Efficacy of the Integrated Harrington Seed Destructor on Weeds of Soybean and Rice Production Systems in the Southern United States

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ABSTRACT

Herbicide-resistant weeds affect every major cropping system today. Worldwide, there are 47 and 51 confirmed cases of herbicide-resistant weed populations in soybean [*Glycine max* (L.) Merr.] and rice (*Oryza sativa* L.) production systems, respectively. Alternatives to herbicides are necessary to help combat herbicide-resistant weeds. The integrated Harrington Seed Destructor (iHSD) has been developed to destroy weed seeds during crop harvest but has yet to be tested on weeds in soybean or rice. Thus, the objective of this research was to determine the effectiveness of the iHSD in soybean and rice and to evaluate any limitations. Three experiments were conducted using a stationary iHSD mill. First, the efficacy of the iHSD was evaluated on weed seeds incorporated into soybean residue or rice chaff. Second, varying soybean chaff feeding rates were tested to determine the amount that could be processed without interfering with weed seed destruction. Third, varying soybean chaff moisture levels were tested to determine any limitations that high moisture content may have on the iHSD. The iHSD demonstrated high weed seed destruction efficacy (<1% survival) for 11 of the 12 weed species of soybean. Common cocklebur (*Xanthium strumarium* L.) seed had 3% survival. In rice, <1% survival was observed in all weed species. The soybean feeding rate and moisture experiments yielded <1% survival across all treatments. These results show that the use of the iHSD can be highly effective in soybean and rice production for reducing inputs to the soil seedbank. These studies highlight the promising seed destruction potential of the iHSD but also demonstrate opportunities for further research evaluating the iHSD as a combine-fitted system operating under commercial scale production fields.

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Abbreviations: BMP, best management practice; HSD, Harrington Seed Destructor; HWSC, harvest-time weed seed control; iHSD, integrated Harrington Seed Destructor.

HERBICIDE resistance is a major constraint to crop production worldwide. Currently, there are 477 unique cases of herbicide-resistant weed species confirmed (Heap, 2017), and many of these biotypes have emerged to dominate agricultural production systems. Similar to other locations, herbicide–resistant weeds have become prevalent in southern US soybean [*Glycine max* (L.) Merr.] and rice (*Oryza sativa* L.) production systems (Riar et al., 2013; Heap, 2017). There is a high frequency of herbicide resistance in the weed species infesting both these production systems. Weeds that escape control, whether resistant or not, are likely to be mature at the time of crop harvest, and the erect seed heads will likely enter the combine harvester (Walsh et al., 2013; Schwartz et al., 2016b). Harvested weed seeds are mostly expelled from the rear of the combine harvester, resulting in their dispersal across the field as additions to the soil seedbank, a process that increases the risk of herbicide resistance evolution.

With no new herbicide sites of action likely to be commercially available in the next 5 to 10 yr (Duke, 2012), it is critical that weed management be focused on ensuring the future use of the currently effective herbicides. Emphasis must be placed on reducing the soil seedbank using diversified tactics (Bagavathiannan

and Norsworthy, 2012; Norsworthy et al., 2012). The soil seedbank allows for long-term persistence of weed species in agricultural fields (Forcella et al., 1992; Cardina et al., 2002). Weed communities present in a given soil seedbank are influenced by production practices and environmental conditions (Schwartz et al., 2015). Some weed species can persist in the soil seedbank for extended periods. For example, morninngglories (*Ipomoea* spp.), a large-seeded weed species, can persist in the soil seedbank for at least 39 yr (Toole and Brown, 1946). Hartzler (1996) found that 25% of the velvetleaf (*Abutilon theophrasti* Medik.) seed introduced into the soil produced seedlings over the following four growing seasons with maximum emergence of 11% occurring during the second year. Emergence in the fourth year declined to 2% of the original seedbank. Burnside et al. (1996) found that tall waterhemp (*Amaranthus tuberculatus* Moq.), a small-seeded species, germinated after 17 yr in the soil seedbank. Historically, management strategies have focused on short-term reduction of the most troublesome weeds in a field based on annual economic thresholds, without a specific focus on the long-term ramifications of soil seedbank management (Norsworthy et al., 2012; Vencill et al., 2012). Restricting weed seedbank inputs has a large impact on the population densities and therefore management of these species in soybean and rice production systems. Weed management strategies that incorporate best management practices (BMPs) to reduce the risk of herbicide-resistant weeds evolving should include cultural, mechanical, and chemical options that will prevent an influx of weed seed into the soil seedbank (Norsworthy et al., 2014; Gibson et al., 2016). Thus, a multifaceted, long-term management approach is needed for effectively targeting the soil seedbank.

Alternatives to herbicides are necessary to help combat herbicide-resistant weeds and ensure the sustainability of cropping systems. Harvest-time weed seed control (HWSC) tactics incorporate mechanical and cultural management strategies to target weed seeds present at harvest (Walsh and Powles, 2007). There are three main HWSC options: narrow-windrow burning, chaff removal (using chaff carts), and mechanical seed destruction (e.g., Harrington Seed Destructor [HSD]) (Walsh and Newman, 2007; Walsh et al., 2013; Schwartz et al., 2016a). Narrow-windrow burning has been shown to reduce Palmer amaranth [*Amaranthus palmeri* (S.) Wats.] soil seedbank when used alone but is much more effective when used in conjunction with an efficacious herbicide program with soil residual activity (Norsworthy et al., 2016). In soybean, narrow-windrow burning reduced subsequent Palmer amaranth plant density by 73% and the soil seedbank by 62% over a period of 3 yr (Norsworthy et al., 2016). The HSD, a tow-behind-the-combine unit for destroying weed seed, has been rigorously tested in Australia with great success. Walsh et al. (2012) found that

the HSD destroyed 99 ± 0.1, 99 ± 0.1, 95 ± 0.8, and 93 ± 2.6% of wild oat (*Avena fatua* L.), brome grass (*Bromus* spp.), rigid ryegrass (*Lolium rigidum* Gaudin), and wild radish (*Raphanus raphanistrum* L.) seed, respectively. An integrated HSD system (iHSD) has been recently developed by de Bruin Engineering using a mill that has been designed to fit within the rear of the combine (Lee, 2012).

The iHSD mill has never been tested on weeds common to the soybean or rice production systems in the southern United States. Thus, the objective was to determine the effectiveness of the iHSD mill on major weeds of these systems and to assess the impact of chaff volume and moisture content on this efficacy. Three experiments were conducted using a stationary iHSD mill. First, the efficacy was evaluated on weed seeds individually incorporated into a known amount of soybean residue (chaff and straw) or rice chaff. Second, varying soybean chaff feeding rates were tested to determine the amount that could be effectively processed by the iHSD mill. Third, varying soybean chaff moisture levels were tested to determine any limitations that high moisture content may cause on the ability of the iHSD mill to process the chaff material. Twelve weed species in soybean and seven in rice were tested in the first objective, whereas the second and third objectives only tested Palmer amaranth and morningglory.

MATERIALS AND METHODS
Chaff Collection

Chaff and straw material was collected from a commercial soybean production field at the Northeast Research and Extension Center at Keiser, AK, in October 2016. The collected harvest residues were placed under a covered shelter until being used for testing. It was decided to use both the chaff and straw fractions for soybean because it is unknown at this time whether the chaff alone or both fractions will be processed in a commercial iHSD, although the chaff fraction will most likely be targeted. If the iHSD mill is effective on both fractions, there will also be high efficacy when only the chaff fraction is processed. Rice chaff was collected during the harvest of a rice crop at the Rice Research and Extension Center near Stuttgart, AK. The chaff was obtained by attaching a tarp to the rear of the combine, underneath the top sieve, to collect only the chaff fraction.

The amount of soybean and rice chaff sample size (Fig. 1) was weighed prior to processing based on harvest index, and the commercial operational capacity of a Class 9 combine during soybean and rice harvest crops in the midsouthern United States. It was assumed that the operational capacity of this combine would be 13,636 kg h^{-1} (30,000 lbs or 500 bu h^{-1}), which with a harvest index of 55% would produce 11,157 kg h^{-1} of chaff and straw residues. Thus, equivalent to a Class 9 combine, soybean chaff and straw was fed into the iHSD mill at a rate of 1.5 kg s^{-1} (4.4 lbs s^{-1}). On a commercial combine, two iHSD mills would be responsible for processing the chaff exiting the combine. However, for the stationary iHSD tested in this study, only a single cage mill was evaluated; hence, only 50% of the residue sample size was used in testing.
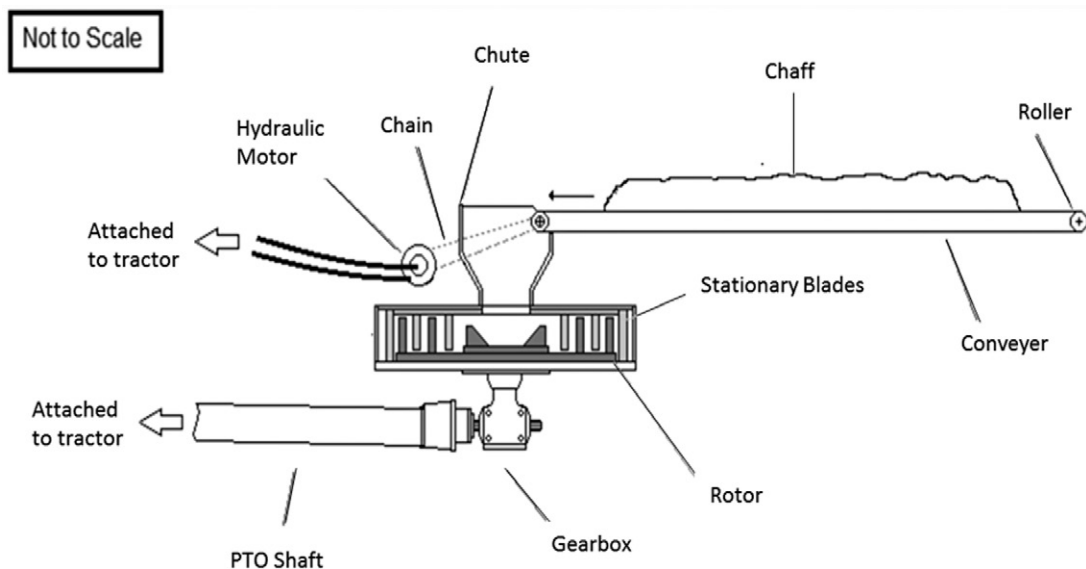
Fig. 1. Schematic of the integrated Harrington Seed Destructor (iHSD) as a stationary unit. The chaff material enters on the 2-m roller feeds into the chute and exits out of an opening. The entire iHSD unit is connected to the hydraulic system of a tractor. PTO, power takeoff.

Similarly, the amount of rice chaff that would be produced by a commercial harvester was determined by assuming that the harvester can cover 33 ha in 10 h, with ~29.3 t of plant material processed in an hour. Furthermore, with a harvest index of 52%, ~15 t of chaff is exiting in an hour. The feeding rate on the iHSD was adjusted to provide the required chaff delivery rate of 2.13 kg s^{-1}. A representative 1-kg sample size was used on the iHSD conveyer belt, and the feeding rate was adjusted to provide the required chaff delivery rate into the mill.

Weed Species Used

Seeds of prominent weed species in both soybean and rice production in the midsouthern United States were selected. In the weed species experiment, 12 weed species were processed in soybean residues: Palmer amaranth, morningglory species (mixture of pitted morningglory [*Ipomoea lacunosa* L.] and entireleaf morningglory [*Ipomoea hederacea* Jacq.]), common cocklebur (*Xanthium strumarium* L.), johnsongrass [*Sorghum halepense* (L.) Pers.], barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh], prickly sida (*Sida spinosa* L.), velvetleaf, sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby], giant ragweed (*Ambrosia trifida* L.), common lambsquarters (*Chenopodium album* L.), and weedy rice (*O. sativa*). The weed species tested in rice were barnyardgrass, weedy rice, hemp sesbania, rice flatsedge (*Cyperus iria* L.), Nealley's sprangletop (*Leptochloa nealleyi* Vasey), waterhemp, and johnsongrass. Waterhemp and johnsongrass were included among rice weeds due to their occurrence on rice levees. Only Palmer amaranth and morningglory were used in the feeding rate and chaff moisture experiments. A sample size of 500 seeds per treatment was used for all seed except for common cocklebur, for which only 200 burs (two seeds per bur) were included per sample. All weed seeds were collected or purchased in 2015 or 2016. Each experiment had four (rice) or eight (soybean) replications.

Experimental Setup with iHSD

Three experiments were conducted with the iHSD mill using soybean harvest residues to evaluate the impact of (1) weed species, (2) residue feeding rate, and (3) chaff moisture on the efficacy of weed seed destruction. For the rice chaff, only the different weed species were compared (Exp. 1 mentioned above) while maintaining the feeding rate and chaff moisture at constant levels that represent typical harvest conditions. Only Palmer amaranth and morningglory were selected for the feeding rate and chaff moisture experiments, because they represent two of the dominant weeds in soybean and selected for a small- and large-seeded broadleaf species. The weed species evaluation experiment used all harvest residues of soybean (straw and chaff), but only the chaff residue for rice. However, the feeding rate and chaff moisture experiments used only the soybean chaff fraction. The chaff only fraction was created by taking the previously collected soybean residue and sieving the material so that the larger straw material was removed. For each treatment, chaff samples were weighed prior to processing with the iHSD mill. Weed seeds were added to the chaff lying on a 2-m conveyer belt that delivered the chaff into the mill at the required feed rate. The mill speed on the iHSD was set at 3000 rpm and verified using a digital tachometer.

Six soybean residue feeding rates (0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 kg s^{-1}) were evaluated to determine the impact of the amount of material being processed by the iHSD mill on the seed destruction efficiency of Palmer amaranth and morningglory. These feeding rates represent 0.3, 0.7, 1, 1.3, 1.7, and 2 times the standard feeding rate of 1.5 kg s^{-1}. The residues stored after the initial moisture content estimation were sieved to separate the chaff fraction, which was subsequently dried at 55°C for 48 h. Dried chaff was weighed and placed in plastic trash bags. The five chaff moisture levels (8, 12, 16, 20, or 24% w/w) were established by adding the required amount of water to each sample. The moistened chaff samples were sealed within plastic bags and incubated for 12 h to ensure even wetting throughout the chaff material. All samples were run in a randomized order within a given experiment.

Estimations of Weed Seed Germination

The processed material was brought to the Weed Science laboratory at the University of Arkansas, Fayetteville, where all but one (three for rice and seven for soybean) replicate were hand sieved to remove large debris while keeping all weed seeds within the processed material. Prior to the estimation of weed seed destruction in the samples, preliminary experiments were conducted to standardize a seed germination methodology. To account for any influence of processed harvest residue on weed seed germination and emergence, a preliminary experiment was conducted to determine the most suitable mixture of residue and potting soil for maximum weed seedling emergence. Processed soybean and rice chaff with 500 germinable Palmer amaranth, morningglory, and barnyardgrass seeds were sown in five (3:1, 2:1, 1:1, 1:2, 1:3 v/v) ratios of chaff to potting mix, with four replications. Since there were no significant differences in emergence among the 2:1, 1:1, 1:2, and 1:3 chaff/potting mix ratios (data not shown), a 1:1 ratio was chosen for weed seed viability testing.

Each sample was mixed at 1:1 chaff/potting mix and placed in 40-cm × 51.4-cm greenhouse trays (F1721 Tray, T.O. Plastics). Every 7 d, emerged seedlings were counted and removed. The trays were watered twice daily and the samples were stirred to promote seedling emergence after each count. The authors note that such disturbance could potentially kill germinating seeds or young seedlings that were yet to emerge. This could account for an overestimation of the treatment effects. The flats remained in the greenhouse until no further emergence was observed for five consecutive days. Additionally, the presence of any weed seed in the original harvest residues material used was tested by planting unprocessed material separately in a 1:1 chaff/potting soil mix ratio.

The final replicate samples were used to verify the accuracy of the emergence assessments. The processed samples were manually sorted, with any recovered weed seed placed in a Petri dish on moistened filter paper. The Petri dishes were placed into an incubation chamber for 2 wk at 30°C with 12-h days and 75% humidity. The number of seeds that produced radicles was determined to be viable. The seeds that failed to germinate were squeezed with forceps to determine if they were dormant or not (i.e., hard seeds were dormant and soft were considered to be dead).

Statistical Analysis

The number of emerged seedlings was recorded and presented as a percentage of the unprocessed control (seeds that were not processed by the iHSD mill) seed samples to estimate seed mortality caused by the iHSD. Each experiment was analyzed individually for each factor (weed species, feeding rate, chaff moisture level) using one-way ANOVA, with mean separations based on Fisher's LSD values ($\alpha = 0.05$). Statistical tests were conducted using SAS 9.1 (SAS Institute, 2003).

RESULTS AND DISCUSSION

The iHSD mill was found to be highly effective in destroying seed of weed species commonly occurring in soybean and rice production systems of the midsouthern United States. The various weed species tested in both cropping systems ranged in seed size, weight, and density (Table 1) and included both broadleaf and grass species that

Table 1. Efficacy of the integrated Harrington Seed Destructor (iHSD) on various weed species. The mean ± SE seed weight and density of each weed species was conducted on unprocessed seeds. The percent (± SE) of destroyed seeds was corrected for by the control.

Weed species	Soybean		Rice		Seed size†	Seed weight	Density
	Control	Treatment	Control	Treatment			
	% emergence‡	% destroyed§	% emergence	% destroyed	mm	g	g cm⁻³
Barnyardgrass	85.7 ± 5	99.8 ± 1	85.7 ± 5	99.3 ± 1	1.57 ± 0.04	0.18 ± 0.04D¶	0.26 ± 0.02D
Common cocklebur	87.5 ± 5	97.5 ± 2	–#	–	7.58 ± 2.03	14.70 ± 3.20A	0.21 ± 0.02D
Giant ragweed	68.9 ± 6	100 ± 0	–	–	2.07 ± 0.51	0.22 ± 0.01D	0.08 ± 0.01E
Hemp sesbania	96.0 ± 3	100 ± 0	96.0 ± 3	99.2 ± 1	2.21 ± 0.38	1.61 ± 0.04B	0.56 ± 0.06C
Johnsongrass††	88.4 ± 5	99.9 ± 0	22.0 ± 8	100 ± 0	1.79 ± 0.05	0.58 ± 0.06C	0.72 ± 0.04B
Common lambsquarters	90.6 ± 4	100 ± 0	–	–	1.17 ± 0.08	0.08 ± 0E	0.80 ± 0.06B
Morningglory	87.4 ± 5	100 ± 0	–	–	3.79 ± 1.14	2.80 ± 0.75B	1.39 ± 0.09A
Nealley's sprangletop	–	–	62.0 ± 6	100 ± 0	0.49 ± 0.03	0.01 ± 0E	0.30 ± 0.04D
Palmer amaranth	98.1 ± 2	100 ± 0	–	–	1.01 ± 0.07	0.04 ± 0E	0.53 ± 0.08C
Prickly sida	70.0 ± 6	100 ± 0	–	–	1.82 ± 0.08	0.14 ± 0.02D	0.28 ± 0.03D
Weedy rice	72.4 ± 6	100 ± 0	72.4 ± 6	100 ± 0	2.21 ± 1.03	1.27 ± 0.08B	0.49 ± 0.04C
Rice flatsedge	–	–	51.0 ± 7	100 ± 0	0.63 ± 0.03	0.01 ± 0E	0.33 ± 0.03C
Sickelpod	82.1 ± 5	99.9 ± 0	–	–	2.54 ± 0.09	1.73 ± 0.06B	0.47 ± 0.04C
Velvetleaf	90.6 ± 4	100 ± 0	–	–	2.94 ± 1.24	0.84 ± 0.07C	0.89 ± 0.06B
Waterhemp††	–	–	11.0 ± 8	98.4 ± 1	0.91 ± 0.67	0.03 ± 0E	0.55 ± 0.05C

† Average seed width measured with Vernier calipers.

‡ Nonprocessed seed grown in a 1:1 v/v mixture of potting mix to soybean chaff.

§ Percentage destroyed is corrected relative to the percentage emergence that occurred in the control (nonprocessed) samples. *P* = nonsignificant.

¶ Means within columns followed by different letters are significantly different based on Tukey's mean separation procedure ($\alpha = 0.05$).

\# Dashes indicate that the weed was not processed in that crop.

†† Indicates weeds that would be found on a rice levee.

are commonly found in the midsouthern United States. The iHSD mill effectively destroyed large-seeded weed species, such as morningglory and cocklebur, as well as small-seeded species such as Palmer amaranth in soybean. Common cocklebur showed 97.5% germination reduction in soybean chaff. Furthermore, this species had the greatest seed weight and the lowest density of all species (Table 1). The low density and the light weight of common cocklebur appeared to allow the seeds to make it through the mill more readily than other weed species. Weed seed destruction ranged from 97.5 to 100% and 99.2 to 100% in soybean and rice, respectively. Nealley's sprangletop, which has one of the smallest seeds in rice production (seed size: 0.46 mm), was 100% destroyed with the iHSD mill (Table 1). Thus, we conclude that the efficacy of the iHSD mill is not limited by seed size, whether small or large. Furthermore, no significant differences in seed mortality among weed species were found, regardless of chaff type. This is significant for weeds that are prominent in multiple cropping systems.

There was no reduction ($P > 0.05$) in the mortality of Palmer amaranth or morningglory seed by the iHSD mill with increasing soybean residue feeding rates (Fig. 2). Weed seed destruction levels remained high across all six soybean residue feeding rates for both of these species. Thus, it was evident that even when high levels of harvest residues were processed, the efficacy of the iHSD mill was not affected. Additionally, chaff moisture levels also did not affect the destruction potential of the iHSD mill for Palmer amaranth and morningglory species. All moisture treatments showed 99.4% or greater destruction of the weed species tested in this study. At moisture contents of 16% or higher, the mill required cleaning after each sample was processed. During commercial operations of the iHSD mill at chaff moisture contents of 16% or higher, it would be likely that the efficacy would decline or the equipment would cease to function properly as a result of clogging.

The manual collection and Petri dish germination of weed seeds produced similar results on germination reduction as the soybean (Fig. 3) and rice chaff (data

not shown) samples. In soybean, common cocklebur germination was reduced by 98.8% and Palmer amaranth by 100%. Palmer amaranth is known to produce an average of $60,221 \pm 21,991$ seeds plant^{-1} in soybean production (Schwartz et al., 2016b), and other studies have shown Palmer amaranth to produce upward of 600,000 seeds
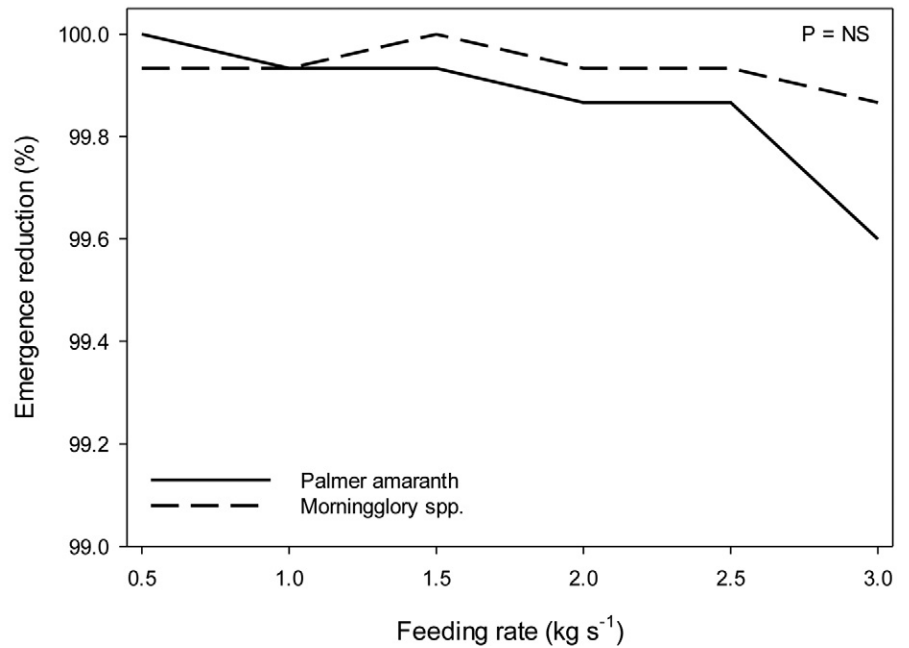
Fig. 2. Emergence reduction (%) of Palmer amaranth and morningglory species after being processed across various soybean residue feeding rates in the integrated Harrington Seed Destructor (iHSD). All values have been corrected for from the control. NS, nonsignificant.
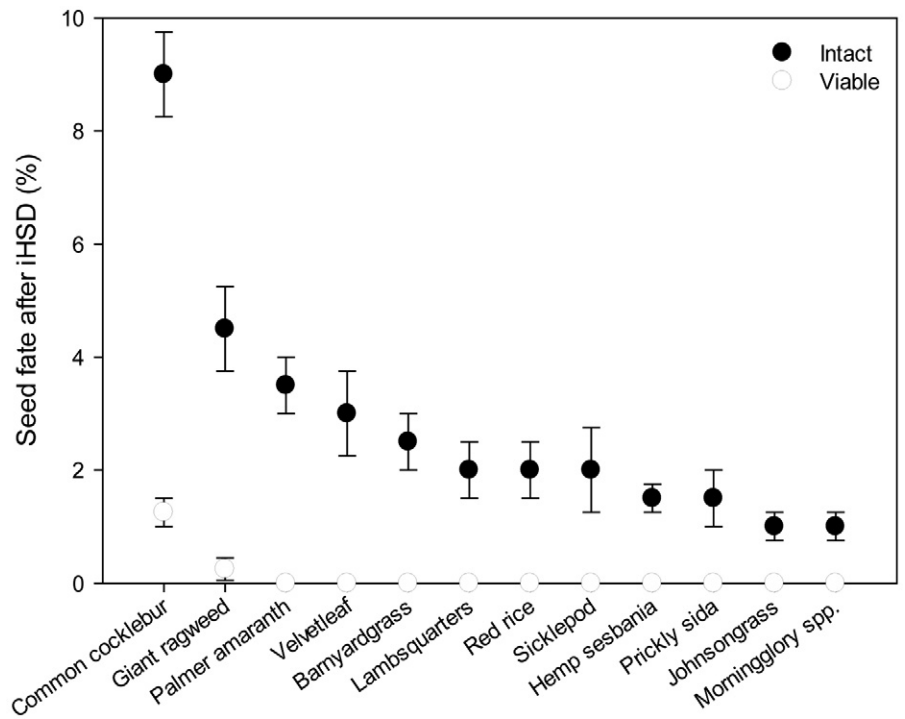
Fig. 3. Petri dish evaluation of the soybean chaff. Intact seeds are considered whole seeds after processing. These seeds may be cracked or have missing fragments from the seed coat, but they were>75% whole. iHSD, integrated Harrington Seed Destructor.

plant^{-1} in the absence of interference (Keeley et al., 1987). Goplen et al. (2016) showed that giant ragweed retained 80% of its seed at the time of soybean harvest, meaning that its addition to the soil seedbank could be substantially reduced through use of the iHSD. Additional weed species have been examined for seed retention at harvest in other cropping systems. For example, Walsh and Powles (2014) found that rigid ryegrass, wild radish, brome grass, and wild oat retained 85, 99, 77, and 84% of seed, respectively, at wheat maturity in Australia. Furthermore, in field pea (*Pisum sativum* L.) and spring wheat (*Triticum aestivum* L.), four weed species in Canada—wild oat, cleavers (*Galium* spp.), wild mustard (*Sinapis arvensis* L.), and green foxtail (*Setaria viridis* (L.) Beauv)—did not differ in seed retention between crop but did differ by weed species. All of the weed species had >70% seed retention at the time of harvest (Burton et al., 2016). Thus, one escaped weed can still cause significant soil seedbank inputs, requiring control in subsequent years. Although there will be some weed seeds that will not be collected during harvest, the high rate of seed destruction indicates its potential across a wide assortment of seed sizes and species.

Further research is needed to test the iHSD mounted in a combine across various cropping systems and environments. Additionally, weed adaptations to the iHSD on various weed species needs to be further examined. Ashworth et al. (2016) showed under a greenhouse setting that wild radish began to flower earlier in just five generations when subjected to selection. This shows the potential evolution of phenological traits that weed species could select for under repeated use of the iHSD. Thus, incorporating other management tactics is critical in sustaining the utility of this system.

CONCLUSIONS

The iHSD is a new weed control tool that has great potential for utility in various cropping systems and has the potential to improve weed management within these systems. The effectiveness of the iHSD mill allows for a high proportion of weed seeds to be destroyed at harvest, which subsequently will help to lower the seedbank. Preventing inputs into the soil seedbank is critical for long-term weed management (Davis, 2008; Walsh et al., 2012). The iHSD has shown to be highly effective in Australian wheat cropping systems, and this experiment using the stationary unit has shown insight to the utility of the iHSD in soybean and rice cropping systems of the southern United States. Further research needs to be conducted in these systems from a production standpoint to determine the threshold of the fully iHSD system in terms of chaff moisture and the capacity of chaff that can be processed.

Conflict of Interest

The authors declare that there is no conflict of interest.

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