

Harvest Weed Seed Control: An Integrated Weed Management Strategy for  
Organic and Conventional Production Systems

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## Abstract

Harvest weed seed controls (HWSC) destroy weed seeds that are retained by the plant at crop harvest, which would typically be spread by the harvester along with other field residues. HWSC exploits coincidental maturity between crops and weeds, so an experiment was designed to collect weed seeds as they shatter throughout the growing season and through a simulated harvest delay. This experiment monitored four economically important broadleaf species and two grass species in a soybean (*Glycine max* (L.) Merr.) field. Results indicated that broadleaf species shattered seed at rates accelerating through the growing season, while grass species shattered more seed early in the growing season. Field experiments in organic and conventional winter wheat (*Triticum aestivum* L.) fields infested with Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot) compared two HWSC techniques to grower-standard weed management programs in each system, including both no-till and full-till standard treatments in the conventional system. Italian ryegrass populations were monitored, and wheat yield was measured both before and after HWSC application. In both organic and conventional cropping systems, HWSC treatments did not provide better Italian ryegrass control than the grower-standard treatments. The conventional program including tillage boosted Italian ryegrass populations. These results suggest that HWSC treatments did not enhance Italian ryegrass control compared to grower-standard practices in either the organic or conventional systems. Additionally, broadleaf weeds may retain enough seeds to be viable targets for HWSC. Incorporating best practices, such as a timely crop harvest, is key for understanding and optimizing HWSC.

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## **General Audience Abstract**

Harvest weed seed controls (HWSC) destroy weed seeds that the weed plant retains at the time of crop harvest. On a typical farm, these weed seeds pass through the crop harvester and get spread across the field along with other plant materials. HWSC directly targets weed seeds, differentiating itself from normal weed management practices, such as herbicides, that kill emerging or emerged weed plants. With HWSC, weed seeds never enter the soil seed bank, thus depleting weed populations over time. HWSC works through mechanical means, such as crushing, burning, or removal. For conventional farmers battling herbicide resistant weeds, HWSC can provide effective weed management by diversifying weed management programs. HWSC also has promise as a new chemical-free weed management for organic farmers.

HWSC relies on crops and weeds having coincidental maturity; seeds released from the plant (shattered) before crop harvest cannot be targeted by HWSC. An experiment was designed to collect weed seeds weekly as they shatter throughout the growing season, continuing until three weeks after the ideal date to harvest crops, thereby simulating a situation where weather or logistical factors prevented a timely crop harvest. This experiment monitored four broadleaf species and two grass species that infest soybean fields. Broadleaf species shattered seeds at increasing rates throughout the soybean growing season, with each species shattering over 50% of captured seed during the simulated harvest delay. Compared to broadleaf weeds, grass species shattered relatively more seed early in the growing season. This experiment indicates that broadleaf weeds may be more suited to control by HWSC.

HWSC was also used in organic and conventional winter wheat fields infested with Italian ryegrass. These experiments compared two HWSC techniques, windrow burning of field residue and residue removal to standard weed management programs in each system. Windrow burning incinerates field residues, eliminating weed seeds within.

Residue removal takes all field residues off the field for disposal elsewhere. While the standard organic weed management program involved tillage by default, the conventional cropping system featured both no-till and full-till standard weed management programs. Italian ryegrass populations were monitored through population counts, biomass collections, and counting of seed remaining at harvest. Wheat yield was also recorded. These measurements were taken both before HWSC application and after the first year of HWSC, to compare year-to-year changes.

In the organic cropping system, Italian ryegrass populations grew and wheat yield decreased at similar rates for both HWSC treatments and the standard weed management program. In the conventional cropping system, Italian ryegrass populations declined and wheat yield increased for HWSC and the no-till standard treatments. Tillage, however, boosted Italian ryegrass populations, keeping them at similar levels to the previous growing season. These results suggest that HWSC treatments did not enhance Italian ryegrass control compared to standard practices in either the organic or no-till conventional systems.

Though these results indicate that broadleaf weeds may retain enough seeds to be viable targets for HWSC, more research is needed to optimize HWSC for Italian ryegrass control, especially for organic growers. Incorporating best agricultural practices, such as a timely crop harvest, is key for improving HWSC's efficacy. Commercial implementation of HWSC depends on further understanding of how specific HWSC practices, such as windrow burning, interact with the agricultural landscape, including effects on landscape aesthetics and soil nutrition. HWSC holds promise for diversifying weed management and limiting reliance on herbicides, but its true potential is yet to be revealed.

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## **Goals and Objectives**

This work aims to investigate the viability of harvest weed seed controls (HWSC) for soybean (*Glycine max* (L.) Merr.) and wheat (*Triticum aestivum* L.) growers in Virginia. The first objective is to understand the phenology of seed shattering for key weed species in soybean and wheat. This knowledge would help determine the proportion of weed seeds that typically pass through growers' equipment at harvest and thus would be subjected to HWSC. It is hypothesized that over 90% of weed seeds are retained on the plant at harvest time. The second objective is to evaluate field efficacy of HWSC in both organic and conventional cropping systems. The comparison of HWSC technologies such as windrow burning and residue removal to tillage and grower-standard management practices will improve understanding of HWSC's benefits relative to current technologies. It is hypothesized that HWSC will provide economically beneficial weed management after its first season of use.

## **Literature Review and Justification**

Herbicide resistant weeds are a large and growing threat to agricultural production around the world (Heap 2014). As one of the largest drivers of yield loss in cropping systems, weeds must be controlled by reliable, practical, and economical methods; herbicides have been the most effective methods for weed management in developed nations (Moss 2010). Especially since the introduction of herbicide resistant crops in the mid-1990s, crop farmers have been able to use herbicides to simplify their weed management regimens (Duke 2015). This simplification has allowed growers to largely ignore weed biology, primarily due to effective weed control across a variety of cropping systems and environmental factors (VanAcker 2009). While crop farmers have historically been forced to time the application of various management strategies with certain weed growth stages, they have increasingly turned to herbicides, especially glyphosate, for economic benefits associated with comprehensive chemical weed management and reduced labor costs, estimated to be worth about \$1.2 billion in the United States in 2005 (Gianessi 2005).

Increasingly, however, herbicide resources have been lost as weed species have evolved resistance to various modes of herbicidal action through this process of repeated selection, including resistance to multiple herbicides within a single weed population (Green 2007). Herbicide resistant weed populations develop quickly, with the first known case of glyphosate

resistant weeds caused by use of genetically modified, glyphosate resistant soybeans being discovered after just three growing seasons (VanGessel 2001). Repeated herbicide use has caused herbicide resistance for decades before genetically modified herbicide resistant crops, as well, with the first instance of triazine resistant weeds occurring in 1968 (Heap 2014). Worsening of herbicide resistance continues today, making current options for weed management less valuable (Beckie 2011, Bonny 2016, Owen 2011).

This change in management practices caused by herbicide resistance can increase farm labor, decrease agricultural productivity, and negatively affect soil health (Duke 2015). For example, herbicide resistant weeds force many growers to abandon conservation tillage, which was a boon for soil health and conservation (Price et al. 2011). Because of this wide variety of complications, growers are being forced to rely once again on multi-tactic weed management approaches that are comprised of control methods which work together to address management concerns (Kumar et al. 2013). Multi-tactic, or integrated, approaches to weed management, specifically those that use cultural and mechanical controls in addition to herbicidal controls, are necessary for slowing the development of herbicide resistance and maintaining the productivity of agronomic cropping systems (Norsworthy et al. 2012).

Integrated weed management has brought about a renewed focus on weed seed bank dynamics. By understanding and targeting weed seed banks, agriculturalists can exploit a rarely used tactic for weed management (Buhler et al. 1997). As the propagule by which most annual weeds spread, seeds are a necessary vehicle for both spatial and temporal propagation of unwanted plants. Seed banks are, simply, the primary sources of future weed problems (Grundy and Bond 1998). In particular, the targeting of weed seeds while they are undispersed on the plant, has been an increasingly important strategy for managing weed seed banks. By coupling this strategy with routine harvest processes, Australian growers have been able to create harvest weed seed controls that have begun to reliably, practically, and economically manage the herbicide resistant weeds that have been a nuisance across their cropping systems (Walsh and Powles 2014a).

**Why Manage Weed Seed Banks?** Weed populations can be very difficult to predict, because their dynamics are influenced by many factors such as weather, landscape heterogeneity, weed genetic diversity, and, importantly, management practices. While weed population dynamics can

often seem chaotic, much of the variation seen in production fields is driven by growers' decisions; an analysis of 12 weed species' populations over a 12 year period in continuous winter wheat in the Broadbalk experiment determined that weed densities were dynamically stable, oscillating in response to management and not simply stochastic change (Freckleton and Watkinson 2002). While current, universal approaches to weed management have been economically effective due to high levels of weed control provided by herbicides, researchers are calling for improvement of these approaches through weed management models that are sensitive to growers' specific cropping systems, weed pressures, and risk for herbicide resistance development (Bagavathiannan and Norsworthy 2012).

This relationship can be especially synergistic when management practices are chosen in consideration of weed seed bank populations, because variation in weed species' time to maturity influences how different practices alter weed seed shattering or shed. In fact, in-crop weed management can actually increase seed shed after harvest, for certain species. For example, post-emergence fenoxaprop applications in spring wheat increased post-harvest seed production by yellow foxtail (*Setaria pumila* (Poir.) Roemer & J.A. Schultes) to levels greater than the amount of yellow foxtail seed produced during the growing season (Kegode et al. 2003). Though growers are taking action to improve their situation in the current crop, they may actually be proliferating weeds for next year's crop and helping that species infest their fields again. This concept has been described in invasion biology as propagule pressure; the number of a species' propagules can have enormous impact on the success of future invasions (Lockwood et al. 2005). Weed seeds are critical propagules in the invasion of cropping systems.

Entire weed communities can be shaped just by the seeds that are entering and allowed to persist in the cropping system. Plant communities can be assembled from seed banks when a certain species' seed traits allow it to overcome environmental filters that prevent other species from invading a system (Booth and Swanton 2002). Environmental filters in an agroecosystem, such as crop competition, herbicide use, or tillage, may remove weed species that lack the traits necessary to overcome these filters. Research on winter wheat systems in Northeastern France found that 11 of 13 studied weed functional traits were correlated with individual species' survival as the cropping system integrated more conservation practices (Trichard et al. 2013). In this example, functional traits like fecundity and moisture requirements helped perennial and

grass species survive the introduction of filters related to increased use of cover crops, while broadleaf weed species generally lacked the traits to overcome this transition.

Weed seed banks that feature species with traits like discontinuous germination, herbicide resistance, or long-term seed dormancies are able to overcome relevant filters and become members of the plant community. In other words, seed traits that prevent a seed from exiting the seed bank through any number of pathways will ensure persistence of that species in the seed bank (Long et al. 2014). Additionally, certain seed traits may allow a species to spread itself by difficult-to-control pathways such as along roadways or through agricultural products like cotton gin trash or grain seed (Michael et al. 2010, Norsworthy et al. 2012, VonDerLippe and Kowarik 2012). In agronomic cropping systems, summer annual weed species may be the most susceptible to filters presented by management practices. More so than species of other life cycles, summer annual weeds tend to have seed traits and reproductive schedules that can be controlled by grower actions, as population models have found that the short-term, cyclical nature of this life cycle makes it especially susceptible to repeated selection by management filters (Davis 2006). Better understanding of the relationship between seed banks and environmental or management filters is important for the development of management practices targeting seeds.

Weed seed bank populations have been known to dictate, to some extent, the level of weed control required. Based on a model derived from field experiments studying foxtails (*Setaria* spp.), common lambsquarters (*Chenopodium album* L.), and redroot pigweed (*Amaranthus retroflexus* L.) in both corn (*Zea mays* L.) and soybean fields, Forcella et al. (1993) found that seed bank populations, summed across species, between 100 and 1,000 weed seeds  $m^{-2}$  were most economically managed by mechanical means, while greater and lesser seed bank populations required chemical management and no management, respectively. This threshold model, however is often of limited value for growers as they have no reliable way of quantifying weed seed bank populations, and seed banks often contain many thousands of seeds  $m^{-2}$  (Forcella et al. 1992). In addition to being variable and often extremely large, soil seed banks can grow rapidly. In a fallow system with no management applied, common lambsquarters has been observed to increase its seed bank population up to 14 fold in a single year (Leguizamón and Roberts 1982). Even at low population levels, weed seed banks can be an important source of weed infestation.

Though weed seed bank populations are hard to measure and predict, their relationship with weed populations is easy to conceptualize: weed population is equal to the seed density multiplied by the emergence rate (Forcella 1992). Therefore, management practices that reduce seed inputs, increase seed losses, or limit germination and emergence can decrease weed populations (Gallandt 2006). Of course, the reality is not so simple in developing new management strategies. Seed bank diversity can allow the collective weed seed bank to overcome certain management practices by having different weed species that are able to individually overcome specific filters. Management practices targeting the weed seed bank should have sufficient diversity to deal with the response of many weed species across multiple scales (Dekker 1999).

Diverse management practices, however, can interact with different weed species and different environmental conditions in unpredictable ways. Decision aid models can be important for helping growers consider and better understand when planning for new weed seed bank management strategies (Bagavathiannan et al. 2013, Lacoste and Powles 2014). While many weed population models are too simplistic to model much of the complexity in cropping systems, taking detailed factors into account, such as seed bank size or seed size, can increase the value of weed population modeling in future weed control decisions (Gardarin et al. 2009, Holst et al. 2006). More complex model parameters also improve the value of seed bank emergence models, compared to simpler calendar- or temperature-based models (Bagavathiannan et al. 2011). Weed seed banks are intrinsically linked with weed populations, and both practical and conceptual understanding of this link is important for the creation of weed seed bank controls (Davis 2006).

**Weed Seed Dispersal.** Weed seed dispersal is a complex process caused by variability across species and agricultural systems. Consideration of this variability can provide context for understanding how weed dispersal patterns are influenced by crop competition. Within a given field, certain crop rotations and environmental conditions can promote weed species of certain life cycles; a continuous rotation of corn and cassava (*Manihot esculenta* Crantz) favored annual weeds, while seed rain was dominated by perennial species in just the second and third years of fallow after this crop rotation (Ekeleme et al. 2000). This interaction between crop competition and weed dispersal can have economically-important agronomic effects. A model based on spring wheat infested with green foxtail (*Setaria viridis* (L.) Beauv.) identified aggressive seed

dispersal as a more important factor determining yield loss than direct competitive ability between crop and weed (Maxwell and Ghera 1992). Spatial distribution associated with seed dispersal can contribute to significantly higher weed populations, and therefore yield loss, directly adjacent to previous seasons' weed patches, such as within the four meters from the edge of a weedy field margin (De Cauwer et al. 2008).

Management practices can spread weed seeds, with combine harvesters known to be important dispersal agents within a field (Ballare et al. 1987, Blanco-Moreno et al. 2004, McCanny and Cavers 1988). Undispersed weed seeds at harvest time can be dragged by harvesters up to 145 m past the edge of a weed patch (Shirtliffe and Entz 2005). This dispersal results in a stretching of weeds' spatial distribution along the direction of harvester travel; areas of variation exist at a scale that is 1.5 to 2 times longer in the direction of the harvester than perpendicular to the harvester (Wiles and Schweizer 2002). Models have calculated that the area directly behind the harvester, where seeds are dispersed at the highest density, can suffer from yield reductions of more than one third compared to areas at the edge of the harvester's spread pattern (Maxwell and Ghera 1992). Additional seeds may be spread on or in harvest equipment as it moves from field to field, when they stick to muddy equipment or get stuck in hard-to-clean corners and crevices. Species with high levels of seed retention at harvest are important targets for HWSC, as their biology currently takes advantage of harvest processes for dispersal, leaving large percentages of their seed to be spread, and therefore controlled, through these mechanisms.

Harvest timing can have additional impacts on HWSC efficacy; as harvest is delayed, weeds may begin to shed seeds, which would no longer be controlled by HWSC. For some species, such as wild oat (*Avena fatua* L.), a four-week delay in harvest reduced seed retention by about half, while other weed species, namely rigid ryegrass (*Lolium rigidum* Gaud.) and wild radish (*Raphanus raphanistrum* L.), retained most of their seeds throughout a simulated harvest delay (Walsh and Powles 2014b). Additionally, many crop weeds have high seed retention at harvest time, but there is great variation across species. Palmer amaranth (*Amaranthus palmeri* S. Wats.) and tall waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer) have exhibited >90% seed retention at soybean harvest time (Green et al. 2016, Schwartz et al. 2016). Additionally, feral rye (*Secale cereal* L.) and wild radish have exhibited >90%, rigid ryegrass has exhibited >80%, and jointed goatgrass (*Aegilops cylindrica* Host.) and downy brome (*Bromus tectorum* L.) have exhibited  $\geq 70\%$  seed retention at wheat harvest (Blanco-Moreno et al. 2004, Soni and Gaines

2016, Walsh and Powles 2014b). However, other species have shown much lower seed retention, with green foxtail reportedly retaining only 20% and early maturing species, such as wild mustard (*Sinapis arvensis* L.), dispersing 100% of seeds by corn harvest time (Forcella et al. 1996). Additionally, barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.) has been observed retaining only 43% of seeds at soybean harvest (Green et al. 2016).

Intraspecific variation in seed shattering time, however, has led separate studies of a weed species to find dramatically different levels of harvest time seed retention, especially in response to various environmental factors. Studies of wild oat have observed seed retention levels ranging from 20 to 84% (Shirliffe et al. 2000, Walsh and Powles 2014b). Similarly, studies of brome grass (*Bromus* spp.) observed seed retention ranging from 40 to 77% (Balsari et al. 1994, Walsh and Powles 2014b). A study of Palmer amaranth found that factors such as germination date and temperature affected seed production levels by up to 750% (Keeley et al. 1987). In addition to magnitude of seed production, temporal patterns in weed biology affect the quality of weed seed shed. Some weed species, such as blackgrass (*Alopecurus myosuroides* Huds.), show higher germination rates in seeds shattered before peak seed shed than those shattered at or after peak seed shed (Moss 1983). Heuristic models, such as growing degree days (GDD) may, however, be less effective when considering multiple species or factors. Forcella et al. (1996) determined that GDD could be a useful tool for understanding the beginning of weed seed shed in many weed species, but other micro- and macro-climatic variations, including single severe weather events, could greatly affect the majority of seed shed timing for most species. More research is needed to create better tools for estimating the relationship between timing of weed seed shed, weed biology, and environmental factors.

Biotic factors also act with environmental factors to affect weed seed shed. Crop by weed interactions can be important. For example, soybean varieties with early maturation and tall growth habits had negative effects on pitted morningglory's (*Ipomoea lacunosa* L.) and hemp sesbania's (*Sesbania herbacea* (P. Mill.) McVaugh) ability to produce seeds, with viable seed production reduced by 48% in some instances (Bennett and Shaw 2000). When comparing equivalent wheat and barley (*Hordeum vulgare* L.) plots, weaker competitive ability of the barley crop caused seed rain to be up to three times higher in barley plots than in wheat plots (Kadzys et al. 2008). Similarly, weed biomass can be a predictor of seed production as larger weeds gain a competitive advantage (Schwartz et al. 2016). In spring barley systems, this

relationship has been quantified as an increase in seed rain from all weed species of 11.3 seeds m<sup>-2</sup> for every increase in total weed biomass of 1 g m<sup>-2</sup> (Pilipavičius 2013).

Most current weed management practices have managed the complexity of weed dispersal by focusing on herbicidal methods, which limit spread by killing the standing and emerging weed plants that directly reduce crop yields. In contrast, late season herbicide applications have shown promise for preventing the production and dispersal of new weed seeds across a variety of weed species and cropping systems (Bennett and Shaw 2000, Rodriguez and Jacobo 2013). Post-harvest paraquat applications have been found to control glyphosate resistant Palmer amaranth to levels that prevent the production of 1,200 seeds m<sup>-2</sup> in a winter wheat production situation (Crow et al. 2015). Across various rates and timings of late season glyphosate applications, seed production by spurred anoda (*Anoda cristata* (L.) Schlecht.), entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* (L.) Jacq. A. Gray), hemp sesbania, and Florida pusley (*Richardia scabra* L.) was reduced by 93% or more (Brewer and Oliver 2007). Late season glyphosate applications, however, have been shown to reduce weed seed shed at greater levels than reductions in weed emergence the following year, signaling that weed seeds shed before crop harvest emerge at higher rates than those shed later in the season (Clay and Griffin 2000). Additionally, post-harvest tillage may be nearly as effective as post-harvest glyphosate, as both methods have been shown to be equally effective in controlling various foxtail species, reducing seed production by 70% or more (Kegode et al. 2015). While herbicidal weed seed management shows promise in limiting seed dispersal, it can fail to be completely effective.

**Weed Seed Bank Emergence.** In order for weed seeds to affect crop yield, the weeds have to germinate, emerge, and grow into standing plants. Some estimates suggest that only about one tenth to one half of a soil seed bank will germinate in a given year (Ball and Miller 1989, Forcella et al. 1992). This germination rate can be extremely variable, with coefficients of variation typically exceeding 50% (Cardina and Sparrow 1996, Forcella et al. 1992, Wilson et al. 1985). While much of this variability can be attributed to difficulty in estimating the size of the soil seed bank, it is clear that many factors can prevent a seed from eventually maturing into a weed plant.

Finding any association between seed density and seedling density can be difficult, and effects of management practices, including species-specific effects, can be more consistent predictors of seedling density (Smith et al. 2009). In fact, one study found that fewer than 25% of species showed any correlation at all between seed bank size and seedling population, though this small percentage of species did often include the dominant grass weeds in their respective systems (Webster et al. 2003). Greenhouse experiments have had higher rates of success correlating seed bank density with seedling density, but, across methods, predictive power has been low and highly variable (Cardina and Sparrow 1996, Teasdale et al. 2004).

Weather could be the single most important factor in determining the rate of seed emergence. As soils warm, summer annual weed species begin to break seed dormancies. In a Minnesota study, emergence was found to be related parabolically to GDD in April; emergence rates were lower at extreme levels of April heat or cold. These parabolic emergence patterns were centered on different dates and temperatures for various species, because each weed species had different required timings and temperatures for emergence conditions (Forcella 1992).

Conditions at the soil surface can also be important for emergence rates. Soil structure can affect qualities like water holding capacity and infiltration rate. Because of water's importance in imbibition and the germination process, the availability of water in the soil can help or hinder the emergence process for various weed species (Corbin et al. 2010). Additionally, soil structure and texture can work together to bury seeds or move water in a way that washes seeds, especially small seeds, away (Benvenuti 2007). High residue systems, such as systems with cover crops, can smother seeds or create stale seedbed conditions that reduce soil seed bank populations by up to 80% in a single year, though residue biomass and soil surface cover are poorly correlated to seed bank size (Mirsky et al. 2010, Moonen and Bàrberi 2004). Soil can also act as a medium for organisms that may predate weed seeds. Microorganisms can lead to seed decay, and their populations can be influenced by soil management practices (Davis et al. 2006, Kremer 1993). Insects, too can predate weed seeds at levels up to 70% (Westerman et al. 2003, 2011).

Despite the many factors affecting emergence, weed seed communities often remain relatively stable from year to year. In a grain production situation, dominant weed species have been observed to stay the same across chemical, mechanical, and integrated weed management strategies, with only their relative abundance changing (Mayor and Dessaint 1998).

Understanding how and why the relative abundance changes can be difficult. Species dominant in the soil seed bank can represent greater than 90% of seeds in the seed bank, but relative abundance levels in emerged weed populations are rarely similar to that of the soil seed bank (Vasileiadis et al. 2007). In a study of corn-soybean-wheat rotations, organic and reduced input systems were dominated by common lambsquarters and common chickweed (*Stellaria media* (L.) Vill.), while no-till and conventional systems were dominated by summer annual grasses (Davis et al. 2005). Management practices like tillage and herbicide treatment can favor the emergence of certain weed species by burying small seeds or killing species with early emergence. Additionally, certain management practices may be more effective on larger populations of weeds (Buhler 1999). These factors together highlight the fact that weed communities, while often unpredictable, are partly a result of the agricultural systems they invade.

Finally, weed biology is undoubtedly connected to emergence rates and the makeup of weed communities. While seed traits are important for overcoming specific management, environmental, and abiotic filters, the species that dominate weed populations simply have a lot of seeds. The six most dominant species in Illinois corn and soybean fields all retained more seeds at harvest time each year than there were seeds already stored in the soil seed bank (Davis 2008). By generating more seed every year than is already available for next year, these dominant species leverage high fecundity to achieve growing populations. Geographical location, and therefore, endemic weed populations, has been found to be the single best predictor for relating seed bank density, emergence, and overall community composition (Schwartz et al. 2015).

**Managing Weed Seed Banks.** Many studies have investigated the links between specific management practices and weed populations, both in weed seeds and emerged weeds. In addition to the more focused studies above, these system-level observations can provide important insights in how current management practices can be supplemented or augmented by new technologies, such as HWSC. For growers trying to adopt multi-tactic approaches to weed management, it is important to understand the effects of current management tactics. Existing system level experiments typically focus either on crop rotation or tillage as the distinguishing factor between cropping systems. This distinction can be difficult to make, however, and many

management filters affecting weed seeds are linked between these two dimensions of cropping system.

Crop rotations can have direct effects on weed diversity and density, with long, polycultural rotations increasing weed diversity (Sosnoskie et al. 2006, 2009). Crop rotations have accounted for up to 75% of variation in soil seed banks (Buhler et al. 2001, Cardina et al. 2009). This variation has been attributed to the increased complexity associated with crop rotations; temporal diversity in crop rotations increases the number of environmental and management filters that weeds must overcome. Weed communities respond to this increase by adding community members with diverse adaptations that can continue to survive in the face of many challenges. Perennial rotation components, especially, lead to increased weed seed bank diversity, possibly by giving weed communities more time to respond to management and recruit new constituent species (Wortman et al. 2010).

In addition to the length of crop rotation, specific rotation crops can affect weed seed communities. While perennial rotation components increase emerged weed diversity, diversity is lost during the annual years of a crop rotation, causing some seed bank diversity to be masked by the presence of annual crops (Leon et al. 2015). Single crop years can have multi-year effects on weed populations, as well. Just one year of a specific crop in rotation can result in higher levels of weed species associated with that crop for three continuous years (Bohan et al. 2011). The starting crop can have long-lasting effects on a crop rotation such that a corn-soybean-alfalfa crop rotation starting in corn will have weed populations that look more like the weeds of a short, annual rotation than the same rotation starting in alfalfa (*Medicago sativa* L.) (Teasdale et al. 2004). Because of the potentially rotation-long effects of individual crop species, crop rotations could be designed to attenuate gains and losses in seed bank density (Bellinder et al. 2004). For instance, legumes, which were associated with small gains in weed seed bank density, could be planted after cereal rye (*Secale cereale* L.), which has been associated with larger gains in weed seed bank density.

Certain crops in a rotation are also associated with use of specific herbicides. While current herbicides do not act directly on seeds, the shift in weed populations can have important implications for the weed seed bank, especially when additions to the seed bank are targeted by the herbicide application as with post-harvest applications. Glyphosate resistant crops have been associated with seed banks with lower densities but higher rates of emergence; standard, post-

emergent glyphosate applications in a sugar beet (*Beta vulgaris* L.) rotation reduced total seed rain by over 60% but only reduced subsequent weed biomass, pooled across species, by 20% compared to management programs that relied on conventional, selective herbicides (Heard et al. 2003). Conversely, crops where pre-emergent herbicides are unavailable or typically not used faced increased seed bank populations (Dorado et al. 1999). Similarly, organic systems, where herbicides are not used in-crop, have higher seed bank densities, especially of summer annual broadleaves, lower seed bank diversities, and higher levels of single-weed-species dominance (Graziani et al. 2012). The presence or absence of herbicides in a cropping system can increase the effects of individual rotation crops on the weed seed bank.

Opposite crop rotation, tillage stands out as a critical cultural practice affecting weed seed banks. Tillage has been called out as the single greatest predictor of weed emergence in an eight year experiment considering many management practices, including crop nutrition, weed management, and cover crops (Moonen and Bàrberi 2004). Tillage can act directly on weed seeds by burying some at levels where they cannot emerge and bringing others to the surface to promote early germination in a stale seed bed approach. Changes in vertical distribution of seeds can be quite dramatic; 15 times as many seeds have been found in deep soil cores from a conventionally tilled field compared to a no-till field (Kelton et al. 2011). This burial can both decrease seed bank size by burying weed seeds too deep to persist or increase seed bank size by incorporating more seeds into the seed bank and allowing these seeds to be sheltered from environmental hazards such as insect predation (Ball 1992, Ghosheh and Al-Hajaj 2005). Because of this paradox, shallow tillage (tillage to a depth of 5 to 8 cm) or fall stubble tillage may be an effective middle ground and has been shown to be able to reduce seed bank density by half after five continuous years of use by maximizing the effects of a stale seedbed after harvest (Pekrun and Claupein 2006). Tillage timing can be a factor in addition to tillage depth. Spring tillage, for example has led to more C4-grasses and broadleaves that flower early, while fall tillage has favored C3-grasses and late-flowering broadleaves, as each timing interacts with the life cycle of each weed group (Smith 2006).

While heavy tillage can hinder weed seed emergence, the absence of tillage can promote weed seed losses. On average, 60% of weed seeds stay on the soil surface in no-till systems, and this sort of exposure to the elements can promote natural losses through insect predation and other mechanisms (Baraibar et al. 2009, Bàrberi and Lo Cascio 2001). No-till systems have been

shown to reduce weed seed banks from 41,000 to 8,000 seeds m<sup>-2</sup> over 6 years (Murphy et al. 2006). The effects of increased biodiversity of bacterial and insect predators and improved soil structure helped to explain this increase in weed seed losses.

Overall, links between tillage and weed seed banks are unpredictable. Closely related species can be affected differently by different levels of tillage, with junglerice (*Echinochloa colona* (L.) Link) emergence suppressed by conventional tillage and barnyardgrass emergence suppressed by no-tillage (Singh et al. 2015). While links between individual tillage practices have been difficult to predict, the presence of an effect can be quite strong. The multiple realities associated with tillage and seed bank populations have necessitated more understanding of their links with weed management, especially given their long-lasting impacts on a cropping system. A three-year persistence of the soil seed bank has been observed in sugar beet production, where three years of intense tillage have been needed before responses in weed populations were observed (Sester et al. 2006).

In a four year corn rotation, intense weed management for the first three years did not prevent yield loss in the fourth year, when weed management was halted, simply from pressure from emerging weeds whose seeds had persisted in the soil seed bank since the beginning of the rotation (Burnside et al. 1986). Even small-seeded species such as redroot pigweed, which are usually unable to survive in the soil seed bank for long periods of time, have had meaningful, yield-damaging weed populations come up from the soil seed bank after a loss of 99% of seed bank populations (Schweizer and Zimdahl 1984). This lag time between management action and change in weed communities has created problems in predicting the effects of management practices, highlighting the importance of developing HWSC tools that complement existing cropping systems.

**Methods for Harvest Weed Seed Destruction.** Harvest weed seed controls are a new frontier in mechanical weed management that can be effective as part of a multi-tactic approach to weed management (Walsh and Powles 2014a). In light of the herbicide resistance epidemic, herbicidal weed management must be complemented by cultural approaches in order to continue to be effective (Bonny 2016, Owen 2011). Current cultural weed controls focus on managing weed emergence rate. HWSC is novel because it directly targets weed seeds before they enter the seed bank, limiting increases in seed bank density (Davis 2006). By combining weed management

with routine harvest practices, growers could potentially destroy or capture weed seeds that would have previously been spread through the harvester and broadcast for the following growing season.

HWSC can be achieved through a variety of techniques. Collection of chaff with chaff carts, direct baling of crop residue, windrow burning or rotting of crop residue, and cage mill processing have all been used to destroy field residue containing weed seeds (Walsh et al. 2013). Chaff carts simply collect all of the fine, chaff portion of crop residue and weed seeds therein and remove them from the field. Additionally, commercial growers have begun to use a chaff deck, which deposits fine field residues in the tire tracks of a controlled-traffic farming system, leaving agriculture equipment to repeatedly run over germinating weeds. Some seeds are coarse enough to be included in the straw portion of crop residue, resulting in, for example, 26% of wild oat seed being returned to the field in a spring wheat harvest using chaff carts (Shirtliffe and Entz 2005). By only removing the chaff portion of crop residue, these systems rely on the ability of the harvester to accurately separate weed seeds out of straw, stover, and other heavy residues. In contrast, bale direct systems collect all of a crop's field residue in a bale before removing it from the field. These systems present an opportunity for additional grower revenue as residues are contained within a salable form for end uses such as livestock bedding or cellulosic biofuel production (Walsh et al. 2013).

Windrow burning and rotting involves the placement of field residues in a narrow windrow. In the case of burning, the residue is set aflame, which generates enough heat to exceed the 400 to 500°C temperatures required to kill most weed seeds in 10 seconds but affects only about 10% of land area on the field (Walsh and Newman 2007). In the field, this technique has been found to reduce Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot) emergence to levels just 1% of that species' seed production (Lyon et al. 2016). In fact, many weed species have been found to lose viability at much lower temperatures, especially if exposed to longer durations of heat. Half of large crabgrass (*Digitaria sanguinalis* (L.) Scop.) seeds lost viability if exposed to about 103°C temperatures for 5 seconds, while that temperature was reduced to 83°C if time is increased to 20 seconds in one thermal death study (Hoyle and McElroy 2012).

This relationship between temperature and time can allow for the death of weed seeds at even lower temperatures. A study of six different weed species determined that 100% of seeds

lost viability if exposed to 60°C for 3 or fewer hours (Dahlquist et al. 2007). These temperatures are easily attainable in compost piles, which are similar in nature to windrows that have been left to rot without burning, though spatial heterogeneity within a pile can cause nearly one quarter of the volume of commercial compost piles, especially where edges are cooler, to fail to reach thresholds for sanitation (Isobaev et al. 2014). While more research is needed to understand how effective thermal processes are at killing weed seeds at field levels, windrow burning or rotting present opportunities for growers to experiment with HWSC without high levels of economic capital, since only slight modification of existing equipment is required to create windrows.

Cage mill processing uses a machine towed behind the combine known as the Harrington Seed Destructor (HSD) to grind chaff via rotating cages that repeatedly impact chaff at high speeds, destroying more than 95% of weed seeds by pulverizing them (Walsh et al. 2012). Because the HSD does not remove or chemically alter crop residue, it does not alter the nutrient value of a field. Because of this reason and its ease of use, the HSD can actually be profitable, despite its cost of AU\$240,000, especially to crop farmers with high levels of herbicide resistance and over 3,000 ha of high-yielding land (Jacobs and Kingwell 2016). Further refinements of HSD technology will continue to improve prospects for farm-scale implementation. The Integrated HSD, which adds a cage mill directly to the combine, will lower cost, increase ease-of-use, and provide broader access to HWSC tools (deBruin Engineering 2016).

The wide array of emerging HWSC technologies provides many challenges for grower adoption. While each technology on its own should be effective at destroying seeds, the complexity involved in predicting weed populations creates demand for additional research. HWSC requires >80% of weed seeds to be destroyed in order to see lasting effects on weed populations (Tidemann et al. 2016). Ensuring that this proportion of seed is retained on the plant at harvest time and is able to be destroyed by HWSC requires more understanding. Weed seeds dispersed before crop harvest, or through other means such as wind or by animals, will not be subjected to HWSC (Goplen et al. 2016). Furthermore, HWSC has potential to place directional selection pressures on weed populations, effectively creating HWSC resistant weeds through early seed shattering, as has been observed with closely related traits such as flowering date (Ashworth et al. 2016). This potential highlights the continued need for integrated weed management and the development of HWSC within the context of a greater cropping system.

Other limitations exist in understanding how HWSC will affect individual farm operations, as well as whole landscapes. As a single management practice, HWSC has been effective but at lower and more variable levels of weed management than effective herbicide programs featuring multiple sites of action (Norsworthy et al. 2016). New educational tools will need to be developed in order to convince growers of HWSC's benefit to a level where they are comfortable spending money on the new equipment or time modifying equipment as necessary for HWSC techniques. Across landscapes, HWSC techniques such as windrow burning and the Harrington Seed Destructor will have aesthetic costs, for example, as the former creates lots of smoke and the latter could potentially create lots of dust during use. Additionally, many of the techniques could have implications for nutrient management, as crop residues are removed or modified. Additional research is required to quantify the cost and identify management strategies for these challenges.

HWSC techniques have the potential to be valuable additions to growers' weed management regimens. As herbicide resistance necessitates greater use of integrated and multi-tactic weed management strategies, researchers are looking for new alternatives in weed management. Targeting weed seeds represents an important shift in weed management. Many existing strategies are being employed to control weed emergence from the soil seed bank, but these strategies have complex relationships with weed populations that can be unpredictable. For these reasons, management techniques that focus on limiting additions to the soil seed bank are new and could be potentially valuable. HWSC could be an important complement to growers' existing weed management strategies

## **Seed Shattering Timing of Six Common Weed Species in Soybean**

Seed shattering is an important biological trait that governs seed dispersal. The coincidental maturity of many annual weed species with the agronomic crops which they infest can mean that harvesting operations play an important role in dispersal. Field experiments to observe seed shattering timing in six key weed species were established in Blacksburg, VA in 2016. Twenty-four individuals each of redroot pigweed, common ragweed, common lambsquarters, common cocklebur, large crabgrass, and giant foxtail, were identified in a soybean field. Plastic trays lined with landscape fabric were secured to cover the ground at the base of each plant, and the contents of the trays were collected each week from the first sign of seed shattering to three weeks after an optimal crop harvest date, simulating a harvest delay. The seeds that had shattered into the trays were then quantified. All species began shattering between three and six weeks before the crop harvest date, with redroot pigweed and large crabgrass starting six weeks and common ragweed, common lambsquarters, and common cocklebur beginning three weeks before the harvest date. All broadleaf species had seed shattering rates accelerate through the season, while giant foxtail shattering rates increased steadily and large crabgrass shattering rates declined. These results indicate that broadleaf weed species may retain their seeds longer into the growing season, making them more likely targets for weed management, such as harvest weed seed controls, that relies on late-season seed retention.

Annual weeds rely on seeds as propagules to spread across space and time (Lockwood et al. 2005). In general, the magnitudes at which weed seeds enter and emerge from the soil seed bank determine the level of weed infestation (Davis 2006, Forcella 1992). The timing of seed bank additions and emergence can also affect efficacy of weed management practices like tillage (Grundy and Bond 1998, Smith 2006). Additionally, seed traits can determine which species' seeds persist in the soil seed bank, unaffected by management filters, and which seeds capitulate to agricultural selection (Booth and Swanton 2002, Long et al. 2014). By understanding and targeting weed seed banks, growers can exploit a largely unused tactic for weed management that affects both weed density and species composition (Buhler et al. 1997).

Seed shattering, the dispersal process by which seeds leave the plant and enter the soil seed bank, often coincides with crop maturity, with harvesters being a known mechanism for weed seed dispersal (Ballare et al. 1987, Blanco-Moreno et al. 2004, McCanny and Cavers 1988). Many weed species retain more seeds at crop harvest than are contained within the soil seed bank, highlighting aggressive species' dependence on the harvester for dispersal (Davis 2008). Harvesters have been found to move weed seeds up to 145 m past the edge of a weed patch, stretching weeds' spatial pattern in the direction the harvester traveled (Shirtliffe and Entz 2005, Wiles and Schweizer 2002). These stretched areas of high seed density can suffer from yield reductions of more than one third compared to areas at the edge of the harvester's spread swath (Maxwell and Ghersa 1992). For weed seeds to be dispersed by the harvester, the weed plant must retain seeds at the time of crop harvest. Therefore, the timing of seed shattering greatly affects how annual weeds move across the agricultural landscape.

Seed shattering timing varies widely across species. Palmer amaranth and tall waterhemp have exhibited >90% seed retention at soybean harvest (Green et al. 2016, Schwartz et al. 2016). Additionally, feral rye and wild radish have exhibited >90%, rigid ryegrass has exhibited >80%, and jointed goatgrass and downy brome have exhibited  $\geq 70\%$  seed retention at wheat harvest (Blanco-Moreno et al. 2004, Soni and Gaines 2016, Walsh and Powles 2014b). Additionally, barnyardgrass has been observed retaining only 43% of seeds at soybean harvest (Green et al. 2016).

Other factors affect temporal patterns in weed seed shattering. Some species, such as wild oat, lose about half of their seeds in the first four weeks after maturity, while species like rigid ryegrass continue to retain most of their seeds through this extended period (Walsh and Powles

2014b). Intraspecific genetic variation could explain some of these differing patterns, with studies of wild oat observing seed retention levels ranging from 20 to 84% (Shirtliffe et al. 2000, Walsh and Powles 2014b). Similarly, studies of bromegrass observed seed retention ranging from 40 to 77% (Balsari et al. 1994, Walsh and Powles 2014b). Environmental factors, such as temperature and other weather factors, multi-species interactions, and individual plant biomass could explain some of weeds' complex seed dispersal patterns, as well (Bennett and Shaw 2000, Forcella et al. 1996, Kadzys et al. 2008, Pilipavičius 2013, Schwartz et al. 2016).

Emerging harvest weed seed control techniques rely on high weed seed retention at harvest for maximum efficacy (Walsh et al. 2013). In other words, weed seeds that shatter before crop harvest do not pass through the harvester and therefore evade harvest weed seed controls. Additionally, dispersal mechanisms, such as dispersal by wind or animals, may preclude harvest weed seed controls from controlling certain weed species. As growers seek to manage herbicide resistance with diversified and integrated weed management approaches, harvest weed seed controls represent a valuable tool for mechanical weed management (Moss 2010). Understanding how various aspects of weed biology and seed dispersal interact with new agricultural selection pressures can increase the successful adoption of harvest weed seed controls and help identify how weed biology may shift over time to survive the new management practice (Ashworth et al. 2016).

Harvest weed seed controls were originally developed by Australian wheat growers to control herbicide resistant ryegrass and are currently under evaluation for use in wheat and soybean cropping systems in the Mid-Atlantic United States. Harvest weed seed controls' efficacy in Mid-Atlantic cropping systems depends on specific information about seed shattering timing of the weed species that infest the region. Of special concern are species that escape current weed management techniques, such as herbicide resistant weeds, as well as species with high fecundity. This experiment aims to quantify seed shattering from six important weed species in Virginia soybean production, including common lambsquarters, redroot pigweed, common ragweed (*Ambrosia artemisiifolia* L.), common cocklebur (*Xanthium strumarium* L.), giant foxtail (*Setaria faberi* Herrm.), and large crabgrass. Identification of the timing and magnitude of these species' annual additions to the soil seed bank can improve understanding of how their biology may make them susceptible to harvest weed seed controls.

## Materials and Methods

Field experiments to determine temporal patterns in weed seed shattering were initiated at Kentland Farm in Blacksburg, VA on May 10, 2016. Soybeans were planted in 76 cm rows at 296,520 seeds ha<sup>-1</sup> in a conventionally-tilled system that was managed according to agronomic practices standard for the area, as recommended by Virginia Cooperative Extension (Holshouser 2014). Twenty-four individuals from each of six key weed species, including redroot pigweed, common lambsquarters, common cocklebur, common ragweed, large crabgrass, and giant foxtail, were identified or transplanted in the field's interrows throughout the growing season. Transplanted weeds were selected such that their maturity and size aligned as if they had emerged with the soybean crop. Each individual plant was a single replication, for a total of 24 replications per weed species, arranged in quadrats with four weeds from the same species, for ease of data collection. Other weeds in the field were controlled by hand weeding or directed herbicide application.

Corrugated plastic, 40 cm by 51 cm trays with drainage holes were lined with landscape fabric, which was secured with adhesive. Four trays were secured to the ground such that they completely surrounded the base of each plant. Trays covered existing soybeans, which were bent to the ground. Tray placement, and therefore soybean destruction, occurred as late as possible in the growing season before weed seed shattering had begun to preserve competition between weed species and soybean to the greatest extent possible. Plants were trained, as necessary, using wire to confine their footprint within the area of the trays. Additionally, some plants were tied to fiberglass stakes to keep them upright after lodging.

After seed shattering had begun, seeds were collected from the trays of an individual weed plant using a handheld vacuum. Seed collection continued weekly until three weeks after the earliest possible (optimal) harvest date, when soybeans had dried down to approximately 15% moisture by October 20, 2016, with weekly collections ending November 9, 2016. Weekly seed collections were cleaned of excess debris by sieving, and clean samples were then weighed. After the last weekly collection, whole plants were collected from the field, and seeds were threshed from these plants in order to obtain a sample of the seeds ultimately retained. Three 100-seed samples were counted and weighed from each week of each species' seed collections, as well as the final seed retention samples, in order to determine a seed count for each collection.

Weekly seed shattering data were analyzed using JMP Pro 13 (SAS Institute, Cary, NC). A generalized linear model with Poisson distribution and log link were used to find overall trends in seed shattering phenology. This model fit an equation in the form:

$$Y=e^{mx+b} [1]$$

where Y is the number of seed shattered by a single plant in only the previous week, and x is the number of weeks between soybean planting and sample collection. When transformed with the log link equation from the generalized linear model, Equation 1 describes a linear equation, where m is the slope of the line and b is the y-intercept of the line.

### Results and Discussion

Seed shattering rates increased throughout the growing season for all weed species in this study except for large crabgrass, which had decreasing seed shattering rates throughout the season. In general, seed shattering rates grew to larger amounts for broadleaf weed species than for grass species. These results suggest that none of the weed species in the study shatter seeds at even rates across the growing season and that broadleaf weed species are more likely to retain seeds late into the fall.

Redroot pigweed began shattering seeds six weeks before the optimal crop harvest date. Of the total seeds shattered by redroot pigweed during the extended growing season in this experiment, 48.2% were shattered before the crop harvest date, while 51.8% of seeds were shattered during the simulated three-week harvest delay (Figure 1). These findings mirror previous research finding that redroot pigweed seed shattering accelerated through the season and that closely related Palmer amaranth retained most of its seeds through the end of the growing season (Forcella et al. 1996, Schwartz et al. 2016). Over five times as many seeds were retained on the plants harvested at the end of the experiment than were captured during weekly seed collections. This highlights redroot pigweed's extremely high fecundity and indicates that, even with a delayed harvest, many of this species' seeds could be controlled by effective HWSC.

Common ragweed began shattering three weeks before crop harvest, and, of the seed shattered during the extended growing season, it shattered 33.7% of seeds before and 66.3% after the harvest delay, respectively (Figure 2). Similar research on giant ragweed (*Ambrosia trifida* L.) also found that well over 60% of seeds would have been retained for a timely harvest (Goplen et al. 2016). Seeds retained on the plant after the simulated harvest delay totaled 3.8

times as many seeds as were captured during weekly seed collections, evidence of HWSC's potential value, even for this relatively large-seeded species.

Common lambsquarters also began shattering three weeks before crop harvest, shattering 9.5% of shattered seeds during the growing season and 90.5% of shattered seeds during the harvest delay (Figure 3). A previous study of common lambsquarters in a corn crop found over 50% of seed shattering occurred before a timely harvest (Forcella et al. 1996). Common lambsquarters plants harvested at season's end retained 1.6 times as many seeds as had been previously captured. Common cocklebur, the final broadleaf species in this study, began shattering three weeks before the optimal harvest date, and, of seed shattered during the extended growing season, it shattered 23.5% of its seed before and 76.5% of its seed after the harvest date (Figure 4). Undispersed seed harvested with the whole plant totaled 1.1 times as many seeds as were shattered during the growing season and harvest delay. Though there were comparatively fewer seeds retained through the harvest delay than other broadleaf species, effective HWSC of common cocklebur could halve soil seed bank additions.

Grass weeds in this study did not shatter as many seeds late in the season. While giant foxtail did increase seed shattering rates throughout the season, 67.7% of seed shattering occurred in the five weeks prior to harvest and 32.3% during the simulated harvest delay (Figure 5), a result consistent with previous research indicating green foxtail shattered around 60% of its seed by corn harvest time (Forcella et al. 1996). Giant foxtail plants retained approximately equal amounts of seed compared to the shattered seed captured in this experiment. Large crabgrass, the only species with a negative rate of seed shattering change, began shattering six weeks before the ideal crop harvest, shattering 77.2% of shattered seed before this date and 22.8% after (Figure 6). Season end seed retention represented only 60% of the seed shattered through the growing season and harvest delay.

Despite highly significant relationships between seed shattering date and number of seed shattered, as well as coincidental maturity between broadleaf weed species and soybeans, the fitted model for each species failed to explain much of the variability in seed shattering found in this study. A lack of independence in the seed shattering response (i.e. when a seed is shattered in one week, it cannot be shattered in the next week) can contribute to this increased variability, but high fecundity in each of the studied species limits this concern. High variability in weekly shattering between individuals is likely to constrain the ability to predict weed seed shattering.

Overall, the great deal of variation in seed shattering phenology between individuals within a weed population makes practical interpretation of seed shattering difficult.

However, these results highlight the importance of a timely harvest for the success of harvest weed seed control techniques, especially for the broadleaf species evaluated. Because broadleaf species especially tend to retain seeds late into the season but begin shattering seeds soon after crop maturity, these species hold promise for harvest weed seed control than grass species that tend to shatter early. Grasses' low growth habit and ability to grow in dense mats may have precluded their need for late-season seed retention and ultimately dispersal by crop harvesters. For all species in this experiment, season end seed retention levels indicate that effective HWSC could prevent thousands of seeds from entering the soil seed bank from each individual parent plant (Table 1).

The sampling method used in this study creates difficulty for understanding how weekly seed shattering rates relate to total seed production in each species, because some species' seeds could have moved past the boundaries of the collection trays by blowing in the wind or moving with animals. However, broadleaf weed species that retain a greater portion of seeds late into the growing season still present a unique opportunity for introducing HWSC at some level, even if other weed management will be needed to target seeds that enter the soil seed bank before crop harvest. Additionally, more research is needed to quantify the number of seeds that shattered but evaded this experiment's apparatus in order to better understand total seed production levels.

Future research to better understand this variability could improve the predictive power of weed seed shattering models. Genetic and epigenetic factors that regulate seed shattering could help explain some temporal variation in shattering rates (Dong and Wang 2015). Future studies may draw upon more weed populations or climatic regions that better integrate these genetic concerns. Implementation of a sampling strategy that collects more of the total seed shattered by each plant could limit variation caused by seeds eluding the experimental apparatus; this sampling strategy could increase the total area at the base of each plant covered by plastic trays, or it could mirror the apparatus used by Goplen et al. (2016). Additional sources of variation may have been caused by the interaction between crop and weed. In this experiment, much of the soybean crop had been destroyed by vertebrate grazing. This important source of influence on weed biology can be more completely accounted for in future studies.

This research represents an important study of weed biology with direct implications for emerging mechanical controls of weed seed dispersal. Seeds shattered before crop harvest will elude harvest weed seed controls (Walsh et al. 2013). Commercially successful implementation of harvest weed seed controls depends on understanding of weed seed shattering timing. While much work must be done to understand this phenology, this research suggests that broadleaf weed species typically retain a majority of their seeds well into the late portions of the growing season, and all of the studied species retained thousands of seeds per individual through a harvest delay.

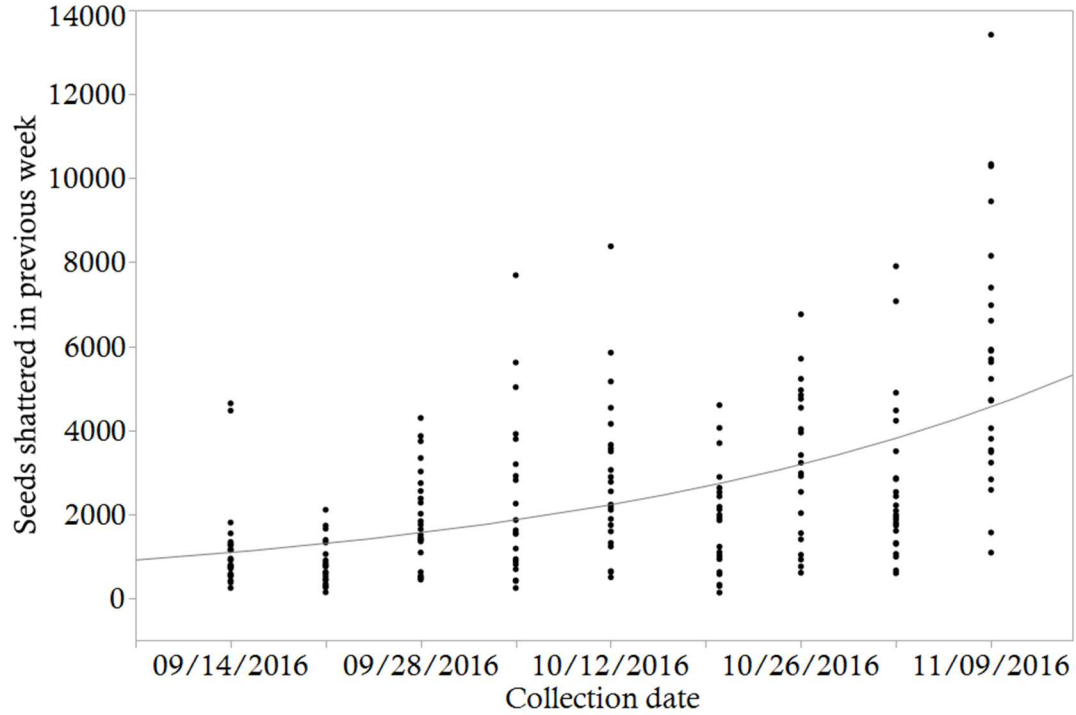


Figure 1. Counts of redroot pigweed seed shattering for all 24 individuals in 2016 in Blacksburg, VA. Soybeans were ready to harvest on October 20, 2016. The regression line is described by the equation  $Y=e^{0.180x+3.750}$ , where Y is the number of seed shattered in the previous week and x is the number of weeks since soybean planting. Each point represents number of seed shattered only in the previous week by a single plant.

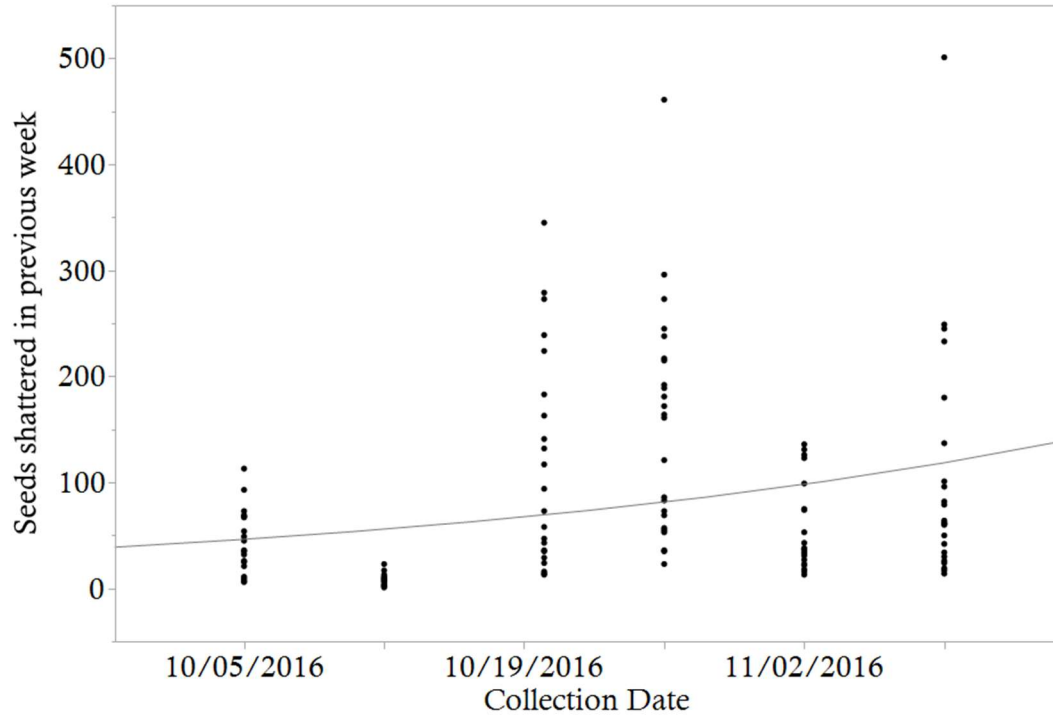


Figure 2. Counts of common ragweed seed shattering for all 24 individuals in 2016 in Blacksburg, VA. Soybeans were ready to harvest on October 20, 2016. The regression line is described by the equation  $Y=e^{0.182x+0.032}$ , where Y is the number of seed shattered in the previous week and x is the number of weeks since soybean planting. Each point represents number of seed shattered only in the previous week by a single plant.

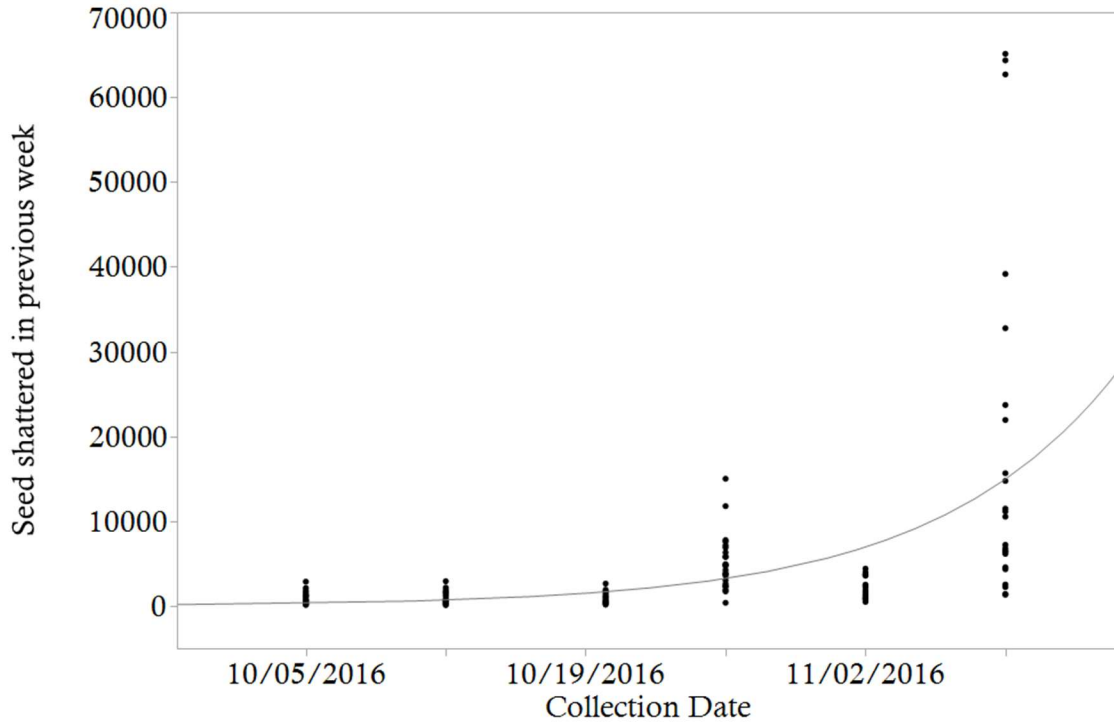


Figure 3. Counts of common lambsquarters seed shattering for all 24 individuals in 2016 in Blacksburg, VA. Soybeans were ready to harvest on October 20, 2016. The regression line is described by the equation  $Y = e^{0.758x - 10.093}$ , where Y is the number of seed shattered in the previous week and x is the number of weeks since soybean planting. Each point represents number of seed shattered only in the previous week by a single plant.

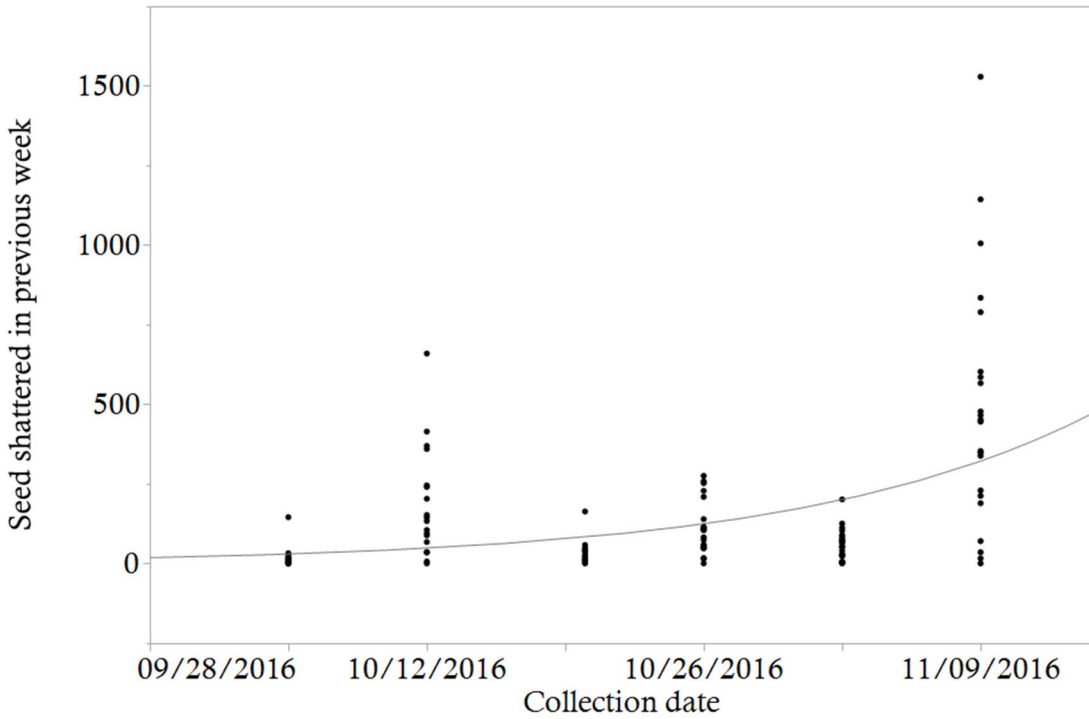


Figure 4. Counts of common cocklebur seed shattering for all 24 individuals in 2016 in Blacksburg, VA. Soybeans were ready to harvest on October 20, 2016. The regression line is described by the equation  $Y = e^{0.472x - 6.490}$ , where Y is the number of seed shattered in the previous week and x is the number of weeks since soybean planting. Each point represents number of seed shattered only in the previous week by a single plant.

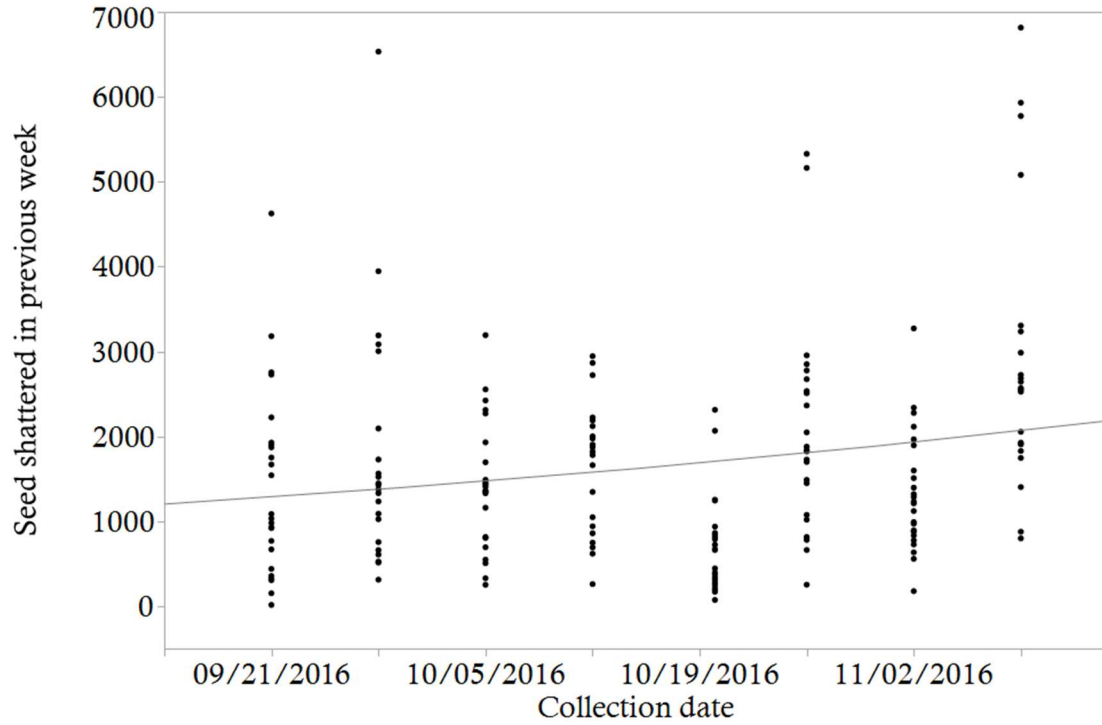


Figure 5. Counts of giant foxtail seed shattering for all 24 individuals in 2016 in Blacksburg, VA. Soybeans were ready to harvest on October 20, 2016. The regression line is described by the equation  $Y=e^{0.070x+5.829}$ , where Y is the number of seed shattered in the previous week and x is the number of weeks since soybean planting. Each point represents number of seed shattered only in the previous week by a single plant.

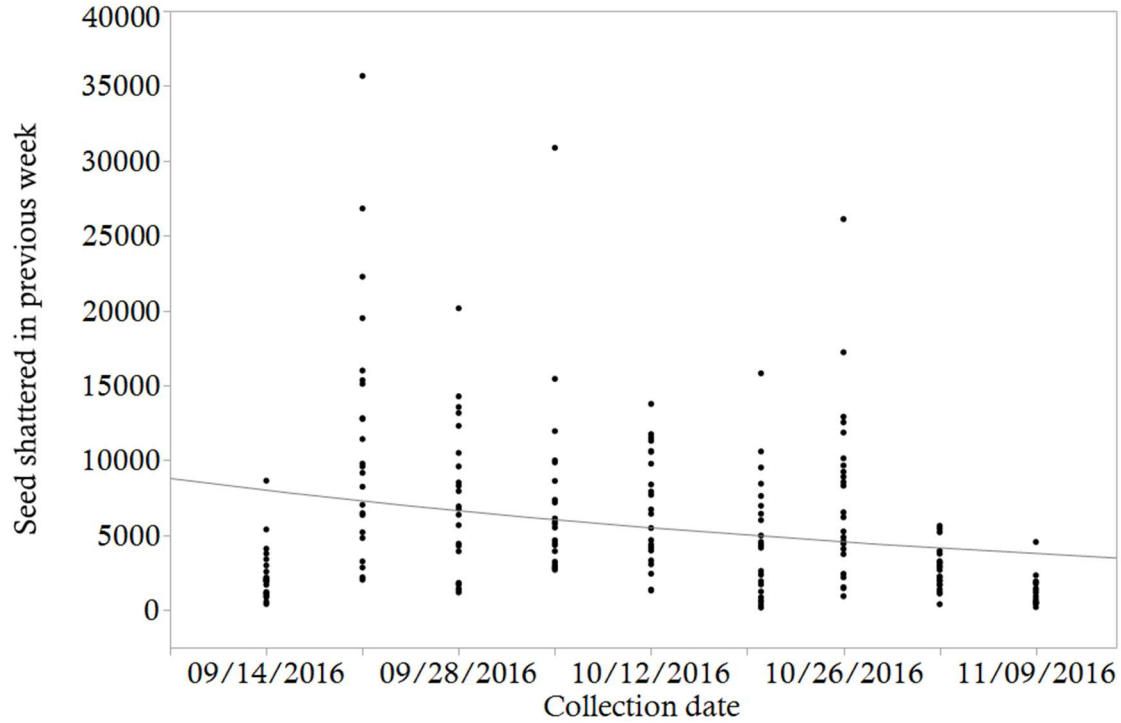


Figure 6. Counts of large crabgrass seed shattering for all 24 individuals in 2016 in Blacksburg, VA. Soybeans were ready to harvest on October 20, 2016. The regression line is described by the equation  $Y=e^{10.686-0.094x}$ , where Y is the number of seed shattered in the previous week and x is the number of weeks since soybean planting. Each point represents number of seed shattered only in the previous week by a single plant.

Table 1. Total seed captured and portions shattered before harvest, during a simulated harvest delay, and at retained at the end of the experiment from various weed species in Blacksburg, VA in 2016. All values include a standard error.

Weed Species	Total seed captured per plant	% Seed shattered before crop harvest	% Seed shattered during harvest delay	% Retained on plant at end of experiment
Redroot Pigweed	149,427 ± 27,267	7.2% ± 1.1	7.7% ± 0.9	85.1% ± 17.5
Common Ragweed	2,204 ± 382	7.2% ± 1.2	14.1% ± 2.4	78.7% ± 15.3
Common Lambsquarters	62,091 ± 11,332	4.3% ± 0.7	40.6% ± 8.1	55.2% ± 12.0
Common Cocklebur	1,325 ± 155	14.4% ± 3.5	48.2% ± 8.2	38.9% ± 5.5
Giant Foxtail	26,334 ± 2,124	26.3% ± 3.6	24.0% ± 2.8	49.8% ± 5.2
Large Crabgrass	84,721 ± 11,637	46.3% ± 6.9	13.7% ± 1.9	40.0% ± 7.7

## **Harvest Weed Seed Control for Italian Ryegrass (*Lolium perenne* ssp. *multiflorum*) in a Wheat-Soybean Rotation**

Herbicide resistant Italian ryegrass represents a major threat to winter wheat production, and new harvest weed seed control techniques are being developed for use in an integrated weed management approach. This study aims to evaluate two HWSC techniques, residue removal and windrow burning, and compare them to grower-standard weed management systems, both with and without tillage. Residue removal eliminates field residues and the weed seeds contained therein simply by taking them off the field, while windrow burning eliminates field residues through incineration. Field experiments were initiated in Lunenburg County, VA in 2015, with HWSC treatments occurring at the first wheat harvest in July 2016, as well as at the following soybean harvest. Throughout the growing season, Italian ryegrass stand counts were taken, and measurements of Italian ryegrass biomass and seed retention were taken at harvest time along with wheat yield. Residue removal and windrow burning performed equally as well as the grower-standard and tillage treatments at reducing Italian ryegrass biomass and harvest-time seed retention after one growing season. For all treatments except tillage, Italian ryegrass population density decreased and wheat yield increased in the second growing season; results for tillage treatments did not change year-to-year. These results fail to support the idea that HWSC techniques control Italian ryegrass any better than grower-standard weed management practices, but they indicate that tillage may not be a useful addition to an integrated weed management program for Italian ryegrass control. Future research must confirm the applicability of HWSC to winter wheat production systems in the Mid-Atlantic United States by integrating best practices for HWSC, including timely crop harvest.

Continued reliance on chemical weed management has proliferated the loss of effective herbicide resources through the process of repeated selection for herbicide resistant weeds (Green 2007). In response to the failure of some herbicides, growers have been, in some cases, forced to increase management intensity, such as through the abandonment of conservation tillage (Beckie 2011, Price et al. 2011). Increasingly rigorous weed management stands in contrast with the nonselective herbicides paired with herbicide resistant crops that saved United States growers an estimated \$1.2 billion in labor costs in 2005 (Gianessi 2005). As the era of simplified weed management comes to a close, growers demand weed management practices that continue to preserve environmental sustainability and farm profitability (Duke 2015).

Growers, wary of the complications associated with increasing herbicide use, have begun to adopt integrated weed management approaches that comprise several control techniques to address multiple management concerns (Kumar et al. 2013). While no single solution exists to meet all of growers' diverse needs across many cropping systems, integrated weed management approaches unite cultural, mechanical, and chemical weed management to preclude the over-use of individual management practices. Sustainable cropping systems need this type of management flexibility to maintain weed management efficacy (Norsworthy et al. 2012).

Harvest weed seed controls represent an emerging set of weed management practices that fit into a broader, integrated approach to weed management. HWSC involves any number of techniques that directly target undispersed weed seeds and prevent them from entering the soil seed bank, including by crushing, burning, or removing field residues that contain mature weed plants and the seeds therein (Walsh et al. 2013). By implementing HWSC at the same time as routine harvest operations, growers can incorporate mechanical weed management into existing agronomic practices (Walsh et al. 2012, Walsh and Newman 2007). Additionally, targeting weeds between maturity and seed dispersal constitutes a novel selection pressure, enhancing the selection diversity of an integrated weed management program (Davis 2006).

HWSC primarily controls weeds through seed bank depletion. By processing field residues such that they no longer contain viable weed seeds, HWSC limits the viability of weed seeds spread through field residue. Weed populations are determined by the product of seed bank density and the emergence rate of weeds from that seed bank (Forcella 1992). Seed banks do not persist if they are not replenished, so HWSC can reduce seed bank density by limiting seed bank additions. HWSC only targets seeds that pass through the crop harvester, as these are the only

seeds subject to field residue treatment. Seeds dispersed by other mechanisms, namely early seed shattering, can replenish the soil seed bank (Goplen et al. 2016). HWSC efficacy relies on weeds that retain seed well after crop maturity.

Australian wheat growers originally developed and have, to date, shown the most enthusiasm for HWSC, in large part to combat herbicide resistant ryegrass species such as rigid ryegrass (Walsh and Powles 2014a). One HWSC method from Australia involves crushing chaff and other fine residues through a specialized cage mill known as the Harrington Seed Destructor (HSD). The HSD is able to destroy over 95% of weed seeds without requiring the grower to make another pass over the field after harvest (Walsh et al. 2012). Despite its current high cost, the HSD can be profitable for growers with large amounts of planted land and high levels of herbicide resistance when amortized over several consecutive growing seasons, and the machine's cost continues to drop (Jacobs and Kingwell 2016).

Other HWSC methods rely on different principles and usually require additional trips across the field. Narrow windrow burning and chaff carts have been popular options for HWSC (Walsh et al. 2013). The former involves putting all field residues into a windrow which is subsequently burned, while the latter involves collection of fine field residues in a chaff cart that is then dumped off-field or on the field in piles to be burned (Walsh and Newman 2007). Across these many HWSC techniques, >80% of weed seeds must be destroyed to affect lasting change on weed populations (Tidemann et al. 2016). Field results have been promising, if subject to natural variability, showing HWSC's ability to destroy economically important levels of weed seed across multiple cropping systems, weed species, and HWSC techniques, including Palmer amaranth in soybeans (Norsworthy et al. 2016), and rigid ryegrass in winter wheat (Walsh et al. 2017), among others (Lyon et al. 2016, Shirtliffe and Entz 2005).

Because of its adaptability to diverse cropping systems, researchers seek to develop HWSC tools for cropping systems in the Mid-Atlantic United States. Growers initially developed HWSC to control a ryegrass species in Australian wheat production. Therefore, HWSC holds promise for controlling herbicide resistant Italian ryegrass in winter wheat production in Virginia, which covered nearly 71,000 ha in 2016 (USDA-NASS 2017). Falling commodity prices and proliferating multiple herbicide resistance has created difficulty for growers looking to economically control Italian ryegrass in wheat. Increasingly, growers have stopped implementing double-crop wheat and soybean rotations in favor of full-season soybeans because of the

enhanced profitability and reduced logistical challenges. This research aims to restore Italian ryegrass control efficacy in these double-crop systems by developing the HWSC techniques of windrow burning and field residue removal for Mid-Atlantic farms and comparing them to a standard no-till weed management program as well as a weed management program using tillage.

### **Materials and Methods**

A field experiment to evaluate the efficacy of Italian ryegrass control with HWSC and compare to conventional techniques was established in Lunenburg County, VA (36.831640°N, 78.144012°W) in November 2015 and maintained through 2017. The experiment was repeated over two growing seasons to establish baseline weed pressure in the first year and evaluate weed control in the second year, after treatments were applied at the first season's harvest. Five experimental replications were used, and plots were 7.5 m by 15 m. Plots were arranged within a larger, factorial experiment that included additional weed species of interest and crop rotations. For the Italian ryegrass control experiment, winter wheat was grown in a double crop system with soybean. Weed management treatments included a grower-standard weed management program alone and in combination with tillage, residue removal, or windrow burning. These factors are described in greater detail below.

Winter wheat was planted after soybean harvest, on December 18, 2015 and December 20, 2016. The winter wheat cultivar was SS 5205 in 2015-16 and SS 8340 in 2016-17 (Southern States Cooperative, Richmond, VA). Immediately following wheat planting in the first year only, an artificial weed population was established by spreading Italian ryegrass seed (Variety "Fria," Southern States Cooperative, Richmond, VA) at a rate of 22.5 kg ha<sup>-1</sup>. Wheat was planted at 135 kg ha<sup>-1</sup> with a drill on 20 cm row spacing. Fertilizer was applied with a broadcast spreader at rates of 22 kg ha<sup>-1</sup> N and 56 kg ha<sup>-1</sup> each P and K at planting each growing season, followed by an additional 56 kg ha<sup>-1</sup> N in February. An herbicide application containing 0.015 kg ha<sup>-1</sup> thifensulfuron-methyl (Harmony SG, DuPont Crop Protection, Wilmington, DE), 0.015 kg ha<sup>-1</sup> mesosulfuron-methyl (Osprey, Bayer CropScience, Research Triangle Park, NC), 3.3 kg ha<sup>-1</sup> ammonium sulfate, and 0.25% v v<sup>-1</sup> nonionic surfactant (Sun Wet, Brewer International, Vero Beach, FL) was made in February of each year.

Double crop soybeans were planted after wheat harvest on July 14, 2016. Soybean cultivar P46T21R (DuPont Pioneer, Johnston, IA) was planted at 444,600 seeds ha<sup>-1</sup> with a drill on 35 cm row spacing. Fertilizer was applied with a broadcast spreader at rates of 56 kg ha<sup>-1</sup> each P and K at planting. An herbicide application containing 0.7 kg ha<sup>-1</sup> paraquat (Gramoxone SL 2.0, Syngenta Crop Protection, Greensboro, NC), 0.09 kg ha<sup>-1</sup> flumioxazin (Valor SX, Valent, Walnut Creek, CA), and 1% v v<sup>-1</sup> crop oil concentrate (Crop Oil Concentrate 83-17, Southern States Cooperative, Richmond, VA) was made at planting. Another herbicide application containing 1.1 kg ha<sup>-1</sup> glyphosate, 0.28 kg ha<sup>-1</sup> fomesafen (Flexstar GT 3.5, Syngenta Crop Protection, Greensboro, NC), and 0.25% v v<sup>-1</sup> nonionic surfactant (Sun Wet, Brewer International, Vero Beach, FL) was made in July when target weeds were 15 to 25 cm tall.

Plots were harvested with a Gleaner K2 combine (AGCO Corporation, Duluth, GA) with a modified 2.4 m small grain header or a Wintersteiger Classic combine (Wintersteiger AG, Ried im Innkreis, Austria) with a 1.5 m small grain header. Weed seed control treatments were applied at harvest time for both wheat and soybean crops, including field residue removal, windrow burning, and tillage. The grower-standard treatments received no special treatment at harvest time, with all residue passing through the residue spreader at the rear of the harvester. For residue removal, all field residues were intercepted as they exited the combine, before they made contact with the soil surface. All residues were removed from the field completely, mimicking the use of a chaff cart. For windrow burning, 0.5 m-wide windrows were formed by replacing the harvester's residue spreader with a chute. The Gleaner combine formed one windrow, containing all field residues, per harvested swath, while the Wintersteiger combine was outfitted with chutes that combined three passes into a single windrow. Windrows were burned the same day as or day following harvest. Windrows were managed with standard burn practices, including the use of propane or gasoline fire starters when necessary and allowing the fire to burn completely until no crop residue remained. Tillage plots received two disking passes after both wheat and soybean harvest.

Data collected included weed density, weed biomass, seed quantity retained at harvest, and crop yield. Weed density was assessed at each crop's postemergent herbicide application and at harvest. Italian ryegrass stand counts were taken to record weed density with two subsample quadrats collected per plot. Weed biomass was collected at harvest by subsampling two random 0.1 m<sup>2</sup> areas, removing the above ground portion, drying, and weighing. Air dried samples were

threshed and seed quantity was determined. Crop yield was also recorded at harvest. Data were analyzed using JMP Pro 13 (SAS Institute, Cary, NC) to compare crop yield and weed population parameters before and after HWSC treatment application. The interaction between HWSC treatment and time (i.e. before treatment and after treatment) was analyzed with ANOVA, as in a before-after control-impact experiment. The blocking factor was treated as a random effect, in order to generalize inference across all possible blocks in that field. Fisher's protected LSD was used for multiple comparisons between treatment means within each year.

## Results and Discussion

**Italian Ryegrass Populations, Biomass, and Seed Retention.** Ryegrass stand counts decreased for all treatments except tillage between 2016 and 2017. Mean ryegrass stand counts were 31 to 37 plants  $m^{-2}$  in 2016, with no differences across the four weed management treatments. In 2017, the HWSC treatments, residue removal and windrow burning, were not different than the grower-standard management practices, ranging from 1 to 4 ryegrass plants  $m^{-2}$ . Ryegrass populations in the tillage treatment, however, remained as high as in 2016, with a mean density of 50 plants  $m^{-2}$ . The overall test for changes in treatments between growing seasons was significant ( $p=0.007$ ), demonstrating that at least one weed management program, in this case tillage, did cause changes in ryegrass population at different levels than the other treatments.

These results fail to indicate that residue removal and windrow burning controlled weed populations any better than the grower-standard management practices that contain no mechanical weed management. Standard management practices, including an effective postemergent herbicide, reduced ryegrass populations sufficiently across these three treatments. Ryegrass populations were greater in the tillage treatment throughout the second growing season; ryegrass stand counts at the time of the herbicide application were 170 plants  $m^{-2}$  in the tillage plots, compared to 18 to 23 plants  $m^{-2}$  in other treatments (Figure 7).

Italian ryegrass biomass, collected at wheat harvest, decreased across all treatments between the 2016 and 2017 harvests. Ryegrass biomass at 2016 wheat harvest ranged from a mean of 365 g  $m^{-2}$  for the grower-standard treatment to a mean of 505 g  $m^{-2}$  for the tillage treatment. Ryegrass biomass at 2017 harvest ranged from a mean of 1 g  $m^{-2}$  for the grower-standard treatment to 131 g  $m^{-2}$  for the tillage treatment (Figure 8). Within each harvest year,

Italian ryegrass biomass did not differ across treatments. The decrease in ryegrass biomass between growing seasons was therefore not different among treatments ( $p=0.879$ ).

Quantities of seed retained by Italian ryegrass at wheat harvest followed similar trends as biomass. Total ryegrass seed retention dropped between the first and second harvest year ( $p=0.045$ ), but no differences existed in the magnitude of seed retention change between treatments ( $p=0.621$ ). Mean ryegrass seed retention was 2,847 seeds  $m^{-2}$  in 2016 and 1535 seeds  $m^{-2}$  in 2017, and no differences existed between treatments within each year (Figure 9). These results suggest that residue removal, windrow burning, and tillage did not reduce ryegrass seed retention compared to the grower-standard weed management program. Italian ryegrass biomass and seed retention produced similar results, matching previous literature that indicated generally that weed biomass and weed seed production mirror one another (Pilipavičius 2013). Results from this study stand in contrast with previous research findings that HWSC, including HSD, narrow windrow burning, and chaff removal, in a commercial winter wheat production setting could reduce ryegrass stands by as much as 60%, thereby reducing season-end seed retention by as much as 90% (Walsh et al. 2017).

**Wheat Yield.** Crop yields increased from 2016 to 2017 for all treatments except tillage. Mean crop yields were 466 kg  $ha^{-1}$  for all treatments in 2016. In 2017, wheat yields for the grower-standard, residue removal, and windrow burning treatments did not differ, ranging from 1359 to 1418 kg  $ha^{-1}$ . The tillage treatment in 2017 yielded 641 kg  $ha^{-1}$ , a statistically similar result to its 2016 yield of 491 kg  $ha^{-1}$  (Figure 10). A significant interaction existed between treatment and year ( $p=0.015$ ), rejecting the hypothesis that crop yield increased equally for all treatments from the first to the second harvest.

These results again suggest that tillage was a poor addition to a weed management program for managing Italian ryegrass in winter wheat. Just as in the ryegrass population results, the HWSC programs, residue removal and windrow burning, performed as well as the grower-standard program, while the weed management program with tillage produced agronomically unfavorable changes year over year. Though HWSC and tillage both improve the diversity of selection pressures in a weed management program, the program featuring tillage actually increased ryegrass populations that were better able to compete with the winter wheat crop. Others studies examining HWSC's effects on crop yield have provided mixed results, and this

study represents one of the first of its kind linking HWSC directly to winter wheat yield (Borger et al. 2016, Norsworthy et al. 2016).

**HWSC Implementation and Future Research.** This research fails to reject the hypothesis that the HWSC techniques of residue removal and windrow burning improve Italian ryegrass control in winter wheat production. Tillage, however, performed worse than either HWSC method or the grower-standard management program and is not a viable method for mechanical control of Italian ryegrass seeds. While more research is needed to determine the mechanism behind tillage's promotion of Italian ryegrass, mechanical soil disturbance may have promoted germination of ryegrass seeds by preparing the seed bed or bringing buried seeds to the soil surface. This germination stimulation is sometimes leveraged by a stale seedbed approach, whereby growers apply a second weed management technique several days after tillage, destroying any emerged seedlings (Gallandt 2006).

Some of the similarities between results from the HWSC treatments and grower-standard treatment could have been explained by discrepancies between the HWSC treatments in this experiment and HWSC as typically applied on a commercial farm. While the residue removal treatment removed all field residues from the field, most growers only remove chaff, or the fine portion of field residue (Shirliffe and Entz 2005). The methods here could have potentially robbed the field of weed seedling-smothering heavy residues. Additionally, the windrows produced by research-sized harvesters in this experiment contained less residue and were more diffuse than the windrows produced by commercial-scale equipment, potentially lowering the temperature and reducing the efficacy of windrow fires compared to the more typical narrow windrows (Lyon et al. 2016). Finally, a timely harvest is of the utmost importance for successful HWSC implementation; mid-summer wheat harvests in this study allowed Italian ryegrass seeds to shatter and evade HWSC.

Future research can integrate some of these changes in treatments to better represent standard commercial practices. Additionally, variability between plots and low weed pressure may have masked some treatment differences, so future experiments may be designed to include more replicates, larger plots, and greater levels of herbicide resistant Italian ryegrass. Reduced seed bank additions are critical for annual weed management using an integrated weed management approach. Disrupting weed dispersal through HWSC tools holds promise for

improving herbicide resistance management, but these tools must be optimized for winter wheat production in the Mid-Atlantic United States before growers may realize the potential benefits of HWSC.

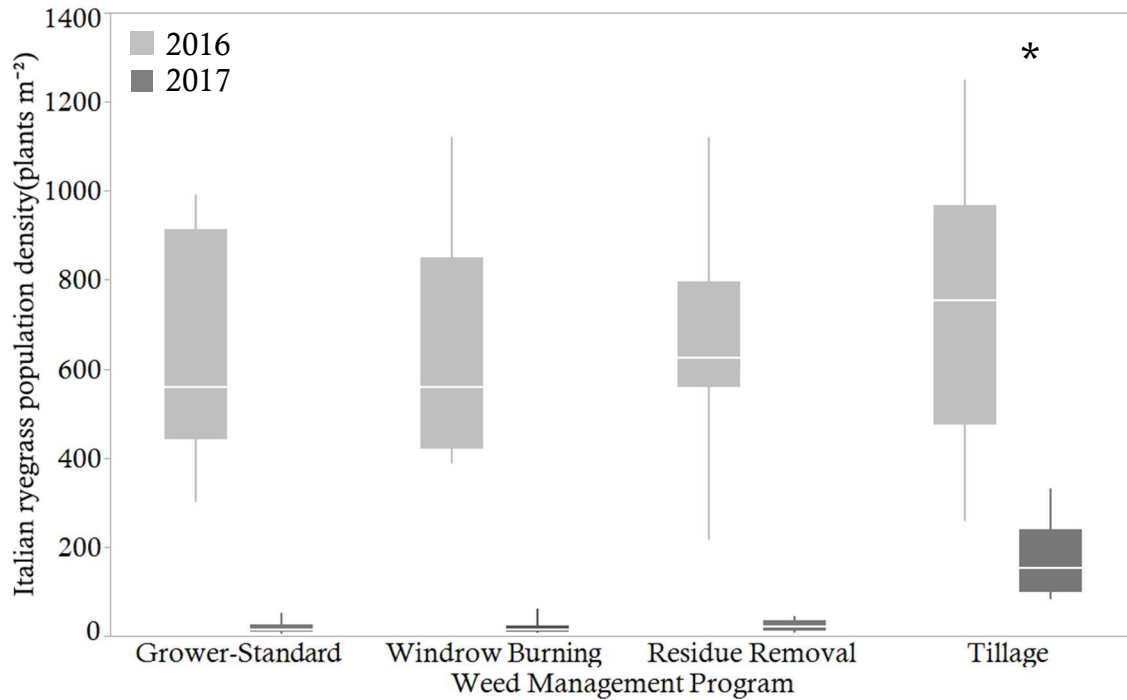


Figure 7. Effects of weed management practice on Italian ryegrass stand count at the time of postemergent herbicide application across two growing seasons, both before and after a single harvest weed seed control application. The line in the box represents mean plant density, upper and lower boundaries represent the upper and lower quartile of the data, respectively, and whiskers indicate the extreme values of the data. Asterisk indicates that year-to-year reductions in population density were smaller for tillage than for other treatments ( $p < 0.05$ ).

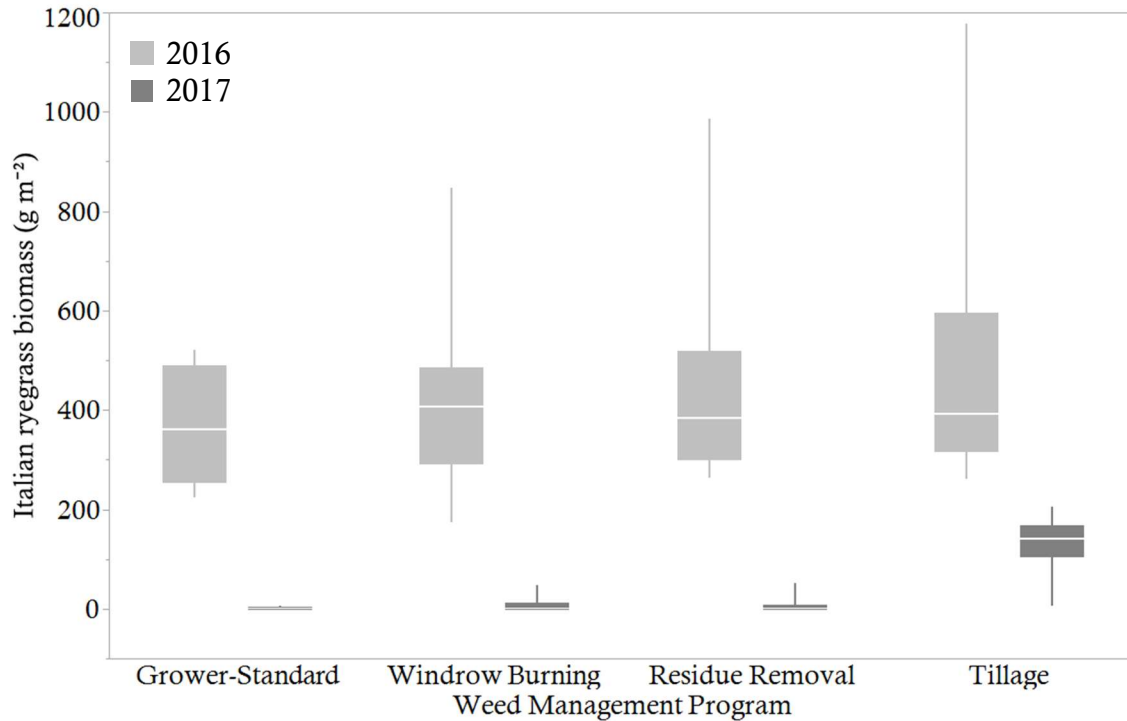


Figure 8. Effects of weed management practice on Italian ryegrass biomass at wheat harvest across two growing seasons, both before and after a single harvest weed seed control application. The line in the box represents mean biomass, upper and lower boundaries represent the upper and lower quartile of the data, respectively, and whiskers indicate the extreme values of the data. No differences existed in the magnitude of year-to-year change across treatments.

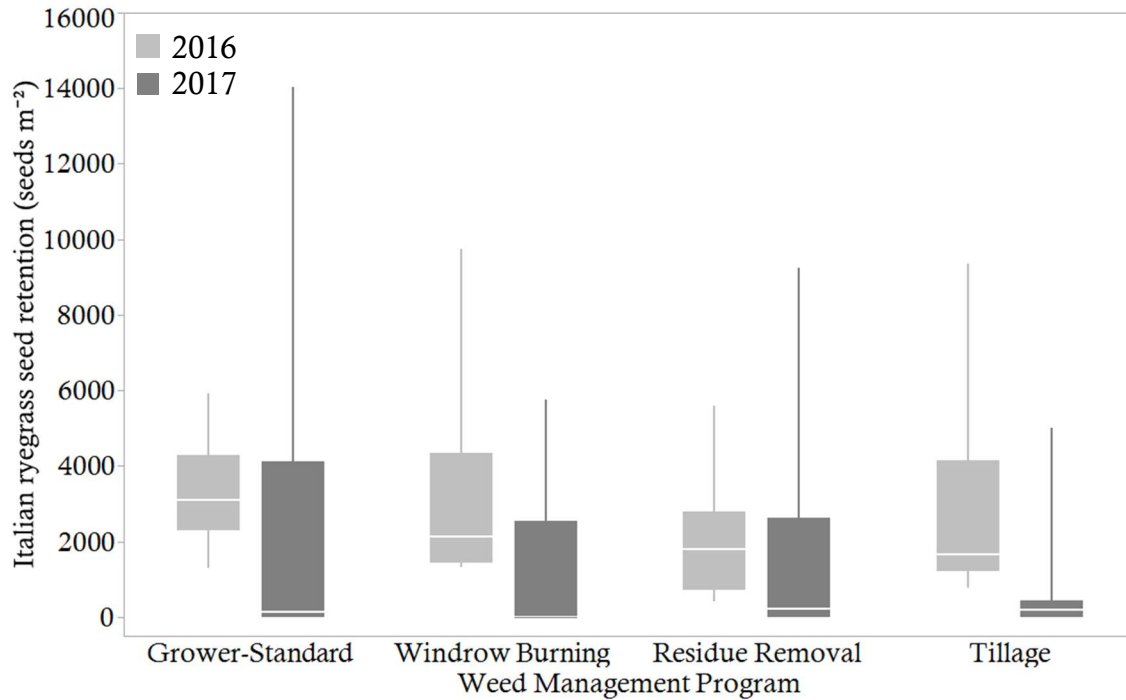


Figure 9. Effects of weed management practice on quantity of seed retained by Italian ryegrass at wheat harvest across two growing seasons, both before and after a single harvest weed seed control application. The line in the box represents mean quantity of seeds retained, upper and lower boundaries represent the upper and lower quartile of the data, respectively, and whiskers indicate the extreme values of the data. No differences existed in the magnitude of year-to-year change across treatments.

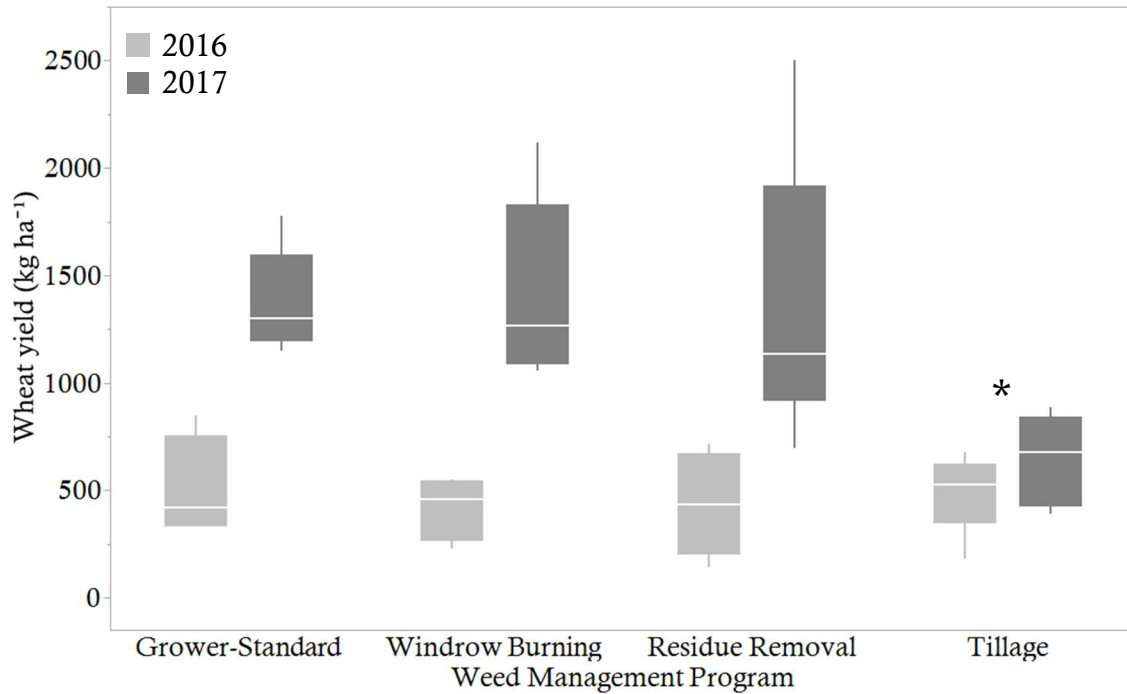


Figure 10. Effects of weed management practice on winter wheat yield across two growing seasons, both before and after a single harvest weed seed control application. The line in the box represents mean yield, upper and lower boundaries represent the upper and lower quartile of the data, respectively, and whiskers indicate the extreme values of the data. Asterisk indicates that year-to-year changes in wheat yield were lower for tillage treatment than for other treatments ( $p < 0.05$ ).

## **Organic Winter Wheat Production Including Harvest Weed Seed Control for Italian Ryegrass (*Lolium perenne* ssp. *multiflorum*) Control**

Organic winter wheat growers must continually integrate new weed management strategies to combat troublesome weeds like Italian ryegrass, and harvest weed seed controls hold promise for use in a diversified weed management system. This study aims to evaluate two HWSC techniques, residue removal and windrow burning, for Italian ryegrass control and compare them to a grower-standard organic weed management system. Residue removal simply takes weed seed-containing field residues off of the field, while windrow burning incinerates field residues and the weed seeds therein. Field experiments were initiated in Blackstone, VA in 2015, with HWSC treatments occurring at the first wheat harvest in July 2016, as well as at the following soybean harvest. Italian ryegrass stand counts were taken throughout the season, and measurements of Italian ryegrass biomass and seed retention were taken at harvest time along with wheat yield. No treatment differences existed in the year-to-year change of Italian ryegrass population density, seed retention at harvest, and biomass at harvest. Italian ryegrass populations increased to the point that wheat could not be harvested in the second growing season in any treatment. These results fail to indicate that either residue removal or windrow burning perform better than grower-standard practices at controlling Italian ryegrass, though they do highlight the importance of continued development of viable weed management for organic wheat production. Future research must optimize HWSC for organic and other chemical-free production systems.

Without the option of synthetic herbicides, organic growers must rely heavily on cultural and mechanical weed management techniques, which can be labor intensive. Organic growers are looking for new, reduced-labor weed management techniques that can mirror some of the labor savings that conventional growers have achieved in the last two decades (Gianessi 2005). Additionally, growers demand weed management practices that allow them to reduce their reliance on tillage in order to continue to preserve environmental sustainability and sustain farm profitability (Armengot et al. 2015).

Organic growers strive to use integrated pest management options across their farms, but tools to use within an integrated weed management approach remain limited (McWhorter and Shaw 1982). Integrated weed management approaches serve organic growers' needs by comprising several control techniques to address multiple management concerns (Kumar et al. 2013). While no single solution exists to manage all weeds, integrated weed management give growers increased adaptability and management diversity by uniting multiple factors of weed management. Sustainable cropping systems need this type of management flexibility to maintain weed management efficacy (Norsworthy et al. 2012).

Harvest weed seed controls represent an emerging set of weed management practices that fit into a broader, integrated approach to weed management. HWSC involves destroying weed seeds that have been retained on the weed plant at crop harvest, preventing their dispersal into the soil seed bank. Any number of techniques, including burning, crushing, or removal of weed seeds can comprise HWSC (Walsh et al. 2013). Because of its coincidental timing with crop harvest, HWSC often takes place alongside harvest operations, incorporating mechanical weed management into existing agronomic practices (Walsh et al. 2012, Walsh and Newman 2007). HWSC can provide added diversity to an integrated weed management program by introducing a novel selection pressure on weed seeds (Davis 2006).

HWSC pressures weed populations by limiting their spread through seed, a primary dispersal mechanism for most annual weed species (Lockwood et al. 2005). Weed populations are determined by the product of seed bank density and the emergence rate of weeds from that seed bank (Forcella 1992). Therefore, by limiting additions to the soil seed bank, HWSC can reduce standing weed populations, a process called seed bank depletion. Because HWSC only processes seeds that pass through the crop harvester, species that disperse seeds prior to harvest or through other mechanisms, such as wind or early shattering, could potentially avoid seed bank

depletion (Goplen et al. 2016). HWSC efficacy relies on weeds that retain seed well after crop maturity, thereby making the harvester a primary dispersal mechanism for those species' seeds.

A variety of HWSC techniques have been developed, primarily by wheat growers in Australia (Walsh and Powles 2014a). Crushing seeds along with chaff and fine residues in a specialized cage mill called the Harrington Seed Destructor (HSD) has been found to destroy over 95% of weed seeds by using a machine towed directly behind the combine (Walsh et al. 2012). Despite the HSD's high initial cost, it has been economical for wheat growers with large farms and high levels of herbicide resistance (Jacobs and Kingwell 2016). Growers perform narrow windrow burning by funneling all field residues into a windrow and burning it, destroying weed seeds through fire (Walsh and Newman 2007). Chaff carts can be used to capture fine field residues, which contain weed seeds, and place them in piles off-field or to be burned (Walsh et al. 2013). Field results of these and other HWSC techniques have been promising across conventional cropping systems, often destroying over 80% of weed seeds as is needed for impacting weed populations (Lyon et al. 2016, Norsworthy et al. 2016, Tidemann et al. 2016). Though the National Organic Program specifically prohibits field residue burning, except in specific cases that do not involve weed seed incineration, narrow windrow burning and chaff removal hold promise as low-cost versions of HWSC that could be accessible to the herbicide-free farmer ("Soil Fertility and Crop Nutrient Management Practice Standard" n.d.).

Italian ryegrass represents a major threat to winter wheat production across the Mid-Atlantic; its broad range of competitive traits interferes with wheat crops (Appleby et al. 1976, Worthington et al. 2015). While falling commodity prices and increased difficulty controlling herbicide-resistant Italian ryegrass have reduced double-crop wheat production in conventional systems, winter wheat production can provide opportunity for organic growers who wish to add a complementary crop to their rotation (Cavigelli et al. 2009). Further development of economical weed management techniques will improve prospects for organic winter wheat production. HWSC tools, because of their chemical-free design and initial development for ryegrass control, could work well for organic weed management. This research aims to apply lessons learned from HWSC developed for conventional cropping systems and apply them to organic systems that already rely heavily on mechanical weed management such as tillage.

## Materials and Methods

Field experiments to evaluate the efficacy of Italian ryegrass control with HWSC were established in Blackstone, VA (37.081816°N, 77.972543°S) in November 2015 and maintained through 2017. Experiments were repeated over two growing seasons to establish baseline weed pressure in the first year and evaluate weed response in the second year, after treatments were applied at the first season's harvest. Plots were 7.5 m by 15 m, with four total replications. Plots were arranged within a larger, factorial experiment that included additional weed species of interest and crop rotations. For this Italian ryegrass control experiment, winter wheat was grown in a double crop system with soybeans. Weed management treatments included a grower-standard weed management program on its own and in combination with residue removal or windrow burning, explained in greater detail below. Though conventional crop varieties were planted on land that had been previously under conventional production, the agronomic practices used in this study mirrored those required by the National Organic Program.

Winter wheat was planted after soybean harvest on December 18, 2015 and December 20, 2016. Winter wheat cultivar SS 5205 was planted in 2015 and SS 8340 in 2016 (Southern States Cooperative, Richmond, VA). Plots were prepared by tilling twice with a heavy disk before planting. Wheat was planted at 196 kg ha<sup>-1</sup> with a drill on 20 cm row spacing. Pelletized chicken litter fertilizer (3-2-3) was applied with a broadcast spreader at rates of 2,242 kg ha<sup>-1</sup> at planting and an additional 2,242 kg ha<sup>-1</sup> N in February each growing season. Immediately following wheat planting in the first year only, an artificial weed population was established by spreading annual ryegrass seed (Variety "Fria," Southern States Cooperative, Richmond, VA) at a rate of 22.5 kg ha<sup>-1</sup>.

Double crop soybeans were planted after wheat harvest on July 1, 2016. Plots were prepared by tilling twice with a heavy disk before planting. Soybeans cultivar P46T21R (DuPont Pioneer, Johnston, IA) was planted at 555,750 seeds ha<sup>-1</sup> with a planter on 76 cm row spacing. Interrow, S-tine cultivation was performed after crop emergence at 5 to 7 day intervals, weather permitting, until crop size prevented passage through the field.

Plots were harvested with a Gleaner K2 combine (AGCO Corporation, Duluth, GA) with a modified 2.4 m small grain header combine or a Wintersteiger Classic combine (Wintersteiger AG, Ried im Innkreis, Austria) with a 1.5 m small grain header. Weed seed control treatments were applied at harvest time for both wheat and soybean crops, including residue removal and

windrow burning. The grower-standard treatments received no special treatment at harvest time, with all field residues passing through the chaff spreader at the rear of the harvester. For residue removal, all field residues were intercepted as they exited the back of the combine, before they made contact with the soil surface. Field residues were completely removed from the field, mimicking the use of a chaff cart. For windrow burning, 0.5 m-wide windrows were formed by replacing the chaff spreader with a chute and depositing all field residues in a windrow. The Gleaner combine formed one windrow per harvested swath, while the Wintersteiger combine was outfitted with chutes that combined three passes into a single windrow. Windrows were burned the same day as or day following harvest. Windrows were managed with standard burn practices including the use of propane or gasoline fire starters when necessary and allowing the fire to burn completely until no crop residue remained.

Data collected included weed density, weed biomass, weed seed retained at harvest, and crop yield. Weed density was assessed approximately four weeks after planting and at harvest. Italian ryegrass stand counts were taken to record weed density with two subsample quadrats collected per plot. Weed biomass was collected at harvest by subsampling two random 0.1 m<sup>2</sup> areas, removing the above ground Italian ryegrass biomass, drying, and weighing. Crop yield was also recorded at harvest. Data were analyzed using JMP Pro 13 (SAS Institute, Cary, NC) to compare crop yield and weed population parameters before and after HWSC treatment application. The interaction between HWSC treatment and time (i.e. before treatment and after treatment) was analyzed with ANOVA, as in a before-after control-impact experiment. The blocking factor was treated as a random effect, in order to generalize inference across all possible blocks in that field. Fisher's protected LSD was used for multiple comparisons between treatment means in each year.

## **Results and Discussion**

High Italian ryegrass populations generally hindered crop production and limited weed control across HWSC and grower-standard treatments. Though early-season ryegrass populations actually decreased year to year ( $p=0.007$ ) from 499 plants m<sup>-2</sup> for the 2016 growing season to 117 plants m<sup>-2</sup> for the 2017 growing season, ryegrass stands at harvest increased ( $p<0.001$ ) from 65 plants m<sup>-2</sup> in 2016 to 288 plants m<sup>-2</sup> in 2017 (Figure 11). Ryegrass populations did not change differently according to treatment for either the early-season count ( $p=0.979$ ) or the harvest count

( $p=0.189$ ). The increase in ryegrass populations at harvest are likely due to an observed flush of spring ryegrass germination. Seed germinating in this late flush could have potentially been dormant seed from the initial population establishment or from the seed shattered before the 2016 wheat harvest. Additionally, this spring flush of germination could have been related to seed burial by tillage, which could have deposited ryegrass seed at a depth where they could still emerge but be protected by soil cover.

Italian ryegrass biomass at harvest increased ( $p<0.001$ ) from  $204 \text{ g m}^{-2}$  in 2016 to  $821 \text{ g m}^{-2}$  in 2017, but this increase did not vary across weed management treatments ( $p=0.625$ ) (Figure 12). This result is consistent with the increase in late-season Italian ryegrass population density noted above. Additionally, quantities of Italian ryegrass seed retained at harvest time mirrored this pattern, increasing ( $p=0.003$ ) from a mean of  $801 \text{ seeds m}^{-2}$  in 2016 to  $18,009 \text{ seeds m}^{-2}$  in 2017 (Figure 13). This greater than 20-fold increase in seed retention highlights the potential value of HWSC for targeting high levels of weed infestation. Ryegrass seed retention increased equally for residue removal, windrow burning, and grower-standard weed management treatments ( $p=0.107$ ), indicating no difference between weed management treatments applied at the 2016 wheat harvest.

Italian ryegrass infestations grew to such high levels in 2017 that no wheat was harvested. Field run wheat was comprised of so much ryegrass seed that the crop would not have been commercially salable; the increase in Italian ryegrass seed retention explained above actually went towards contaminating the grain harvest. Therefore, all weed management practices yielded crop yields of  $0 \text{ kg ha}^{-1}$ . Because poor weed control, from both HWSC and grower-standard treatments, led to a failed wheat crop, specific interpretations about HWSC efficacy cannot be made.

Few studies have directly linked HWSC practice to crop yield, and their results have had varying degrees of efficacy across cropping system and HWSC practice (Borger et al. 2016, Norsworthy et al. 2016). This study represents the first of its kind applying HWSC to an organic or herbicide-free system. Results from this study relating to Italian ryegrass population density, biomass, and seed retention stand in contrast to previous work investigating ryegrass species' response to HWSC. Under field conditions, HWSC techniques including narrow windrow burning, HSD, and chaff removal have been shown to reduce ryegrass population density by up

to 60% and seed retention by up to 90% (Walsh et al. 2017). Different results in this study could potentially be attributable to organic wheat production's interactions with HWSC.

Future research can revisit this study with better execution of organic farming practices. Including best practices for organic weed management, such as early crop planting, two-pass or broadcast crop planting, or finger cultivation, could help manage Italian ryegrass to levels where HWSC could have an effect. Additionally, best practices for HWSC, could help improve their efficacy. Timely harvests, especially, would improve HWSC efficacy by ensuring that as many weed seeds are retained, and therefore controlled, as possible. Residue removal, as performed in this experiment, differs from the chaff removal, or removal of only fine field residues, that is performed commercially (Shirliffe and Entz 2005). Residue removal may have impacted crop nutrition or removed weed seedling-smothering heavy residues from the field. Windrows produced by the research-scale harvesters in this experiment contained less residue and were less concentrated than the windrows produced in a commercial narrow windrow burning practice, potentially lowering the temperature and reducing the efficacy of windrow fires in this experiment (Lyon et al. 2016). High variability between plots in this study created difficulty in detecting differences. An improved experimental design, such as by increasing plot or sampling size, could reduce variability. Finally, future research may include additional HWSC techniques, including techniques without burning that would be more permissible under the National Organic Program, for optimization in Mid-Atlantic winter wheat production.

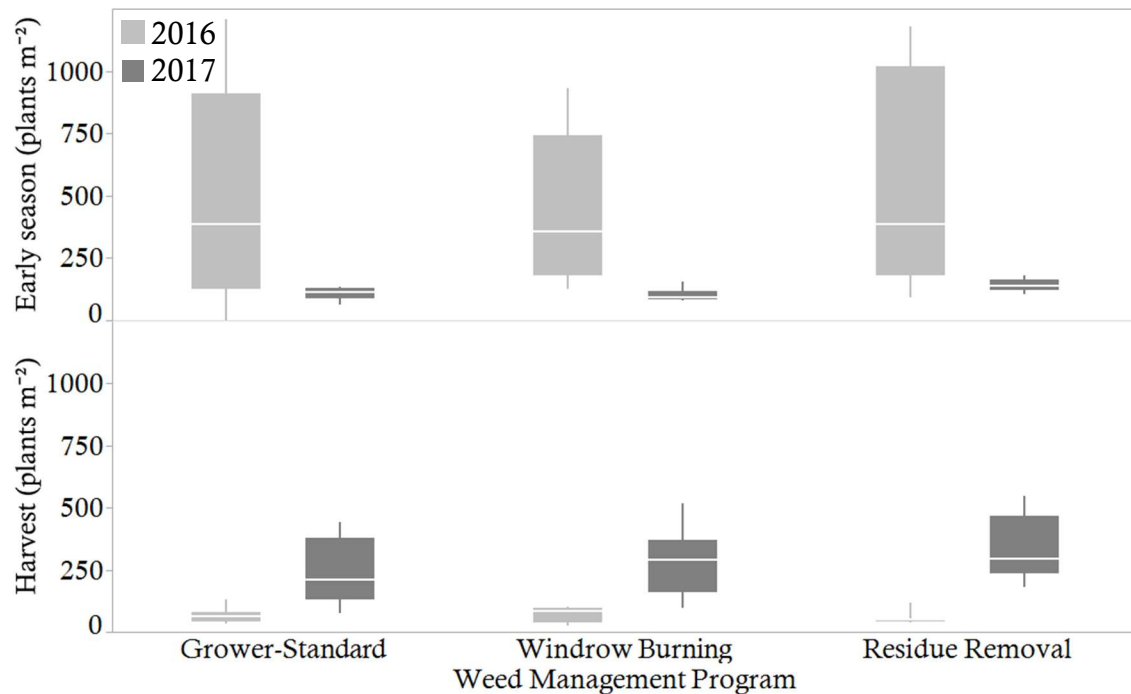


Figure 11. Effects of weed management practice on Italian ryegrass stand count approximately four weeks after planting (top) and at harvest (bottom) across two growing seasons, both before and after a single harvest weed seed control application. The line in the box represents mean plant density, upper and lower boundaries represent the upper and lower quartile of the data, respectively, and whiskers indicate the extreme values of the data. No differences existed in the magnitude of year-to-year change across treatments.

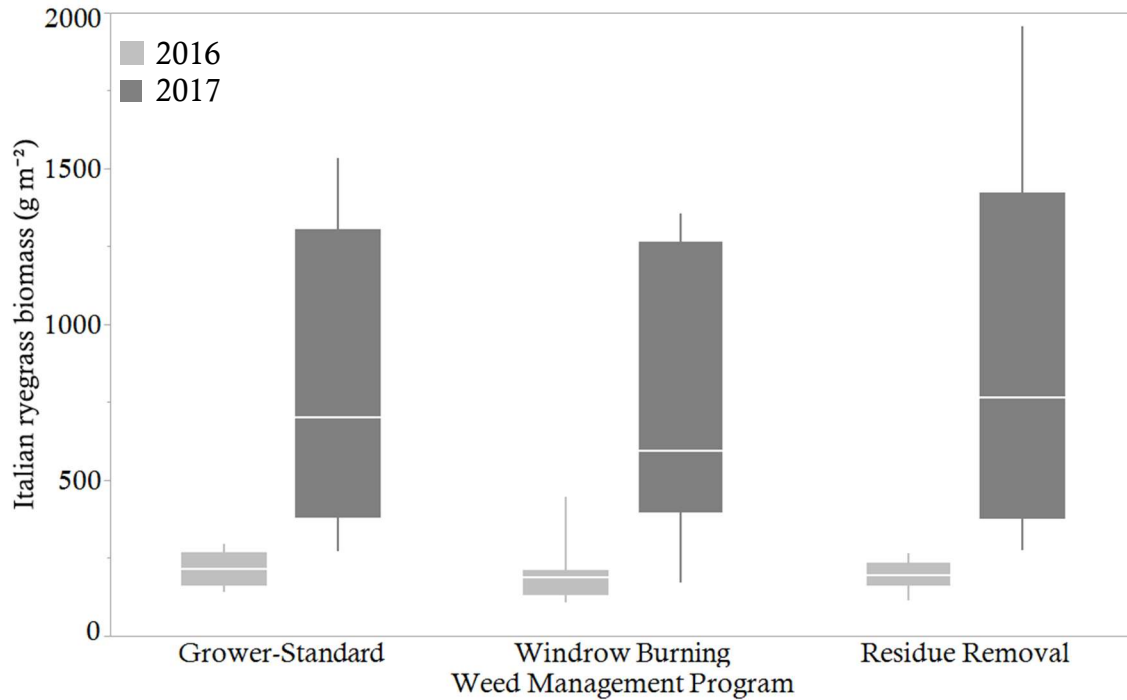


Figure 12. Effects of weed management practice on Italian ryegrass biomass at wheat harvest across two growing seasons, both before and after a single harvest weed seed control application. The line in the box represents mean biomass, upper and lower boundaries represent the upper and lower quartile of the data, respectively, and whiskers indicate the extreme values of the data. No differences existed in the magnitude of year-to-year change across treatments.

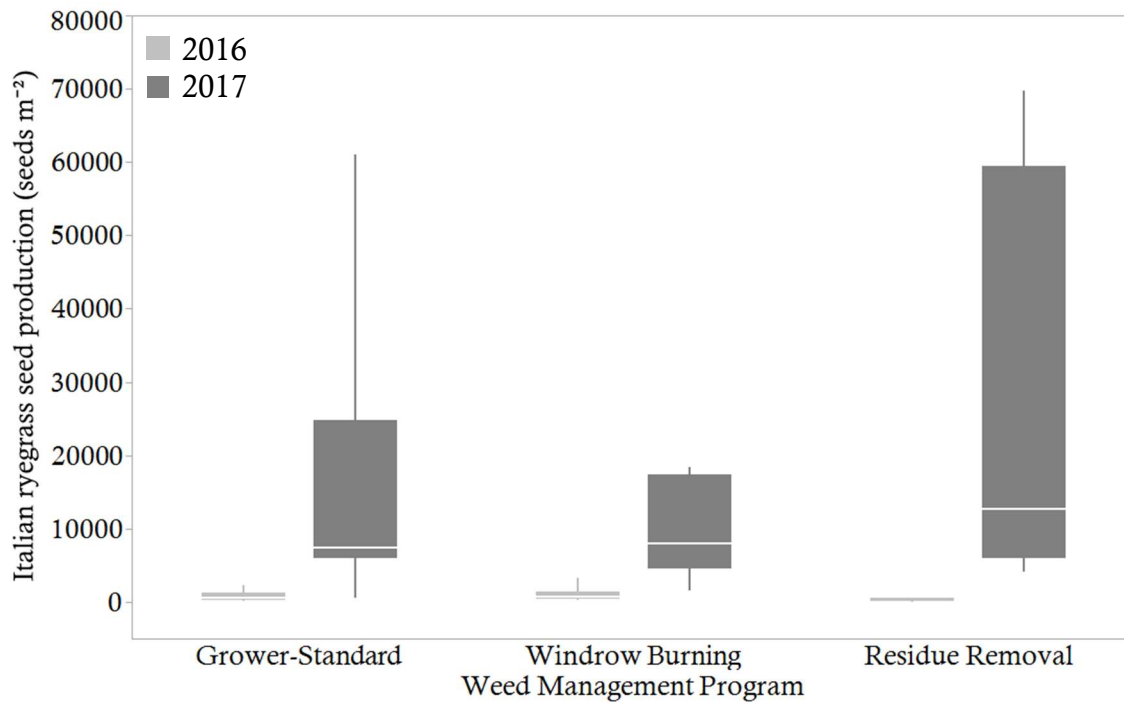


Figure 13. Effects of weed management practice on quantity of Italian ryegrass seed retained at wheat harvest across two growing seasons, both before and after a single harvest weed seed control application. The line in the box represents mean seed production, upper and lower boundaries represent the upper and lower quartile of the data, respectively, and whiskers indicate the extreme values of the data. No differences existed in the magnitude of year-to-year change across treatments.

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