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Review

Targeting Weed Seeds In-Crop: A New Weed Control Paradigm for Global Agriculture

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The widespread evolution of multiple herbicide resistance in the most serious annual weeds infesting Australian cropping fields has forced the development of alternative, non-chemical weed control strategies, especially new techniques at grain harvest. Harvest weed seed control (HWSC) systems target weed seed during commercial grain harvest operations and act to minimize fresh seed inputs to the seedbank. These systems exploit two key biological weaknesses of targeted annual weed species: seed retention at maturity and a short-lived seedbank. HWSC systems, including chaff carts, narrow windrow burning, bale direct, and the Harrington Seed Destructor, target the weed seed bearing chaff material during commercial grain harvest. The destruction of these weed seeds at or after grain harvest facilitates weed seedbank decline, and when combined with conventional herbicide use, can drive weed populations to very low levels. Very low weed populations are key to sustainability of weed control practices. Here we introduce HWSC as a new paradigm for global agriculture and discuss how these techniques have aided Australian grain cropping and their potential utility in global agriculture.

Key words: Bale direct system, chaff carts, Harrington seed destructor, harvest weed seed control, herbicide resistance, narrow windrow burning.

La ampliamente diseminada evolución de resistencia a múltiples herbicidas en las malezas anuales más serias infestando los sistemas de cultivos australianos ha forzado el desarrollo de estrategias de control de malezas alternativas, especialmente nuevas técnicas al momento de la cosecha de granos. Los sistemas de control de semillas de malezas en cosecha (HWSC) se enfocan en las semillas de malezas durante las operaciones de cosecha comercial de granos y actúan para minimizar el suministro de semillas frescas al banco de semillas. Estos sistemas explotan dos debilidades biológicas clave de las especies de malezas anuales de interés: retención de semilla al momento de la madurez y un banco de semillas de corta vida. Los sistemas HWSC, incluyendo las carretas de descarga de grano, la quema de líneas angostas de residuos después de la cosecha, el embalado directo, y el Destructor de Semilla Harrington, se enfocan en los residuos de cosecha que contienen semillas de maleza durante la cosecha comercial de grano. La destrucción de estas semillas de malezas durante o después de la cosecha del grano facilitan la reducción del banco de semillas de malezas, y cuando se combinan con el uso convencional de herbicidas, pueden llevar las poblaciones de malezas a niveles muy bajos. Tener poblaciones muy bajas de malezas es clave para la sostenibilidad de las prácticas de control de malezas. Aquí, nosotros introducimos HWSC como un nuevo paradigma para la agricultura global y discutimos como estas técnicas han ayudado a la producción australiana de granos y su utilidad potencial en la agricultura global.

In global crops, infestations of crop weeds are a ubiquitous annual threat to productivity, especially in the major field crops (wheat [*Triticum aestivum* L.], rice [*Oryza sativa* L.], soybean [*Glycine max* (L.) Merr.], corn [*Zea mays* L.], canola [*Brassica napus* L.], etc.). The significant annual threat from infesting weeds must be minimized to maximize crop productivity and thus global food supply/security. Currently, herbicides are the dominant technology used against infesting weeds. The many advantages of herbicides over other forms of weed control have resulted in almost exclusive reliance on herbicide technology in field cropping systems in many parts of the world. However, the exposure of huge weed populations over vast areas to strong herbicide selection has inevitably resulted in the evolution of herbicide-resistant weed populations (Heap 2013; Powles and Yu 2010). Herbicide-resistant weeds, particularly those of major field crops, pose a significant challenge to global food production/security.

The widespread evolution of resistance to herbicides in weed species threatens herbicide sustainability and necessitates the development of new weed control tools. While herbicide-resistant weeds have evolved in agricultural regions around the world (Heap 2013), the evolution of resistant weed populations across the Australian field crops landscape has been extreme. Multiple herbicide-resistant annual ryegrass (*Lolium rigidum* Gaud.) and wild radish (*Raphanus raphanistrum* L.) populations now dominate in Australian crop production systems (Boutsalis et al. 2012; Broster and Pratley 2006; Owen et al. 2007, 2013; Walsh et al. 2007). The need for new herbicides is high; however, the dramatic slowing of herbicide discovery (Duke 2012) and regulatory removal of some herbicides (Chauvel et al. 2012) means that existing herbicides are at risk from over-use, leading to resistance evolution in weeds. Thus, continuing herbicide resistance evolution is a major threat to future crop weed control and a potent driving force in the search for alternate weed control technologies (Powles and Matthews 1992). Here, we describe

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Figure 1. Chaff cart system in operation during commercial wheat crop harvest.

how a major herbicide-resistant weed problem has been the catalyst for the development of new non-chemical weed control techniques focused on weed seed capture and destruction during commercial grain crop harvest. We illustrate how the inclusion of these techniques in weed control programs allows weed populations to be driven to and maintained at very low levels. Finally, we speculate on the potential for at-harvest weed seed targeting technologies in global field crops.

Current Weed Control Paradigm in Global Field Crops: Target Weed Seedlings

The current dominant paradigm for weed control in field crops is PRE or early POST herbicides to remove weed seedlings in young, establishing crops. Crop yield is secured by controlling weed seedlings during this critical "weed free period" during which crop plants are particularly vulnerable to weed competition (Knezevic et al. 2002; Zimdahl 1988). However, despite herbicide use, some in-crop weeds inevitably escape herbicide control for a range of reasons (eg. adverse environmental conditions, insufficient herbicide, herbicide resistance, delayed emergence) and in the great majority of situations there is no other feasible, practicable method of controlling these surviving weeds. Hence, these weeds survive to maturity with the crop and produce significant quantities of seed which sustain or build a viable weed seedbank (Buhler et al. 1997; Norris 2007).

It is the ongoing, annual production of weed seeds that perpetuates and amplifies many crop-weed infestations in global field crops. Annual weed seedbank replenishment ensures that each year high weed numbers emerge and are herbicide treated, with the inevitable risk of resistance evolution. It has long been recognized that alternate weed control strategies are needed to alleviate intense herbicide selection (Powles and Matthews 1992). Globally, there are few suitable alternatives to herbicides and even when alternatives (eg. cultivation, crop competition, delayed seeding) are considered, the focus remains on preventing weed seedlings from interfering with early crop growth. However, weed adaptations, such as seed dormancy, in response to changes in cultivation and cropping practices, have already occurred in several annual species including annual ryegrass (Owen et al. 2011), wild oats (*Avena fatua* L.) (Jana and Thai 1987), brome grass (*Bromus rigidus* Roth.) (Kleemann and Gill 2006) and barley grass (*Hordeum murinum* L.) (Fleet and Gill 2012). These evolutionary adaptations in response to a selection pressure further highlight the consequences of neglecting seed production and seedbank replenishment by weeds surviving early season control practices. Clearly, new tools are needed that complement early season weed control techniques by targeting annual weed seed production.

New Weed Control Paradigm: Harvest Weed Seed Control (HWSC)

Widespread multiple herbicide resistance in the very important weeds, annual ryegrass, (Boutsalis et al. 2012; Broster and Pratley 2006; Owen et al. 2007, 2013) and wild radish (Walsh et al. 2001, 2007), of Australian cropping has forced the development of additional weed control strategies. Knowledge that the major proportion of an in-crop annual ryegrass population results from the previous season's seed production led to a focus on minimizing weed seed production (Gill and Holmes 1997; McGowan 1970; Monaghan 1980; Pearce and Holmes 1976; Reeves and

Table 1. Efficacy of HWSC systems in targeting weed seeds during cereal crop harvest.

HWSC system	Weed seed control	Weed species	Reference
	%		
Chaff collection	60 to 80	Annual ryegrass	(Gill 1996)
	56 to 63	Annual ryegrass	(Matthews et al. 1996)
	73 to 86	Annual ryegrass	(Walsh and Powles 2007)
	95	Wild radish	(Walsh and Powles 2007)
	74	Wild oats	(Shirtliffe and Entz 2005)
Bale direct	95	Annual ryegrass	(Walsh and Powles 2007)
Narrow windrow burning	99	Annual ryegrass	(Walsh and Newman 2007)
	99	Wild radish	(Walsh and Newman 2007)
Harrington Seed Destructor	95	Annual ryegrass	(Walsh et al. 2012)
	93	Wild radish	(Walsh et al. 2012)
	99	Wild oats	(Walsh et al. 2012)
	99	Brome grass	(Walsh et al. 2012)

Figure 2 a) Chaff chute mounted on the rear of a harvester to form narrow windrows during harvest. b) Burning narrow windrows in wheat stubble in autumn (March to April)

Smith 1975). The biological attribute of seed retention at maturity in annual ryegrass, wild radish, and several other annual crop weed species, means that seeds are attached to the upright plant enabling the weed seeds to be collected (harvested) during grain crop harvest. For example, in field crops a large proportion (up to 80%) of total annual ryegrass seed production can be collected during a typical commercial grain harvest (Walsh and Powles 2007). These weed seeds enter the front of the grain harvester, are processed, and exit the grain harvester in the chaff fraction. An irony is that these "harvested" weed seeds are evenly redistributed across the crop field to become future weed problems. Thus, grain crop harvest presents an opportunity to target weed seed production, thereby minimizing replenishment/increase of the weed seedbank. As outlined below, harvest weed seed control (HWSC) systems have been developed in Australia to target and destroy weed seeds during commercial grain crop harvest, minimizing weed seed inputs into the seedbank (Walsh and Powles 2007).

HWSC Systems

Chaff carts. The recognition that at grain harvest the seeds of important crop weeds are intact and attached to the upright plant and can be "harvested" led to the introduction of chaff cart collection systems into Australian cropping. This relatively simple HWSC system consists of a chaff collection and transfer mechanism, attached to a grain harvester that delivers the weed seed bearing chaff fraction into a bulk collection bin, usually a trailing cart (Figure 1). Chaff cart collection systems have been shown to achieve the collection and removal of high proportions of seed from crop-infesting populations of annual ryegrass, wild radish (Walsh and Powles 2007) and wild oat (Shirtliffe and Entz 2005) (Table 1). The collected chaff material must be managed in order to prevent the weed seeds present from returning to the cropping field. The large volume of collected chaff is typically dumped in chaff heaps in lines across fields in preparation for subsequent burning to achieve weed seed destruction. Alternatively, chaff material is a valuable livestock feed source and can be grazed *in-situ* or, in some instances, collected for use in feed-lots. This necessity for post-harvest management of chaff material has limited the Australian adoption of chaff cart collection systems despite their recognized efficacy in the management of major herbicide-resistant weed problems. However, the weed seed targeting efficacy of chaff cart collection systems (Walsh and Powles 2007) maintained the continuing interest in the development of additional HWSC systems.

Figure 3. Bale direct system collecting and baling chaff and straw residues during wheat harvest.

Figure 4. First commercially available Harrington Seed Destructor (Photo. courtesy de bruin engineering)

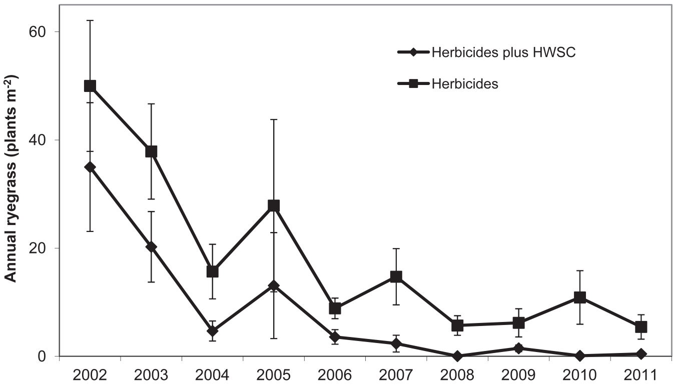

Figure 5. Influence of the long-term use of herbicides alone and herbicides plus harvest weed seed control (HWSC) on in-crop annual ryegrass plant densities in northern WA cropping fields. Capped bars represent the standard error values showing variation around the mean annual ryegrass populations in 17 fields (Herbicides) or 8 fields (Herbicides plus HWSC).

Narrow windrow burning. The simple but effective narrow windrow burning system is currently the most widely adopted HWSC system in Australia. This inexpensive system uses a grain harvester mounted chute to concentrate all of the exiting chaff and straw residues into a narrow-windrow (500 to 600mm) (Figure 2a). These narrow windrows are subsequently carefully burnt under the right environmental conditions, avoiding burning the entire crop field (Figure 2b). The concentration of chaff and straw residues increases the duration and temperature of burning, creating the highest potential for weed seed destruction. Weed seed kill levels of 99% for both annual ryegrass and wild radish have been recorded from the narrow windrow burning of wheat, canola, and lupin (*Lupinus angustifolius* L.) chaff and straw residues (Table 1, Walsh and Newman 2007). The simplicity and low cost of this narrow-windrow system has resulted in its adoption by an estimated 70% of crop producers in the major grain production state of Western Australia.

Bale direct. The Bale Direct System consists of a large square baler directly attached to the harvester that constructs bales from the chaff and straw residues exiting the grain harvester (Figure 3). This system serves to both capture weed seeds and bale harvest residues for livestock feed. Our studies (Table 1) have determined that very high proportions (95%) of annual ryegrass seeds are collected and removed from fields (Walsh and Powles 2007). However, the availability of suitable markets for the baled material has limited the adoption of this system by Australian producers.

Harrington Seed Destructor (HSD). The effective processing of the weed-seed bearing chaff material during grain crop harvest has been a long held goal for Australian grain growers. In 2005, innovative Australian crop producer Ray Harrington commenced evaluating the chaff processing potential of a cage mill. Cage mills are a robust technology with a wide variety of uses in crushing rock and ore materials (Stedman 1996). We subsequently established the ability of a stationary cage mill to process wheat chaff sufficiently to destroy at least 90% of the contained annual ryegrass seeds (Walsh et al. 2012). These encouraging results led to the development of what is now termed the Harrington Seed Destructor (HSD); a trailer mounted cage mill, with chaff and straw transfer systems, and a diesel motor as a power source (Figure 4). Evaluation of the HSD during commercial wheat crop harvest determined that the HSD will destroy at least 95% of annual ryegrass, wild radish, wild oat, and brome grass seed present in the chaff fraction of harvest residues (Table 1). These results confirm the potential of the HSD as an effective system for weed seed destruction during grain crop harvest. A distinct advantage of this HWSC system is the retention of all harvest residues, a critical attribute for soil moisture and nutrient conservation. With the efficacy of this system established (Walsh et al. 2012), the HSD system has recently progressed into commercial production (de-bruin 2013).

Driving Weed Populations to Very Low Densities

The real value of HWSC systems is as part of a system embracing early-season weed control practices (herbicides etc.) on weed seedlings and HWSC on late-season mature seed bearing weeds. The at-harvest targeting of these weeds minimizes seedbank contributions facilitating seedbank decline. The combined impact of herbicides plus HWSC over 10 consecutive seasons (2002 to 2011) on annual ryegrass populations was monitored in 25 large, commercial Western Australian cropping fields (Figure 5). This study commenced with producers nominating "problem fields" with high (35 to 50 plants m^{-2}) in-crop annual ryegrass densities. Over 10 consecutive growing seasons, herbicide focused weed management practices were implemented on these fields with the aim of reducing annual ryegrass populations to acceptably low plant densities of < 1 plant m^{-2}. In-crop annual ryegrass population densities were recorded annually in 10 random 0.1 m^{2} quadrats at crop flowering. As expected, effective herbicide treatments reduced in-crop annual ryegrass populations to < 10 plants m^{-2} within five consecutive growing seasons. However, it was only in the fields where both early-season herbicides and HWSC were routinely practiced that the targeted low weed densities were achieved. In these fields, annual ryegrass numbers were

Table 2. Proportion of total weed seed production retained at crop harvest for species present in global grain crops.

Species	Seed retention	Crop, location	Reference
	%		
Ivy leaf morning glory (*Ipomea hederacea* L. Jacq. IPOHE)	75	Corn, US	(Davis 2008)
	85	Soybean, US	(Davis 2008)
Giant foxtail (*Setaria faberi* Herrm. SEFTA)	55	Soybean, US	(Davis 2008)
	65	Corn, US	(Davis 2008)
Prickly sida (*Sida spinosa* L. SIDSP)	60	Soybean, US	(Davis 2008)
	80	Corn, US	(Davis 2008)
Velvetleaf (*Abutilon threophasti* Medik. ABUTH)	35	Corn, US	(Davis 2008)
	50	Soybean, US	(Davis 2008)
Wild oats	20	Wheat, Canada	(Shirtliffe et al. 2000)
	50	Wheat, Canada	(Feldman and Reed 1974)
	34	Barley, Canada	(Metz 1969)
	84	Barley, Germany	(Wilson 1970)
	20	Wheat, UK	(Barroso et al. 2006)
Annual ryegrass	96	Wheat, Spain	(Blanco-Moreno et al. 2004)
Chinese thornapple (*Datura ferox* L.)	90	Soybean, Argentina	(Ballaré et al. 1987)
Common lambsquaters (*Chenopodium album* L. CHEAL)	34 to 46	Corn, US	(Forcella et al. 1996)
Leersia oryzoides (L), *Echinochloa* spp. and *Scirpus* spp.	95[a]	Rice, Italy	(Balsari et al. 1994)
Echinochloa spp., *Raphanus raphanistrum*, *Polygonum persicaria*, *Vicia sativa*, *Setaria glauca* and *Chenopodium* spp.	56[a]	Wheat, Italy	(Balsari et al. 1994)

[a] Proportion of weed seed production combined for all species.

reduced from an average of 35 plants m^{-2} in 2002 to just 0.5 plants m^{-2} in 2011. In contrast, where herbicides alone were used, average annual ryegrass plant densities remained above 4 plants m^{-2}. It is emphasized that in these fields annual ryegrass populations were not resistant to the herbicides used.

The Global Potential for HWSC Systems

The potential for HWSC systems to effectively target weed seed production during commercial harvest of global grain crops can obviously only be effective on crop weed populations that have high seed retention at the time of crop maturity. At present, to our knowledge, HWSC is only practiced in Australia. However, the problems of weed seed present at crop harvest are well recognized in major crop producing countries including the USA (Davis 2008), Canada (Shirtliffe and Entz 2005), Spain (Barroso et al. 2006), Italy (Balsari et al. 1994), and Argentina (Ballaré et al. 1987). Across these regions it is well recognized that grain harvester dispersal from weeds bearing mature seeds at crop harvest is a major factor in weed seedbank replenishment. Importantly many studies in these cropping systems have reported high proportions ($> 50\%$) of total seed production retained on weed plants at a height that allows collection by the harvester (Table 2). The efficacy of HWSC systems in targeting weed seed production at crop maturity is directly related to the amount of seed that harvesters collect during commercial grain harvest. Therefore, high proportions of weed seed retention at harvest in global crops clearly highlight the potential for HWSC systems as a new non-chemical weed control tool. We believe that HWSC should be viewed as a tool to help achieve herbicide sustainability. We do not envision HWSC as a "stand-alone" weed control tool but as a diversity introducing technique, helping avoid an exclusive reliance on herbicides for weed control.

Preserving Weed Control Resources

The practical implications of HWSC are a more resilient crop production system that minimizes resistance evolution in weed populations. As shown here, the combination of effective herbicides plus HWSC techniques reduced and maintained annual ryegrass populations at very low densities (< 1.0 plant m^{-2}) (Figure 5). In cropping systems, low weed densities allow flexibility in crop choice, seeding time, and herbicide use. This flexibility provides producers with the capacity to readily adjust production practices in tune with seasonal and market considerations. Low weed densities in crop fields also play a critical role in sustaining herbicide resources for the ongoing control of crop-weeds, despite their demonstrated potential for herbicide resistance evolution (Jordan and Jannink 1997; Mortimer 1997). Resistance evolution is related to population size and resistance endowing traits are initially rare (i.e. 10^{-4} to 10^{-9}), but resistance will evolve rapidly in large populations exposed persistently to herbicide selection (Diggle and Neve 2001). Thus targeting of weed seed production to restrict population densities to very low levels not only has production benefits but importantly reduces the potential for resistance evolution to our remaining highly valued herbicide resources. Of course, the HWSC practices outlined are also a selection pressure on weed populations for gene traits enabling weed seed production in the presence of HWSC practices (e.g. earlier maturity and seed shattering/dispersal before HWSC practices). Thus, as for any weed control tool, diversity in use is essential to long-term sustainability.

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