soil OM (Gunapala and Scow 1998; Kramer et al 2002; Shaner 2014). Injury from prosulfuron can be attributed to its average half-life of 118 days for a soil with a pH of 6.1 to 6.6, which is the range of our soils for this study (Shaner 2014).

Management Implications. Even though there were no differences detected in cover crop biomass by herbicide treatment, visual injury suggests that there is the potential for some residual herbicides applied in the previous cash crop growing season to affect cover crop establishment. All herbicides resulted in visible injury on at least one cover crop species, but most injury was low and often below what would be considered unacceptable by commercial growers. Thus, with limited exceptions, small grains and hairy vetch can be planted without significant concern of herbicide carryover from commonly used residual herbicides affecting cover crop establishment or biomass accumulation.

Fomesafen resulted in the greatest injury among all herbicides with 58% visible injury on forage radish in Blacksburg in 2017, suggesting that forage radish should not be utilized as a cover crop if fomesafen was applied in the previous cash crop. Growers should avoid planting forage radish following applications of atrazine and trifloxysulfuron as our results show they have the potential to interfere with cover crop establishment. Crimson clover should not be planted following an application of trifloxysulfuron in the previous growing season. Flumioxazin also injured crimson clover in Suffolk on a coarser textured soil compared to Blacksburg's finer textured soil, so crimson clover should be avoided on sandy soils where flumioxazin was applied. Prosulfuron and isoxaflutole resulted in 17 and 19% injury 6 WAP, respectively, on rapeseed suggesting it has the potential to persist in the soil and effect establishment when applied in the previous cash crop growing season.

Some results from previous studies were corroborated, while some were different. Herbicide persistence is known to vary with location (i.e. soil type) and year (i.e. weather) (Braschi et al. 2011). Results do support that soil texture has an impact on herbicide carryover potential, but the interaction between the herbicide and all the factors associated with its ability to persist in the soil is complex. Fomesafen resulted in the greatest injury at Blacksburg on a finer textured soil with greater organic matter, which is supported by fomesafen's extended half-life in clay soils documented by Mueller et al. (2014). However, flumioxazin and trifloxysulfuron resulted in greater injury at Suffolk on a coarser textured soil, suggesting that herbicides differ in how the interact with soil and the climate. The interaction between herbicide persistence and cover crop injury is complex and site specific, so additional localized research is needed. Little research was found on the carryover potential and the factors influencing the persistence and degradation of the sulfonylurea herbicides utilized in this study, suggesting the need for additional research to be conducted.

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Table 8. Cover crop species, cultivar, and seeding rate used in the herbicide carryover experiments in Blacksburg and Suffolk, VA in 2016 and 2017.

Species	Cultivar	Seeding rate
Grasses		kg ha^{-1}
Winter wheat	Red Gore	134
Winter barley	P919	134
Cereal rye	Elbon	134
Winter oats	Bob	134
Annual ryegrass	Winterhawk	22.4
Broadleaves		
Forage radish	Nitro	9
Austrian winter pea	VNS[a]	56
Crimson clover	Dixie	22.4
Hairy vetch	TNT	28
Rapeseed	Trophy	6.7

[a] Abbreviation: VNS, variety not stated

Table 9. Preemergence timing herbicide treatments, applied 14 weeks prior to cover crop planting, used in the herbicide carryover experiment in Blacksburg and Suffolk, VA in 2016 and 2017.

Common Name	Trade Name	Rate	Manufacturer		
			Name	Location[a]	Website[a]
		kg ai ha^{-1}			
Atrazine	Aatrex	2.2	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngentacropprotection.com
Bicyclopyrone + Mesotrione + *S*-metolachlor	Acuron Flexi	0.05 + 0.2 + 1.8	Syngenta Crop Protection, LLC		
Flumioxazin	Valor	1.1	Valent U.S.A. Corporation	Walnut Creek, CA	www.valent.com/
Fluometuron	Cotoran	1.1	ADAMA	Raleigh, NC	www.adama.com/us/
Isoxaflutole	Balance Flexx	0.1	Bayer CropScience	Research Triangle Park, NC	www.cropscience.bayer.com
Isoxaflutole + Thiencarbazone-methyl	Corvus	0.02 + 0.05	Bayer CropScience		
Linuron	Linex	1.1	Tessenderlo Kerley, Inc.	Phoenix, AZ	www.novasource.com
Metribuzin	Tricor	0.3	United Phosphorus, Inc.	King of Prussia, PA	www.upi-usa.com/
Pyroxasulfone	Zidua	0.2	BASF Corporation	Research Triangle Park, NC	www.basf.com/us
Saflufenacil	Sharpen	0.07	BASF Corporation		
Simazine	Princep	2.2	Syngenta Crop Protection, LLC		
Sulfentrazone	Spartan	1.7	FMC Corporation	Philadelphia, PA	www.fmc.com/

[a] Location and website only listed at the first mention of the manufacturer.

Table 10. Postemergence timing herbicide treatments, applied 10 weeks prior to cover crop planting, used in the herbicide carryover experiment in Blacksburg and Suffolk, VA in 2016 and 2017.

Common Name	Trade Name	Rate[a]	Manufacturer		
			Name	Location[b]	Website[b]
		kg ai or ae ha^{-1}			
Acetochlor	Warrant	2.1	Monsanto Company	St. Louis, MO	monsanto.com
Chlorimuron-ethyl	Classic	0.01	du Pont de Nemours and Company	Wilmington, DE	cropprotection.dupont.com
Clopyralid	Stinger	0.3	Dow AgroSciences LLC	Indianapolis, IN	www.dowagro.com/en-US
Cloransulam-methyl	FirstRate	0.02	Dow AgroSciences LLC		
Dimethenamid-*P*	Outlook	0.7	BASF Corporation	Research Triangle Park, NC	www.basf.com/us
Fomesafen	Reflex	0.4	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngentacropprotection.com
Imazamox	Raptor	0.04	BASF Corporation		
Imazethapyr	Pursuit	0.07	BASF Corporation		
Mesotrione	Callisto	0.1	Syngenta Crop Protection, LLC		
Pendimethalin	Prowl H2O	1.6	BASF Corporation		
Primisulfuron-methyl	Beacon	0.04	Syngenta Crop Protection, LLC		
Prosulfuron	Peak	0.03	Syngenta Crop Protection, LLC		
Rimsulfuron + Thifensulfuron-methyl	Resolve Q	0.02	du Pont de Nemours and Company		
S-metolachlor	Dual II Magnum	2.1	Syngenta Crop Protection, LLC		
Tembotrione	Laudis	0.09	Bayer CropScience	Research Triangle Park, NC	www.cropscience.bayer.com
Thifensulfuron-methyl	Harmony SG	0.007	FMC Corporation	Philadelphia, PA	www.fmc.com
Topramezone	Impact	0.02	AMVAC Chemcial Corporation	Los Angeles, CA	www.amvac-chemical.com
Trifloxysulfuron	Envoke	0.01	Syngenta Crop Protection, LLC		

[a] Herbicide rate is listed as active ingredient or acid equivalent as appropriate.

[b] Location and website only listed at the first mention of the manufacturer.

Table 11. Rainfall totals and average temperature for Suffolk and Blacksburg, VA in 2016 and 2017 from the duration of the studies.

	Suffolk				Blacksburg			
	Rainfall		Average Temperature		Rainfall		Average Temperature	
Timing	2016	2017	2016	2017	2016	2017	2016	2017
	---cm---		---ºC---		---cm---		---ºC---	
June 1st to Planting	27	30	26	25	29	16	22	21
July 1st to Planting	20	24	26	26	20	12	23	22
Planting to 3 WAP[a]	36	6	23	22	1	3	21	17
3 WAP to 6 WAP	31	3	20	22	11	40	21	18
Total	114	64			82	70		

[a] Abbreviation: WAP; weeks after planting.

Table 12. Visible injury from herbicide carryover on grass cover crop species 3 weeks after planting pooled across year in Suffolk and Blacksburg, VA in 2016 and 2017.[a]

Timing[b]	Wheat		Barley		Cereal Rye	Oats	Annual Ryegrass	
Treatment	Suffolk	Blacksburg	Suffolk	Blacksburg	Suffolk	Blacksburg	Suffolk	Blacksburg
Preemergent				------------------------------%------------------------------				
Atrazine	11	8	6	8	6	.	.	.
Bicyclopyrone + mesotrione + *S*-metolachlor	5	9	12	.	6	.	.	.
Flumioxazin	.	.	4	.	.	.	.	.
Fluometuron	5	11	11	4	14	.	4	4
Isoxaflutole	16	.	5	.	14	.	14	.
Isoxaflutole + thiencarbazone-methyl	7	.	5	.	7	.	3	.
Linuron	5	4	8	.	9	3	8	.
Metribuzin	8	4	9	.	4	.	11	.
Pyroxasulfone	.	.	3	.	10	.	.	.
Saflufenacil	9	18	13	.	.	.	.	.
Simazine	9	.	.	.	3	.	.	.
Sulfentrazone	7	.	10	.	7	.	8	.
Postemergent								
Acetochlor	2	.	.	.	4	.	5	.
Chlorimuron-ethyl	7	8	.	.	.	.	.	.
Clopyralid	3	.	6	8	8	.	8	.
Cloransulam-methyl	6	10	18	8	17	3	.	.
Dimethenamid-*P*	.	.	8	.	3	2	5	.
Fomesafen	4	.	8	.	.	3	.	.
Imazamox	.	4	.	.	.	3	.	11
Imazethapyr	16	.	8	.	8	.	6	.
Mesotrione	7	3	9	.	.	.	13	.
Pendimethalin	3	.	8	9	.	.	7	.
Primisulfuron-methyl	.	9	3	3	6	.	.	.
Prosulfuron	.	2	9	4	12	.	14	.
Rimsulfuron + thifensulfuron-methyl	.	.	9	.	9	6	4	7
S-metolachlor	.	.	4	.	3	.	.	.
Tembotrione	.	.	2	.	.	.	.	.
Thifensulfuron-methyl	.	.	6	.	5	.	3	4
Topramezone	3	.	4	.	5	.	6	.
Trifloxysulfuron	3	.	14	3	4	4	11	4
P-value[c]	0.867	0.739	0.534	0.837	0.752	0.893	0.770	0.657

[a] Periods (.) in the data set indicate omitted data from Tukey's HSD means separation analysis because that herbicide treatment did not significantly injure the cover crop species according to a

generalized linear model with a binomial distribution and logit link test. No significant differences were detected among treatments that caused injury according to Tukey's HSD at $\alpha=0.1$ within column.

[b] Cover crops were planted in early September, approximately 14 weeks after preemergence and 10 weeks after postemergence treatment application to a fallow field.

[c] The p-value displayed was derived from the ANOVA analysis comparing treatments that had some injury according to the generalized linear model with a binomial distribution and logit link test.

Table 13. Visible injury from herbicide carryover on grass cover crop species 6 weeks after planting in Suffolk and Blacksburg, VA in 2016 and 2017.[a]

	Wheat		Barley		Cereal Rye	Annual Ryegrass
Timing[b]	Suffolk	Blacksburg	Suffolk		Suffolk	Suffolk
Treatment	2016-2017	2016-2017	2016	2017	2016-2017	2016-2017
Preemergent	------------------------------%------------------------------					
Atrazine	.	5	6	.	.	.
Bicyclopyrone + mesotrione + *S*-metolachlor	6	.	4	.	4	9
Flumioxazin	.	.	.	.	.	5
Fluometuron	.	.	.	.	7	3
Isoxaflutole	7	4	15	.	5	.
Isoxaflutole + thiencarbazone-methyl	3	6	.	.	4	3
Linuron	.	.	.	.	.	3
Metribuzin	5	8	9	.	3	.
Pyroxasulfone	.	3	.	.	.	.
Saflufenacil	.	4	.	.	.	10
Simazine	3	.	5	.	4	.
Sulfentrazone	.	5	5	.	6	.
Postemergent						
Acetochlor	.	3	.	.	.	.
Chlorimuron-ethyl	.	.	.	.	.	.
Clopyralid	.	.	.	.	8	.
Cloransulam-methyl	.	.	10	.	7	.
Dimethenamid-*P*	.	.	.	.	.	.
Fomesafen	.	.	.	19	.	1
Imazamox	.	.	.	.	.	3
Imazethapyr	.	.	9	.	.	.
Mesotrione	.	4	.	.	.	3
Pendimethalin	3	.	4	.	6	.
Primisulfuron-methyl	.	.	.	.	.	3
Prosulfuron	6	.	13	.	4	10
Rimsulfuron + thifensulfuron-methyl	.	.	.	.	5	4
S-metolachlor	7	.	.	.	3	.
Tembotrione	4	8	.	.	.	4
Thifensulfuron-methyl	.	6	11	.	.	.
Topramezone	.	4	.	.	4	.
Trifloxysulfuron	.	.	9	.	.	4
P-value[c]	0.867	0.985	0.842	<0.001	0.986	0.767

[a] Periods (.) in the data set indicate omitted data from Tukey's HSD means separation analysis because that herbicide treatment did not significantly injure the cover crop species according to a

generalized linear model with a binomial distribution and logit link test. No significant differences were detected among treatments that caused injury according to Tukey's HSD at $\alpha=0.1$ within column.

[b] Cover crops were planted in early September, approximately 14 weeks after preemergence and 10 weeks after postemergence treatment application to a fallow field.

[c] The p-value displayed was derived from the ANOVA analysis comparing treatments that had some injury according to the generalized linear model with a binomial distribution and logit link test.

Table 14. Visible injury from herbicide carryover on broadleaf cover crop species 3 weeks after planting pooled across year in Suffolk and Blacksburg, VA in 2016 and 2017.[a]

Timing[b]	Forage Radish		Austrian Winter Pea	Crimson Clover		Rapeseed
Treatment	Suffolk	Blacksburg	Suffolk	Suffolk	Blacksburg	Suffolk
Preemergent			--------------------------------%--------------------------------			
Atrazine	10 ab	.	8	14	.	8
Bicyclopyrone + mesotrione + *S*-metolachlor	9 ab	.	11	7	.	19
Flumioxazin	.	.	3	11	.	13
Fluometuron	.	.	6	7	.	8
Isoxaflutole	.	13	3	11	.	18
Isoxaflutole + thiencarbazone-methyl	.	.	.	.	.	4
Linuron	.	.	.	10	.	11
Metribuzin	4 ab	.	8	16	.	13
Pyroxasulfone	4 ab	4	3	9	.	.
Saflufenacil	.	9	9	6	.	8
Simazine	4 ab	8	.	6	.	16
Sulfentrazone	.	5	.	13	.	15
Postemergent						
Acetochlor	6 ab	.	.	8	.	5
Chlorimuron-ethyl	3 b	8	3	16	.	3
Clopyralid	4 ab	3	.	.	.	13
Cloransulam-methyl	.	.	.	8	4	6
Dimethenamid-*P*	.	9	.	.	.	.
Fomesafen	24 a	10	3	6	10	4
Imazamox	3 b	5	4	19	.	.
Imazethapyr	.	5	.	4	.	14
Mesotrione	6 ab	.	.	21	.	19
Pendimethalin	.	.	4	4	.	8
Primisulfuron-methyl	.	8	4	9	.	9
Prosulfuron	4 ab	11	.	13	4	21
Rimsulfuron + thifensulfuron-methyl	5 ab	12	.	9	5	16
S-metolachlor	.	.	9	11	.	6
Tembotrione	.	.	.	14	.	9
Thifensulfuron-methyl	.	.	.	9	3	5
Topramezone	8 ab	4	4	10	.	7
Trifloxysulfuron	23 ab	18	.	26	13	9
P-value[c]	0.019	0.919	0.743	0.493	0.194	0.833

[a] Periods (.) in the data set indicate omitted data from Tukey’s HSD means separation analysis because that herbicide treatment did not significantly injure the cover crop species according to a

generalized linear model with a binomial distribution and logit link test. Shared letters within column indicate no significant difference according to Tukey's HSD at α=0.1.

[b] Cover crops were planted in early September, approximately 14 weeks after preemergence and 10 weeks after postemergence treatment application to a fallow field

[c] The p-value displayed was derived from the ANOVA analysis comparing treatments that had some injury according to the generalized linear model with a binomial distribution and logit link test.

Table 15. Visible injury from herbicide carryover on broadleaf cover crop species 6 weeks after planting in Suffolk and Blacksburg, VA in 2016 and 2017.[a]

	Forage Radish				Crimson Clover				Hairy Vetch	Rapeseed
Timing[b]	Suffolk		Blacksburg		Suffolk		Blacksburg		Blacksburg	Suffolk
Treatment	2016	2017	2016	2017	2016	2017	2016	2017	2016-2017	2016-2017
Preemergent	------------------------------%------------------------------									
Atrazine	13	.	20	.	9	.	.	.	.	9
Bicyclopyrone + mesotrione + *S*-metolachlor	.	.	.	.	11	.	.	13	.	12
Flumioxazin	.	.	.	.	18	.	.	.	.	9
Fluometuron	.	.	.	.	3	8 b	.	.	.	8
Isoxaflutole	8	.	.	.	8	.	.	14	.	19
Isoxaflutole + thiencarbazone-methyl	.	.	.	.	4	8 b	.	.	6	8
Linuron	.	.	.	.	.	8 b	.	.	.	4
Metribuzin	.	.	.	.	5	.	.	.	.	8
Pyroxasulfone	.	.	.	.	.	.	.	.	.	.
Saflufenacil	.	.	.	.	.	.	.	.	.	9
Simazine	.	.	13	.	6	.	3	5	.	5
Sulfentrazone	.	.	.	.	8	.	.	.	.	6
Postemergent										
Acetochlor	.	.	.	.	.	.	.	.	.	.
Chlorimuron-ethyl	.	.	.	.	.	.	.	.	5	.
Clopyralid	.	.	.	.	.	.	.	.	.	6
Cloransulam-methyl	6	.	.	.	8	10 b	3	5	.	4
Dimethenamid-*P*	.	.	10	.	5	.	.	.	.	.
Fomesafen	.	24	8	58 a	6	.	5	.	.	5
Imazamox	5	.	.	.	9	.	.	.	5	.
Imazethapyr	.	.	8	3 b	.	.	.	.	4	1
Mesotrione	.	.	.	.	.	.	.	.	.	8
Pendimethalin	.	.	.	.	.	.	.	.	.	.
Primisulfuron-methyl	.	.	.	.	5	.	.	.	.	3
Prosulfuron	.	.	.	.	5	.	.	.	.	17
Rimsulfuron + thifensulfuron-methyl	.	.	.	.	6	.	.	.	.	4
S-metolachlor	.	.	.	.	.	.	.	.	.	.
Tembotrione	.	.	.	.	.	10 b	.	.	3	.
Thifensulfuron-methyl	.	.	.	.	.	.	.	.	4	4
Topramezone	.	.	.	.	8	.	.	13	.	4
Trifloxysulfuron	8	.	19	.	13	30 a	15	.	3	3
P-value[c]	0.762	0.032	0.897	<0.001	0.823	<0.001	0.791	0.465	0.981	0.184

[a] Periods (.) in the data set indicate omitted data from Tukey's HSD means separation analysis because that herbicide treatment did not significantly injure the cover crop species according to a

generalized linear model with a binomial distribution and logit link test. Shared letters within column indicate no significant difference according to Tukey's HSD at α=0.1.

[b] Cover crops were planted in early September, approximately 14 weeks after preemergence and 10 weeks after postemergence treatment application to a fallow field

[c] The p-value displayed was derived from the ANOVA analysis comparing treatments that had some injury according to the generalized linear model with a binomial distribution and logit link test.