Harrington Seed Destructor: A New Nonchemical Weed Control Tool for Global Grain Crops

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ABSTRACT

Global grain production is under threat from the escalating evolution of herbicide-resistant weed populations. Worldwide, herbicide-reliant grain crop production systems have driven the proliferation of herbicide resistant populations of major weed species. Alternatives or adjuncts to herbicides are needed for sustainable control of crop weeds in grain crops worldwide. Here we introduce and prove the ability of a new weed control tool, the Harrington Seed Destructor (HSD), to intercept and destroy weed seeds during grain crop harvest. The interception and destruction of weed seeds exiting the grain harvester in the chaff fraction during grain crop harvest is a hitherto unrealized opportunity. We have developed a cage mill-based chaff processing unit that consistently destroys weed seed infesting grain crop chaff fractions. The subsequent construction of the HSD incorporating this unit had >95% weed seed destruction efficacy when used during commercial harvest of three major grain crops, wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and lupin (*Lupinus angustifolius* L.). The HSD system has the potential for a dramatic impact on global grain production by providing the unique combination of effective weed control with complete retention of grain crop harvest residues. Only herbicides offer this same combination of highly effective weed control and complete residue retention in large scale grain crop production systems.

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Abbreviations: HSD, Harrington Seed Destructor; HWSC, harvest weed seed control; rpm, revolutions per minute.

Every year about a quarter of the world's food needs are delivered by the global grain crops wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), soybean [*Glycine max* (L.) Merr.], maize (*Zea mays* L.), and canola (*Brassica napus* L.) (FAOSTAT, 2010). Global food security is dependant on the sustained productivity of these crops. While there are many constraints to the productivity of grain crops, infestation by wild plant species (weeds) is an annual challenge. In industrialized and increasingly in developing nations, control of crop-infesting weeds is achieved with herbicides. Herbicides effectively remove crop weeds, minimizing their damaging effects on food production and thereby underpinning global food security. Additionally, herbicide technology has facilitated and driven the worldwide adoption of the sustainable and highly productive conservation cropping systems based on minimal soil disturbance and maximum crop residue retention (Beckie et al., 2008; D'Emden et al., 2008; Thomas et al., 2007). The adoption of conservation cropping systems dramatically increased following the introduction of herbicide-tolerant crops but so too did the reliance on herbicidal weed control (Christoffoleti et al., 2008; Johnson et al., 2009; Kumar et al., 2008; Powles and Shaner, 2001). This herbicide dependence is resulting in the global evolution of herbicide resistance in important weeds of grain crops. Herbicide resistance evolution now threatens global grain productivity in the five major grain exporting nations:

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the United States, Brazil, Argentina, Canada, and Australia (Beckie et al., 2008; Christoffoleti et al., 2008; Heap, 2011; Owen et al., 2007; Powles and Shaner, 2001; Scott et al., 2009; Walsh et al., 2007; Webster, 2005).

The continuing evolution of herbicide resistance in major crop weeds is a driving force necessitating new technologies for weed control in field crops. Here, we introduce a new nonchemical tool and strategy for weed control in global grain crops. The great majority of crop weeds are annuals that rely on annual seed production for long-term persistence. Crop and weed seed maturation in many species is synchronized and, therefore, at grain harvest both weed and crop seed are collected by the harvester. Modern grain harvesters are efficient at sorting weed seed from crop grain, with the weed seeds returned to the field, primarily in the chaff fraction (Balsari et al., 1994; Petzold, 1955; Walsh and Powles, 2007). For example, the globally important weed of grain crops, annual ryegrass (*Lolium rigidum* Gaudin), retains most seed heads intact and attached to the plant at the same height as the crop seed heads at grain harvest. Some 95% of ryegrass seeds pass intact through the grain harvester to be returned to the crop field in the chaff fraction, therefore perpetuating an ongoing weed problem (Walsh and Powles, 2007). As grain harvesters capture and sort weed seeds we propose that the grain harvesting process presents an excellent opportunity to intercept and destroy weed seeds (Walsh and Powles, 2007). We define practices that target weed seed at grain harvest as "harvest weed seed control" (HWSC). The HWSC systems currently in use, at least in Australia, are chaff carts, direct harvest residue baling, and narrow windrow burning (Walsh and Powles, 2007). We describe a new mechanical system in which weed seeds are captured and destroyed during grain harvest. The device, termed the Harrington Seed Destructor (HSD), is attached to grain harvesters as a trailer-mounted system incorporating a high capacity cage mill to process chaff residue sufficiently to destroy weed seeds. Moreover, we report the potential of the cage mill to destroy infesting weed seeds present in chaff material and quantify the weed seed destruction efficacy of the HSD system during commercial grain crop harvesting.

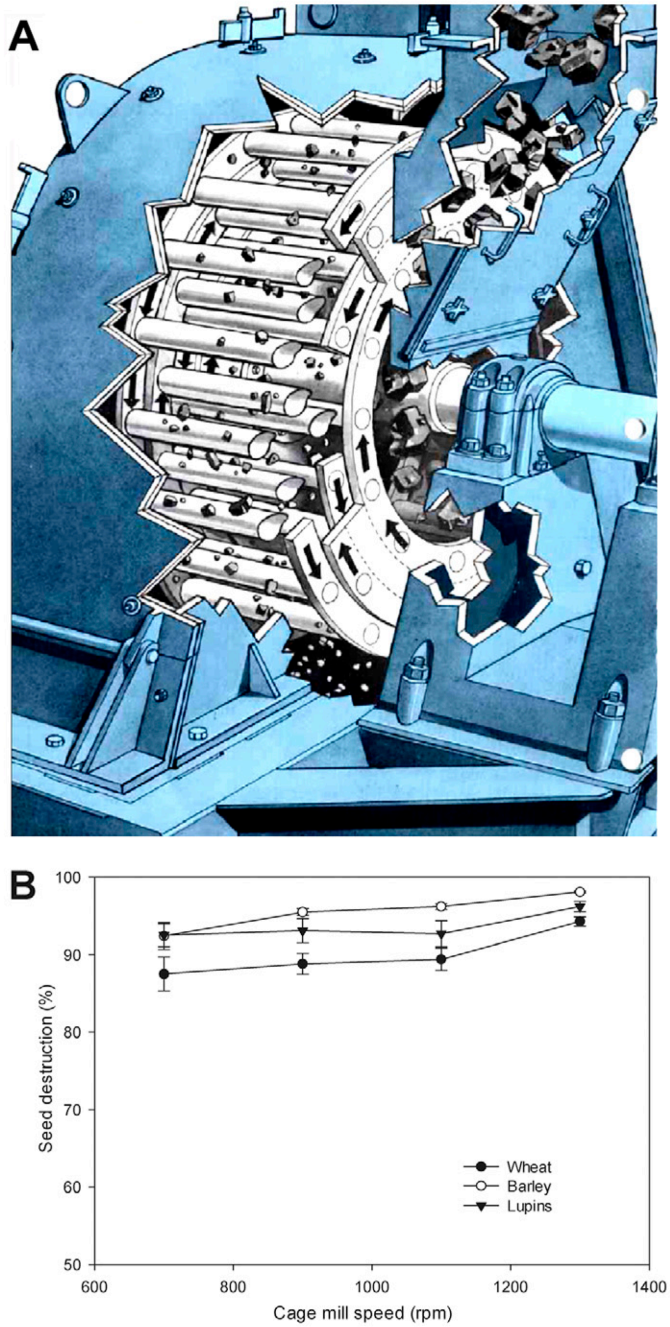

Figure 1. (A) Schematic view of a cage mill showing material entry (from Stedman, 1995) and (B) effect of cage mill speed on the destruction of ryegrass seed present in wheat, barley, and lupin chaff. rpm, revolutions per minute.

MATERIALS AND METHODS

Cage Mill Capacity to Destroy Weed Seeds in Chaff Fraction

Commercially available ryegrass seed was used in testing the stationary cage mill and in subsequent field testing of the HSD system. Seed of prominent weed species wild radish (*Raphanus raphanistrum* L.), wild oats (*Avena* spp.) and brome grass (*Bromus* spp.) were collected (in 2007) from field-grown populations (29°11.35′ S, 115°26.53′ E) within the Australian grain belt. Before each experiment, seed viability was determined by placing seed on 1% (w/v) water based agar in petri dishes and incubating for 14 d at 25/15°C day/night temperatures with a 12 h photoperiod. After this period, ryegrass seeds were classified as viable if they had germinated or remained firm and not decayed. To assist with their recovery from processed chaff material, weed seeds were stained by soaking for 30 min in a 10% solution of blue food dye. This staining procedure did not affect seed viability.

The cage mill is a high impact crushing device with counter-rotating cages in which material is introduced via a feed chute directly into the center of the innermost rotating cage (Gundlach Equipment Corporation; Pennsylvania Crusher, 2003) (Fig. 1a). Cage mills are typically used for heavy duty processing in several mining industries (Rodriguez et al., 2010). The cage mill evaluated in this study consists of two counter-rotating cages each consisting of four rings of standard low-carbon 16-mm diameter steel bars. The cages are approximately 1 m in diameter at their

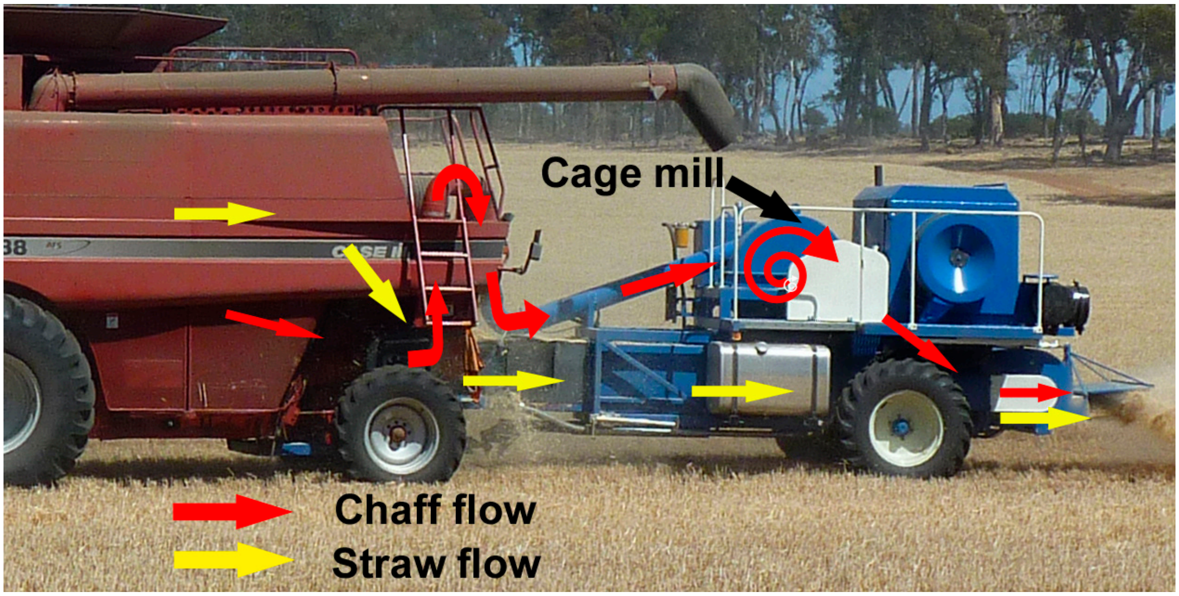

Figure 2. Schematic of Harrington seed destructor and harvester depicting chaff and straw transfer and the cage mill processing unit

outermost ring and have an overall depth of 200 mm. The alternating rows of bars are separated by a 10 mm space. First, the cage mill, as a stand-alone unit, was assessed for its efficacy in destroying ryegrass seed present in crop chaff fractions. The cage mill was evaluated at operating speeds of 700, 900, 1100, and 1300 revolutions per minute (rpm) with 50-L chaff samples containing 1000 stained ryegrass seeds introduced into the mill within a 4 s time period. The processed material was manually and carefully sieved to quantify ryegrass seed and seed fragments surviving passage through the cage mill. The viability of intact seed and seed fragments was assessed using the procedures described above.

Harrington Seed Destructor System Capacity to Destroy Weed Seeds during Harvest

The HSD system is based around the cage mill as the chaff processing unit operating at 1450 rpm (Fig. 2). A pneumatic chaff delivery system, incorporating a cross auger and blower fan, collects and delivers crop chaff material exiting the rear of the grain harvester into the center of the cage mill. Separately, a conveyor belt moves the crop straw material from the rear of the grain harvester beneath the cage mill and motor to a spreader dispersal system at the rear of the HSD unit. The chaff processing and straw and chaff delivery systems are all powered by a dedicated 120 kW (160 horsepower) motor. The HSD system, attached to a 2388 Case International grain harvester (Fig. 2), was evaluated in a wheat crop under commercial harvest conditions (in 2008) (30°53.53′ S, 116°43.01′ E). Stained seed lots of ryegrass (20,000), wild radish (10,000), wild oat (2000), and brome grass (3000) were introduced into the front of the harvester at a uniform rate during the harvest of 20 m length plots. This was conducted four times for each of the four weed species. In each plot, processed chaff samples were collected at the cage mill outlet chute of the HSD. During harvest of the control plots (no HSD treatment) all four weed species were introduced into the front of the harvester and unprocessed chaff was collected from the chaff transfer chute. Weed seeds were subsequently recovered from collected chaff samples and their viability tested using the procedures described above.

To evaluate the HSD efficacy in different crops, field studies were conducted in commercial wheat, barley (*Hordeum vulgare* L.), and lupin (*Lupinus angustifolius* L.) crops (33°20.323′ S, 116°44.44′ E). Dyed lots of ryegrass seed (10,000) were introduced at a uniform rate into the HSD chaff stream during the harvest of wheat, barley, and lupin plots. To vary chaff quantity, four plot widths of 3, 5, 7, and 9 m were used with a constant harvester speed maintained throughout. ryegrass seed collected from the processed chaff material was tested for viability as described previously.

Data Analysis

The number of germinable seeds recovered was recorded and presented as a percentage of the unprocessed control seed lots. One-way ANOVA was conducted on the weed seed destruction data from the 2008 field evaluation of the HSD system. Two-way ANOVA was conducted on annual ryegrass seed destruction data from cage mill testing (speed and chaff type) and 2009 HSD system capacity testing (chaff volume and crop type). With no differences ($p > 0.05$) detected mean standard error values are presented with treatment means.

All data were analyzed using one- (weed species) or two-way (chaff type and mill speed) ANOVA, as appropriate, with significant differences between means determined by an LSD test with a selected α of 0.05. Statistical tests were conducted with SAS (SAS Institute, 2009).

RESULTS AND DISCUSSION

Cage Mill Capacity to Destroy Weed Seeds within Crop Chaff

A cage mill is a high impact crushing device in which material is introduced via a feed chute directly into the center of counter-rotating cages each containing three rows of steel bars (Fig. 1a) (Gundlach Equipment Corporation; Pennsylvania Crusher, 2003). When tested across a range of operating speeds (700–1300 rpm) the high speed impact action of this cage mill consistently destroyed greater than 90% of ryegrass seed present in wheat, barley, and lupin grain crop chaff samples (Fig. 1b). At 700 rpm, ryegrass seed destruction was high (>85%) and was further elevated with increasing mill speeds to maximum seed destruction levels of >94% at the fastest mill speed of 1300 rpm. There were no differences ($p > 0.05$) in ryegrass seed destruction due to the type of crop chaff material being processed.

Harrington Seed Destructor System Capacity to Destroy Weed Seeds during Commercial Grain Harvest

Following the successful evaluation of the stand-alone cage mill, a prototype HSD system was constructed and attached to a commercial grain harvester (Fig. 2). This system was assessed by introducing known weed seed quantities directly into the front of the harvester during commercial wheat harvest. The resulting processed weed seed-bearing chaff material was also collected during harvest to assess the survival of the introduced weed seeds. The action of HSD system processing of wheat chaff resulted in over 90% destruction of ryegrass, wild radish, wild oat, and brome grass seeds. The largest effect was observed on the larger seeded brome grass and wild oat, both of which incurred 99% (±0.1) seed destruction, followed by ryegrass with 95% (±0.8). Slightly lower seed destruction, 93% (±2.6), was observed for wild radish introduced as seed contained within the hardened silique (pod) segments. In further studies, 98% ryegrass seed destruction was maintained across a wide range of chaff quantities (0.1–0.5 t ha^{-1}) produced during the grain harvest of typical commercial wheat, barley, and lupin crops. The range in chaff quantities was achieved by varying harvester swath widths while maintaining constant harvester speed for 20 m long crop strips. For all three crops there was no effect ($p > 0.05$) of chaff quantity on ryegrass seed destruction in wheat 99% (±0.1), barley 99% (±0.1), or lupin 99% (±0.1) crops.

Herbicides are the current paradigm for crop weed control and the HSD system is envisioned as a completely new and complimentary weed control technology for modern conservation crop production systems. The possibility of an effective at-harvest system for targeting of weed seeds and preventing their input to seed banks has been a long held but unrealized objective (Norris, 2007). It is the soil seed bank of annual weed species that is key to their persistence in all of the world's grain producing regions and there is no doubt that the prevention of fresh seed inputs is essential in long-term sustainable weed population decline (Cavers and Benoit, 1989). Although targeting weed seeds by hand control has been practiced since antiquity the HSD is a new tool for modern industrialized large scale crop production systems. Researchers have envisioned the potential for mechanical HWSC systems to target crop weed seed but studies did not extend beyond the laboratory (Balsari et al., 1994; Gossen et al., 1998; Hauhouot-O'Hara et al., 1998). Here, we have developed and proved a mechanical HWSC system with the ability to destroy very high proportions of crop weed seed under commercial grain harvest conditions. On very large crop fields we demonstrated the ability of this system to destroy crop weed seeds entering the harvester during harvest of major grain crops. A further indicator of the potential widespread applicability of the HSD system was that consistently high weed seed destruction was maintained with varying crop chaff type and quantity. This system with its ability to efficiently process large quantities of chaff to destroy infesting weed seeds represents a new and unique weed control tool, potentially effective for any weed species in which weed seeds remain on plants at the time of grain harvest.

The HSD system, by retaining in the field all crop harvest residues, creates the opportunity to realize the full benefits of a conservation farming system and ethos. Current Australian HWSC systems targeting weed seeds at harvest (e.g., chaff carts, residue baling, and windrow burning) all result in the loss of valuable crop residues from the field (Walsh and Powles, 2007; Walsh and Newman, 2007). The preservation of all available residues in a conservation cropping system is critical in delivering the full benefits of this system for agro-ecosystem productivity and sustainability. Residue retention has been demonstrated to improve the conservation of soil moisture (Incerti et al., 1993), enhance soil structure (Díaz-Zorita et al., 2004), allow soil organic C sequestration (Potter et al., 1997), and reduce soil erosion (Fryrear, 1995).

The introduction of the HSD system as a new and unique weed control tool for broad area cropping systems has the potential to dramatically improve the management of annual weed species in grain production systems. As established here, this system destroys very high proportions of weed seeds during the harvest operation, preventing their input to the soil seed bank. Preventing seed bank augmentation is critical to the long-term management of annual weed species (Davis, 2008; Norris, 2007; Taylor and Hartzler, 2000). In Western Australia the annual use of HWSC systems, chaff cart or narrow-windrow burning, have been proven to reduce in-crop annual ryegrass emergence by over 90% in just 4 yr (Newman, 2009). Despite this the adoption of these systems is hampered by constraints associated with postharvest management of collected chaff residues. The ability of the HSD to effectively intercept weed seed inputs without interfering with commercial grain harvest represents a significant technological advance for the grain production industry. Currently, we are conducting extensive field trials of the HSD system across a broad range of agro-ecosystems with a view to commercialization of this system for Australian and world agriculture.

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