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Seed retention of winter annual grass weeds at winter wheat harvest maturity shows potential for harvest weed seed control

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Research Article

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Nomenclature:
Downy brome, *Bromus tectorum* L. BROTE; feral rye, *Secale cereale* L. SECCE; jointed goatgrass, *Aegilops cylindrica* Host, AEGCY; wheat, *Triticum aestivum* L. TRZAX

Keywords:
Weed seed retention; weed control; seedbank management; ecological weed management; integrated weed management

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Abstract

Downy brome, feral rye, and jointed goatgrass are problematic winter annual grasses in central Great Plains winter wheat production. Integrated control strategies are needed to manage winter annual grasses and reduce selection pressure exerted on these weed populations by the limited herbicide options currently available. Harvest weed-seed control (HWSC) methods aim to remove or destroy weed seeds, thereby reducing seed-bank enrichment at crop harvest. An added advantage is the potential to reduce herbicide-resistant weed seeds that are more likely to be present at harvest, thereby providing a nonchemical resistance-management strategy. Our objective was to assess the potential for HWSC of winter annual grass weeds in winter wheat by measuring seed retention at harvest and destruction percentage in an impact mill. During 2015 and 2016, 40 wheat fields in eastern Colorado were sampled. Seed retention was quantified and compared per weed species by counting seed retained above the harvested fraction of the wheat upper canopy (15 cm and above), seed retained below 15 cm, and shattered seed on the soil surface at wheat harvest. A stand-mounted impact mill device was used to determine the percent seed destruction of grass weed species in processed wheat chaff. Averaged across both years, seed retention (±SE) was 75% ± 2.9%, 90% ± 1.7%, and 76% ± 4.3% for downy brome, feral rye, and jointed goatgrass, respectively. Seed retention was most variable for downy brome, because 59% of the samples had at least 75% seed retention, whereas the proportions for feral rye and jointed goatgrass samples with at least 75% seed retention were 93% and 70%, respectively. Weed seed destruction percentages were at least 98% for all three species. These results suggest HWSC could be implemented as an integrated strategy for winter annual grass management in central Great Plains winter wheat cropping systems.

Introduction

Weed control in wheat agroecosystems is imperative to prevent yield losses due to competition for light, nutrients, physical space, and water (Van Heemst 1985). Major winter annual grass weed species threatening wheat productivity in the western United States are downy brome, feral rye, and jointed goatgrass (Fleming et al. 1988; Lyon and Baltensperger 1995). For instance, feral rye densities at 40 plants m^{-2} and downy brome at 65 plants m^{-2} can cause 60% and 20% yield loss in winter wheat, respectively (Pester et al. 2000; Stahlman and Miller 1990). An additional threat posed by jointed goatgrass is the potential to hybridize with wheat. High densities of jointed goatgrass increase the risk of gene flow between these two species, leading to a potential for herbicide-resistance traits to transfer from wheat to jointed goatgrass (Donald and Ogg 1991; Gaines et al. 2008; Hanson et al. 2005; Mallory-Smith et al. 2018; Zemetra et al. 1998).

The most common weed-control practices in wheat cropping systems are tillage, crop rotation, and herbicides (Daugovish et al. 1999). Combining these strategies has substantially decreased winter annual grass densities and increased wheat yield (Lyon and Baltensperger 1995; Young et al. 1994). Selective POST herbicides available for feral rye and jointed goatgrass control in wheat are limited to imazamox (Tan et al. 2005) (Group 2, Clearfield® wheat) and quizalofop-p-ethyl (quizalofop) (Anonymous 2019; Ostlie et al. 2015) (Group 1, CoAXium® wheat). Multiple, selective Group 2 herbicides are registered for downy brome control in wheat, with resistance to several Group 2 herbicides documented (Mallory-Smith et al. 1999; Park et al. 2004). Integrated weed management (IWM) is a preventive approach to reduce the occurrence of individuals that evolved resistance to repeated practices (Buhler 2002). Variability in weed control practices diversifies the selection pressure in weed populations, which is expected to extend the utility of current methods. To maintain the efficacy of current weed management approaches, it is necessary to develop additional IWM alternatives.

Harvest weed seed control (HWSC) methods are conducted at crop harvest to reduce the input of weed seed into the soil seedbank (Walsh et al. 2013a). Seedbank inputs were reduced from 80% to 95% for certain weed species by targeting the weed seed containing chaff fraction. The chaff fraction corresponds to the husk (consisting of the lemma, palea, and glumes) and other light residual material after the grain has been threshed (Walsh and Powles 2007; Walsh et al. 2013b). HWSC systems are widely used in Australia due to the high seed retention of dominant weed species, particularly annual ryegrass (*Lolium rigidum* Gaudin). Adoption in Australia is expected to double in the next 5 years to greater than 80% of growers using some form of HWSC (Walsh et al. 2017a).

There are six HWSC systems currently available, including chaff carts, narrow-windrow burning, bale direct system, chaff lining, chaff tramlining, and weed seed destruction using an impact mill system (Walsh and Powles 2007; Walsh et al. 2017b). In the central Great Plains, crop residues are used as erosion management and moisture retention; therefore, a suitable HWSC system in this area must return all residues to the field. Thus, systems compatible with retaining all residues (including chaff) are chaff lining, chaff tramlining, and impact mill systems for weed seed destruction (Walsh et al. 2013a; Walsh et al. 2017b). Chaff lining and chaff tramlining involve modifications to the combine to redirect the chaff material in a single line (lining) or on the harvester wheel tracks (tramlining). These methods aim to reduce weed germination by concentrating the seeds in large amounts of chaff, thereby creating favorable conditions to increase seed decay and reduce emergence (Ruttledge et al. 2018). Currently, there are two commercially available impact mill devices: the integrated Harrington Seed Destructor® (iHSD; De Bruin Engineering, PO Box 52, Mount Gambier, South Australia 5290, Australia) and the Seed Terminator® (Seed Terminator, 1284 South Road, Tonsley, South Australia 5042, Australia). These are attachments integrated into the combine that physically destroy up to 98% of weed seeds while returning the chaff to the field (Walsh et al. 2013a; Walsh et al. 2012).

As a transformative IWM practice, there currently is much interest in the use of HWSC in cropping regions across the United States and Canada because a number of important weed species have high levels of seed retention at crop harvest (Walsh et al. 2017b). In addition, HWSC has become an integrated strategy to manage species with multiple herbicide-resistance such as Palmer amaranth (*Amaranthus palmeri* S. Watson) in soybean cropping systems (Schwartz et al. 2016). Although producers in the midwestern and southeastern United States have documented potential for HWSC, little is known about the effectiveness of HWSC in controlling weeds in central Great Plains winter wheat fields. Downy brome, feral rye, and jointed goatgrass have similar growth habits and maturity timing as wheat (Daugovish et al. 1999). Therefore, we hypothesized that the majority of downy brome, feral rye, and jointed goatgrass seeds are retained in the harvestable fraction of the wheat upper canopy. Our main objective was to assess the seed retention of downy brome, feral rye, and jointed goatgrass at wheat maturity as an indicator of potential HWSC efficacy. A secondary aim was to determine the effectiveness of an iHSD mill in destroying the seed of these species when processed in wheat chaff.

Materials and Methods

Seed Retention and Plant Height

To determine whether weed-seed retention at wheat harvest would be sufficient to justify HWSC methods, a field survey was conducted at wheat maturity in eastern Colorado during the summers of 2015 and 2016 using a similar experimental approach as described by Walsh and Powles (2014) and Walsh et al. (2017b). Forty winter wheat sites were sampled at crop maturity. Sites were selected when one or more plant(s) from the studied weed species were present in the field. At each site, four replications of a 1-m^2 quadrat were collected. Sampling was conducted to simulate a crop harvest and was conducted when the wheat reached 18% to 20% moisture content. Wheat and weed species present in a 1-m^2 quadrat were hand cut at 15 cm above the soil surface and carefully placed in the same bag to prevent any seed shattering. No weed seed heads below 15 cm were identified across sites. Weed seeds on the soil surface were collected with a small broom and dust pan after the remaining wheat biomass was removed. Samples were air-dried and placed in dry storage conditions for processing. Weed plants from the upper canopy were separated and threshed by hand. Likewise, weed seed found on the soil surface was sorted by hand using multiple sieve sizes. Weed-seed quantity was determined per sample by dividing the total weight by the 100-seed weight. Seed retention percentage is the proportion of weed seed retained in the upper canopy, calculated by the following equation:

$$\text{seed retention } \% = [\text{total no. of seed upper canopy}/(\text{total no. of seed upper canopy} + \text{total no. of seed soil surface})] \times 100 \quad [1]$$

Wheat and the winter annual grass weeds downy brome, feral rye, and jointed goatgrass produce a single spikelet per tiller located near the top of the plant canopy. Plant height was used as a descriptive parameter to compare the harvest height of these winter annual grasses with wheat. Height was measured of the tallest tiller of five plants from each weed species present in the sampling area and from five wheat plants in each site.

iHSD Efficacy

A stand-mounted iHSD unit was used to determine downy brome, feral rye, and jointed goatgrass seed destruction efficacy with the impact mill. In the summer of 2016, wheat chaff was obtained from weed-free wheat research plots grown at the Colorado State University Agriculture Research, Development, and Education Center, Fort Collins, CO. This wheat chaff was collected from a belt thresher. To replicate harvester-produced material, the chaff was passed through a combine. Similar to Walsh et al. (2018a), before processing with the iHSD mill, 1,000 seeds of a weed species were mixed with 2 kg of wheat chaff. A single seed lot for each species was used, obtained from collections at the Colorado State University Weed Research Laboratory made in 2015. Seed germination was tested in Petri dishes, with average germination of 80%, 85%, 65% for downy brome, feral rye, and jointed goatgrass, respectively.

For each weed species, four samples following the previous description were prepared. A weed seed–containing chaff sample was then spread across the 2-m long conveyor belt that feeds

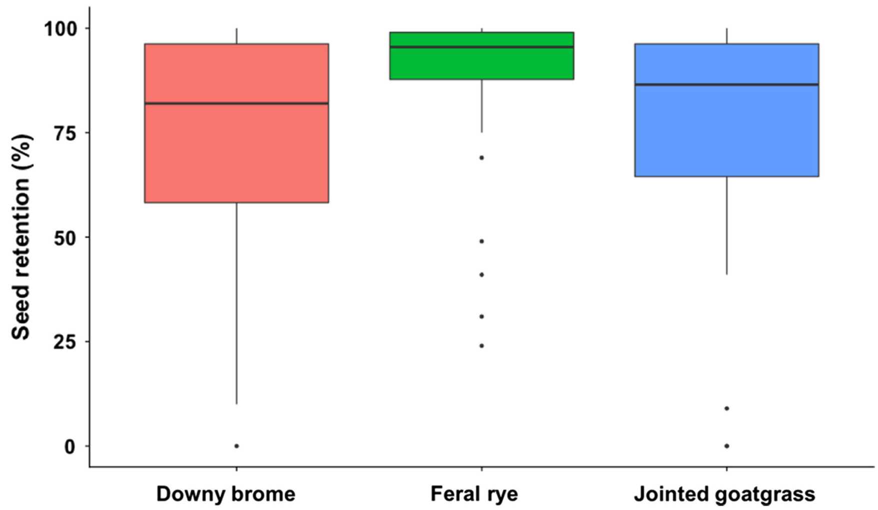

Figure 1. Box plot describing the seed-retention percentage in the wheat upper canopy harvestable section (15 cm and higher) at crop maturity during the summers of 2015 and 2016 for downy brome (n = 17 sites), feral rye (n = 24 sites), and jointed goatgrass (n = 10 sites).

samples into the mill. With the mill operating at 3,000 rpm, the conveyor belt was operated and delivered the chaff into the mill at a rate of 12 t hr^{-1}. A large (2 × 2 m) 0.5-mm mesh bag was attached to the outlet chute of the mill to collect the processed samples. After the samples were processed through the iHSD, seedling emergence was determined to assess seed destruction efficacy. A previous test was conducted with intact weed seed to determine the amount of chaff that could inhibit weed-seed germination. Results showed that 400 g of chaff did not reduce weed emergence across the three species. Processed samples were split in 400-g subsamples, mixed with 600 g of potting soil and placed in 60- × 30-cm trays. Trays were watered and maintained at field capacity over 8 wk. During this time, seedlings were counted and removed. Control treatments consisting of the same proportion of iHSD-processed chaff and potting soil were mixed with 100 intact seeds from each weed species from the same seed lot used for the iHSD tests to determine expected seedling emergence for each species. Destruction percentage was calculated by the following equation to account for seedling emergence in the seed lot when mixed with chaff and potting soil in the control:

$$\text{\% seed destruction} = [1 - (\text{no. seedlings emerged in iHSD} - \text{processed sample/no. seedlings emerged in control treatment})] \times 100 \quad [2]$$

Data Analysis

Seed retention and seedling emergence were analyzed with descriptive statistics using the R package 'plyr' (Wickham 2018). To determine the height difference between weed species and wheat, a linear mixed-effects model using the 'lme4' package in R, version 3.5.2, testing at an α of 0.05 was used (Bates et al. 2019). The fixed factor included in this model was weed species, whereas year and location where considered random effects. To obtain the comparisons from all least square means by species with a Tukey adjustment ($P < 0.05$), the R package 'emmeans' was used (Lenth 2019).

Results and Discussion

Seed Retention and Plant Height

HWSC systems have potential to reduce seed-bank inputs of winter annual grasses during the harvest of central Great Plains wheat crops, with the highest potential reduction for feral rye out of the three species measured and lower potential for downy brome and jointed goatgrass. All three weed species had greater than 75% average seed retention at wheat crop maturity, indicating that a large proportion of total seed production could be targeted during harvest (Figure 1). Feral rye consistently produced the highest average seed retention (90%) and, therefore, has the greatest potential for HWSC. Seed retention of downy brome averaged 75% but was highly variable, ranging from 20% to 95% (Figure 1). Jointed goatgrass had an average of 76% seed retention. Approximately 60% of the downy brome samples had 75% or greater seed retention, whereas 70% and 93% of jointed goatgrass and feral rye samples, respectively, had 75% or greater seed retention. The percentages of samples that had 10% or less seed retention were 3%, 0%, and 8% for downy brome, feral rye, and jointed goatgrass, respectively. Additional work is necessary to understand if this variability could be related to an interaction between genotype and environment.

Plant height was considered as a measurement for potential weed-seed collection at harvest. Downy brome height was not different from wheat (Figure 2). Feral rye was 50% (approximately 40 cm) taller than wheat (Figure 2); consequently, it is highly likely that retained seed will be collected during harvest. Conversely, jointed goatgrass was 25% shorter than wheat (Figure 2). Weed species of similar or taller height compared to wheat would increase the likelihood of retained seed being collected with the combine at harvest. Therefore, downy brome and feral rye have a higher likelihood that the retained seed would be collected at the same time as wheat harvest, benefiting the HWSC system. Jointed goatgrass retained-seed collection could be increased by lowering the combine harvest height.

High seed-retention percentages indicate good potential impact for the use of HWSC systems during harvest (Walsh et al. 2013a). Downy brome and jointed goatgrass had intermediate HWSC

Figure 2. Plant height of wheat compared with downy brome (n = 17 sites), feral rye (n = 24 sites), and jointed goatgrass (n = 10 sites) during the summers of 2015 and 2016. Letters indicate significant differences based on mixed-effects model (α ≤ 0.05).

potential, whereas feral rye showed a higher potential (Figure 1), based on the total seed proportion retained above a 15-cm harvest height. Seed retention at plant maturity appears to be related primarily to weed species but also potentially to environmental conditions and location. Preliminary data collected in the Pacific Northwest region showed approximately 80% of downy brome seed had shattered by wheat harvest, whereas feral rye seed retention was greater than 60% (J. Barroso, unpublished data). Tidemann et al. (2017b) suggested that the differences in seed retention among wild oat (*Avena fatua* L.), false cleavers (*Galium spurium* L.), and volunteer canola (*Brassica napus* L.) were due to shattering habits, growing degree days, and crop competition. For instance, Shirtliffe et al. (2000) reported a growing degree-day interval for wild oat with full seed shattering between 1,470 and 1,680. Different weed-seed shattering patterns have been reported depending on the cropping system and harvest approach (swathing vs. direct harvest) (Beckie et al. 2017; Burton et al. 2016). In addition, wild oat and ryegrass species retained twice as much seed in Australia compared with the Great Plains region (Walsh et al. 2017b). Other species such as Palmer amaranth and tall waterhemp [*Amaranthus tuberculatus* (Moq.) J. D. Sauer] were reported to have a consistent seed retention between 94% to 100% across different regions (Schwartz et al. 2016).

Weed species of similar or taller height than the crop will increase the seed collection efficiency at harvest. Among the studied winter annual grasses, jointed goatgrass is the species that had more height disadvantage; downy brome and feral rye are optimal compared to wheat (Figure 2). However, Donald and Ogg (1991) found that even when growers tried to take advantage of the height difference between wheat and jointed goatgrass by raising the combine header, they were not able to avoid jointed goatgrass seed contamination in their grain. Jointed goatgrass and downy brome heights varied depending on the wheat variety and annual precipitation. These species can reach a similar or higher height than wheat when they are competing against semidwarf varieties and/or in dry conditions (Blackshaw 1994; Yenish and Young 2004). Feral rye height is also affected by wheat variety and growing conditions; however, the minimum height reported in previous research is 66 cm, which is taller than most commercial wheat varieties (Anderson 1998). Weed height can be modified by increasing planting density. Recent research showed that greater wheat planting densities can lead to increases in height and seed retention for rigid ryegrass (Walsh et al. 2018b), thereby potentially increasing the seed collection using a HWSC system.

Colorado winter wheat is mostly grown in no-till production systems. This farming practice favors downy brome, feral rye, and jointed goatgrass seed establishment. In a no-till system, these species have higher germination and lower dormancy when they are on the soil surface compared with a burial status (Donald and Ogg 1991; Stump and Westra 2000; Thill et al. 1984). HWSC as an IWM tool can disrupt the reproductive cycle for these species, thereby reducing new seeds contributed to the seedbank over time.

iHSD Efficacy

Downy brome, feral rye, and jointed goatgrass seeds processed through the iHSD in wheat chaff had greater than 98% reduction in seedling emergence compared with untreated seeds germinated in wheat chaff (Figure 3). Average seedling emergence in the controls (i.e., untreated seed germination in iHSD-processed chaff and potting soil to mimic germination conditions in iHSD-treated samples) was 88% for downy brome, 16% for feral rye, and 75% for jointed goatgrass, with similar germination rates in potting soil alone. Visual examination of iHSD-processed seeds and chaff before planting in potting soil found only broken seed pieces and no intact seeds for all three species. These results indicated that iHSD efficacy is similar and very high across the studied weed species despite differences in seed density and weight for the three species (Figure 3). Previous research demonstrated that the impact mills are highly effective (>88% control) across several weed species and different chaff types (Walsh et al. 2017b). Impact mill efficacy can be affected by the mill speed, crop chaff type, chaff feeding rate, weed-seed number, and density. Despite the significant effect of those factors on seed destruction, observed average destruction percentages are greater than 85% (Schwartz-Lazaro et al. 2017; Tidemann et al. 2017a; Walsh et al. 2018a). Using a similar stationary prototype, Tidemann et al. (2017a) reported that

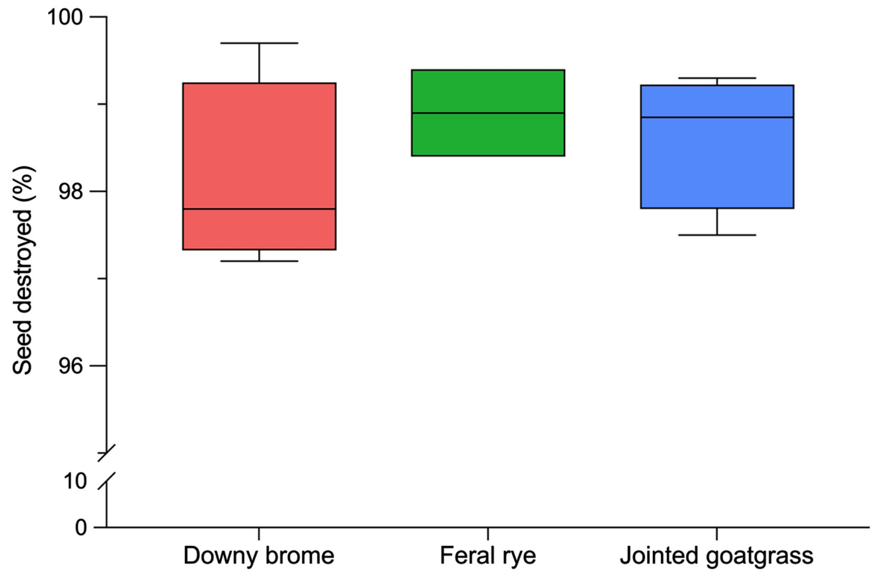

Figure 3. Box plot describing the percentage of seed destroyed by the integrated Harrington Seed Destructor for downy brome, feral rye, and jointed goatgrass, as measured by reduction in seedling emergence compared with untreated controls (see Equation 2).

weed seed destruction only decreased from 99% to 98.5% when the chaff volume was doubled. In addition, they showed a chaff-type effect where barley (*Hordeum vulgare* L.) and pea (*Pisum sativum* L.) had greater than 98.5% weed-seed destruction, whereas canola chaff had a 5% reduction in efficacy; however, iHSD field trials in canola and barley crops showed no difference in seed destruction among several weed species (Walsh et al. 2018a).

Proactive HWSC implementation in current weed-management practices in the central Great Plains is key to maintain POST herbicide efficacy on downy brome, feral rye, and jointed goatgrass in winter wheat production systems. POST herbicides are at a high risk for resistance evolution due to their frequent use in these cropping systems. Currently, no cases of herbicide resistance in Colorado have been reported for downy brome, feral rye, or jointed goatgrass (Heap 2019); however, downy brome and jointed goatgrass imazamox resistance cases were reported in Montana and Washington, respectively (Kumar and Jha 2017; Mallory-Smith et al. 2018). A modelling study considering an integrated management approach (e.g., PRE, POST, and HWSC) indicated the frequency of resistance alleles could be eliminated or greatly reduced in weed populations and that weed density decreased to two plants m^{-2} (Somerville et al. 2018). Similar to herbicides, repetitive use of HWSC would increase natural selection pressure for escape traits such as early flowering, lodging, shattering, or shorter winter annual grass weed biotypes. Greenhouse experiments described that after five recurrent selection generations for early flowering, 77% of a wild radish (*Raphanus raphanistrum* L.) population flowered 30 d earlier than a nonselected population (Ashworth et al. 2016).

Our field studies investigating the potential for HWSC to be implemented in the central Great Plains wheat fields found that this practice could provide an important new tool for IWM practices. Downy brome, feral rye, and jointed goatgrass are troublesome winter annual grasses that affect winter wheat production. Harvest weed-seed control techniques are effective if the weed species has a high proportion of total seed production retained at crop maturity. Weed species with similar or taller plant height have higher weed-seed collection during harvest. On the basis of our results, HWSC can potentially reduce seedbank inputs for downy brome, feral rye, and jointed goatgrass, with higher potential for feral rye than for downy brome and jointed goatgrass. Our findings suggest HWSC methods could strengthen IWM practices in winter wheat fields to reduce winter annual grass interference.

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