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Harvest weed seed control: impact on weed management in Australian grain production systems and potential role in global cropping systems

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ABSTRACT

The introduction of harvest weed seed control (HWSC) techniques and associated machinery has enabled the routine use of an alternative weed control technology at a novel weed control timing in global grain cropping fields. Driven by the significant threat of widespread populations of annual ryegrass (*Lolium rigidum*) with multiple-herbicide resistance, in the 1990s Australian growers and researchers developed techniques to target, at grain harvest, the seed production of annual ryegrass and other important weed species. The HWSC approach to weed management is now routinely used by a majority of Australian grain producers as an integral component of effective weed control programs. Here we detail the development and introduction of current HWSC systems and describe their efficacy in Australian grain production systems. The use of HWSC has likely contributed to lower annual ryegrass population densities and thus mitigated the impacts of herbicide resistance as well as slowing further evolution of resistance. In addition, low weed densities enable the introduction of site-specific weed control technologies and the opportunity to target specific in-crop weeds with non-selective alternative weed control techniques. With an awareness of the evolutionary potential of weed species to adapt to all forms of weed control, there is an understanding that HWSC treatments need to be judiciously used in grain cropping systems to ensure their ongoing efficacy. The successful use of Australian developed HWSC systems has attracted global interest and there is now a considerable international research effort aimed at introducing this alternative weed control approach and timing into the world's major cropping systems.

Keywords: bale direct system, chaff cart, chaff lining, chaff tramlining, herbicide resistance, HWSC, impact mill, narrow windrow burning, weed seed retention.

Introduction

In Australia, up to 50 Mha of agricultural land is annually devoted to rainfed field crops (wheat, barley, canola, pulses, sorghum, etc.) producing grains for global consumption. Throughout the vast grainbelt regions, rainfall and soil constraints have driven the universal adoption of conservation cropping practices based on reduced tillage and crop residue retention (Kassam *et al.* 2012; Llewellyn *et al.* 2012; FAO, 2012). Established in the 1990s, conservation cropping systems, based on sound agronomic practices, have been responsible for significant and sustained crop yield increases, as well as production stability (Kirkegaard and Hunt 2010; Angus 2001). The availability of highly effective herbicides for broad-spectrum pre-seeding and selective in-crop weed control enabled the successful adoption of conservation cropping systems which greatly enhanced production (D'Emden *et al.* 2008). Thus, despite low and variable rainfall as well as inherently poor soil fertility, Australian cropping systems adapted and flourished.

The use of herbicides for successful control of crop weed infestations has been integral to the success of conservation cropping systems in Australia. However, high reliance on herbicides without diversity led to the widespread evolution of herbicide-resistant weed populations, especially in the damaging weed, annual ryegrass (*Lolium rigidum* Gaud.) (Boutsalis *et al*. 2012; Owen *et al*. 2014; Broster *et al*. 2019). Herbicide resistance has evolved in many of the dominant weeds of the world's cropping regions; however, in Australia this problem was prominent earlier and was more devastating than elsewhere owing to the near ubiquitous presence of high-density, naturalised annual ryegrass populations throughout the cropping regions (Donald 1965; Kloot 1983). With high numbers, innate genetic diversity and obligate cross-pollination, this weed is especially prone to evolving resistance. Within 10–15 years of widespread adoption of conservation cropping systems, there were high frequencies of multiple-herbicide-resistant populations throughout the vast crop production regions. Most resistant annual ryegrass populations exhibited resistance across some to many different herbicide modes of action, and control could not be achieved by simply changing to a different herbicide. This loss of herbicidal weed control was exacerbated by a major decrease in the discovery and introduction of new herbicides to control the multi-resistant populations (Duke 2012; Peters and Strek 2018). Further contributing to the lack of herbicide resources has been regulatory action in response to increasing public concern over herbicide use that has removed some herbicides and added use restrictions for others. From several viewpoints, there has been a need to develop alternative weed-control technologies to reduce high reliance on herbicides for weed control in conservation cropping systems (Walsh *et al*. 2019).

Development of harvest weed seed control (HWSC) in Australia

Modern grain harvesters are sophisticated machines with a large and high-speed capacity to collect, process and separate grain from residues (e.g. crop and weed plant material). When operating to harvest condition specifications, these harvesters efficiently collect and clean the crop grain then spread the chaff and straw residues from the rear of the harvester (including collected weed seed). This process disperses harvested weed seeds uniformly across the harvested field, which ironically and inadvertently is an efficient process for maintaining ongoing weed infestations. Disrupting this cycle by capturing and minimising the return of weed seed to crop fields is the common objective of the HWSC systems, as previously described in an earlier review of HWSC introduction and development (Walsh *et al*. 2018*c*).

As with several significant innovations in agriculture, it was the efforts of Australian grain growers that led to the development of HWSC systems that target weed seeds during crop harvest. Faced with the adversity of herbicide resistance, primarily in annual ryegrass, grower innovations focused on targeting the seed of this species to minimise weed seed return to crop fields. In Australian cropping systems, annual ryegrass matures concomitant with crops, and most seed is retained at a height ensuring that significant amounts are also 'harvested' during grain harvest (Walsh and Powles 2014). This smaller, lighter weed seed is expelled from the harvester, principally in the chaff fraction (processed crop residue). Research has established that, with optimum harvester setup and operation, ~95% of the harvested annual ryegrass seed exited the harvester in the chaff fraction (Walsh and Powles 2007; Broster *et al*. 2016). Armed with this knowledge, several HWSC systems have been developed that target the chaff fraction containing weed seed during harvest to minimise soil seedbank inputs (Walsh *et al*. 2013). Recently, there have been significant system developments and subsequent evaluations of HWSC systems, those that concentrate chaff into narrow rows (chaff lining and chaff tramlining) and chaff-processing impact mills.

Chaff tramlining and chaff lining

Two HWSC approaches involve the concentration of chaff material into narrow rows (~20–30 cm) as it exits the grain harvester: (*i*) chaff tramlining, in which chaff is placed on dedicated wheel tracks such as those used in controlled traffic systems; and (*ii*) chaff lining, where the chaff is placed between the wheel tracks. Chaff lining and chaff tramlining are simple, low-cost approaches to HWSC that have gained in popularity over the last few years, and it was recently estimated that 12% of Australian growers were using these techniques (Kondinin-Group 2020). The concentration of chaff material into these narrow rows confines the collected weed seed into an area that typically represents <5% of the field area. In a series of field trials, the concentration of chaff material ensured high proportions of over-summer survival of weed seed compared with seed exposed on the soil surface (Walsh *et al*. 2021). It was also noted that the beneath-chaff seed survival was influenced by chaff type and climate. Although high amounts of chaff material can increase weed seed survival, the concentrated chaff acts as a physical barrier to weed seedling emergence. A pot study found that regardless of chaff type, every 1 t ha^{-1} increase in chaff quantity resulted in a further reduction of ~2% in weed seedling emergence (Walsh *et al*. 2021). Obviously, very high amounts of chaff (>40 t ha^{-1}) will be required for potential prevention of annual ryegrass emergence. These levels of concentrated chaff material will be achieved only when harvesting high-yielding crops that produce enough chaff residue (e.g. wheat at >5 t ha^{-1}).

Impact mills

We have previously reviewed the introduction and development of impact mill systems such as the Harrington Seed Destructor (HSD; Walsh *et al*. 2012) and subsequently the iHSD (integrated HSD) mounted to the rear of the grain harvester (Walsh *et al.* 2018*b*, 2018*c*). The introduction of the iHSD has created substantial commercial interest in the use of impact mill systems for HWSC and resulted in the development of similar machinery for weed seed destruction including the SeedTerminator, Weed Hog and Seed Control Unit. With increasing adoption and use of impact mill systems, there has been ongoing product development in response to identified system constraints. For example, the iHSD has switched from horizontal to vertically mounted chaff-processing mills. The internal mill configurations have also changed in efforts to reduce wear and increase material flow. Throughout these modifications, there has been a focus on maintaining a high level (>90%) of weed seed destruction (Walsh *et al.* 2020). The increasing popularity of impact mill systems will stimulate the ongoing development and refinement of these systems as their use is expanded across the world's production systems and regions.

Comparison of HWSC systems

In order to demonstrate to Australian growers the HWSC opportunity and to compare system efficacy on annual ryegrass populations, an extensive multi-state evaluation of three HWSC systems was conducted across the vast Australian rainfed cropping region. The seed targeting efficacy of these three HWSC practices was assessed by quantifying seedling emergence counts in the season following their use during harvest. Across 25 sites spanning the large states of Western Australia, South Australia, Victoria and New South Wales, the chaff cart, narrow windrow burning and HSD treatments were found to be similarly effective in reducing annual ryegrass emergence in the following season by 60% compared with the no HWSC treatment (Walsh *et al.* 2017*a*). These trials also identified the negative influence of annual ryegrass infestation level on the impact of HWSC. The density of the annual ryegrass soil seedbank strongly influenced the subsequent reduction in annual ryegrass plant populations. Where there were high soil seedbank densities, the immediate impact of HWSC was just a 30% reduction in annual ryegrass emergence. By contrast, a 90% reduction in emergence was observed when seedbank densities were low.

Adoption of HWSC

Adoption of HWSC, initially limited by the availability of suitable systems, has recently increased dramatically with the introduction of more user-friendly techniques. There had been generally low adoption of the chaff carts, first used in the late 1980s (Llewellyn *et al.* 2004). Although some difficulties arose in using this trailing cart system during harvest, these were minor compared with the logistics of the post-harvest management of the collected chaff material. In particular, burning of collected chaff to destroy weed seeds poses a significant risk of fire escapes. The slow burning chaff piles, often smouldering for several days, are a significant fire risk and create severe smoke hazes. Although chaff cart systems effectively target weed seeds (Walsh *et al.* 2013), and they have demonstrated the value of HWSC, the complications of towing a cart during harvest, along with the fire and smoke hazards, have restricted their adoption.

Narrow windrow burning was introduced in the 1990s as a low-cost chute system that during harvest funnels all crop residues, including weed seeds, into narrow windows. This technique does not impede harvest and ensures a mostly trouble-free HWSC treatment. There is a post-harvest (autumn) requirement to burn windrows for weed seed destruction, however this can be completed more rapidly with lower fire risks and fewer smoke issues compared to burning chaff heaps. Grower adoption of narrow windrow burning has been substantial, and in 2000, it was estimated that 21% of Western Australian growers were using this technique, compared with 7% using chaff cart systems (Llewellyn *et al.* 2004). A 2014 survey of 600 Australian grain growers estimated that adoption of narrow windrow burning had increased to 30% of growers nationally and 50% in Western Australia (Table 1) (Walsh *et al.* 2017*b*). This level of adoption was considerably greater than the use of chaff tramlining (7%), chaff carts (3%), bale direct system (3%), and the then recently available impact mill system, the HSD (<1%). At the time of the 2014 survey, it was estimated that 63% of Western Australian growers were using some form of HWSC, representing a three-fold increase over the previous estimated level of adoption of 21% in 2000 (Table 1). The 2014 survey also estimated significant levels of HWSC system adoption by growers in the southern (38%) and northern (19%) Australian cropping regions. This level of adoption was believed to represent a significant recent increase in the use of these systems in these areas, although there are no previously recorded estimates to support this perception.

In the 5 years after the 2014 grower survey, HWSC system adoption has further increased. A national survey of 229 growers in 2019 estimated that HWSC adoption had increased to 75%, representing a 32% increase since the 2014 survey (Table 1) (Walsh *et al.* 2017*b*; Kondinin Group 2020). The 2019 survey (Kondinin Group 2020) highlighted the continued widespread use of narrow windrow burning (43%) along with significant increases in the use of chaff lining/tramlining systems (24%). The availability of integrated impact mill systems has resulted in an increase in the adoption of these systems to a level similar to that of chaff carts (6%). The high levels of HWSC adoption clearly indicate that Australian growers now consider HWSC an

Table 1. Adoption of narrow (40–60 cm) windrow burning, chaff lining/tramlining, chaff cart, bale direct and impact mill HWSC systems, and corresponding frequency of herbicide resistance (from randomly collected annual ryegrass populations with ACCase- or ALS-inhibiting herbicide resistance) in Australian cropping regions and zones within these regions.

Cropping regions and zones	HWSC system adoption (% of growers)						Annual ryegrass herbicide resistance frequency (%)
	Narrow windrow burning	Chaff lining/ tramlining	Chaff cart	Bale direct system	Impact mills	Total adoption	
Northern cropping region average	4	13	1	1	–	19	–
Central Queensland[A]	–	18	4	–	–	22	–
North-eastern New South Wales and south-eastern Queensland[A]	–	18	–	–	–	18	–
North-western New South Wales and south-western Queensland[A]	11	4	–	2	–	17	–
Southern cropping region average	28	6	1	4	–	39	67
Central New South Wales[A,B]	12	2	–	2	–	16	43
New South Wales and Victorian slopes[A,B]	33	12	–	12	–	57	70
South Australian Mid North, Lower Yorke and Eyre peninsulas[A,C]	31	–	4	–	–	35	76
South Australian Bordertown and Victorian Wimmera[A,C]	38	2	–	4	–	44	65
South Australian and Victorian Mallee[A,C]	21	6	–	6	–	33	61
Victorian High Rainfall and Tasmania[A,C]	33	12	2	2	–	49	88
Western cropping region average	51	4	7	1	–	63	90
Western Australian central[A,D]	56	7	13	2	–	78	84
Western Australian eastern[A,D]	45	4	–	–	–	49	100
Western Australian Sandplain-Mallee[A,D]	33	4	9	2	–	48	83
Western Australian northern[A,D]	75	3	8	–	–	86	94
National average 2014	30	7	3	3	<1	43	
National average 2019[D]	43	24	6	6	–	75	

[A]2014 HWSC survey (Walsh *et al.* 2017*b*).
[B]2007 and 2009 herbicide resistance surveys of randomly collected annual ryegrass populations (Broster *et al.* 2011, 2013).
[C]1998–2009 herbicide resistance surveys of randomly collected annual ryegrass populations (Boutsalis *et al.* 2012).
[D]2010 herbicide resistance surveys of randomly collected annual ryegrass populations (Owen *et al.* 2014).
[E]2019 HWSC survey (Kondinin Group 2020).
–, no data available.

established weed control practice that they are prepared to use routinely in their grain production systems.

The adoption of HWSC systems by Australian growers was driven by the need to mitigate the impact of herbicide-resistant weeds on crop production systems. Initially, frequencies of herbicide-resistant annual ryegrass populations were substantially higher in the Western Australian cropping region than elsewhere in Australia (Llewellyn and Powles 2001) (Table 1). This was likely a significant driver in the rapid development and adoption of HWSC systems by Western Australian growers. The relationship between occurrence of herbicide resistance and adoption of HWSC is evident in results from the 2014 adoption survey and the herbicide-resistance survey data at this time (Table 1). A regional-scale comparison of the proportion of resistant annual ryegrass populations and HWSC adoption indicates a positive linear relationship (Fig. 1). The inference from this comparison is that as issues with herbicide-resistant weeds increased, more growers began using HWSC systems to manage these recalcitrant weed populations.

Impact of HWSC on Australian grain production

HWSC systems are well suited to inclusion in integrated weed management programs as an end-of-season weed-control strategy that targets the seed production of weeds surviving in-crop weed-control treatments. Although no evidence is available concerning the agronomic and economic consequences of HWSC for crop production systems, there are clear indications of the effects on weed populations. When included in a weed management program, HWSC acts as a preventative weed-control practice by targeting weed seeds

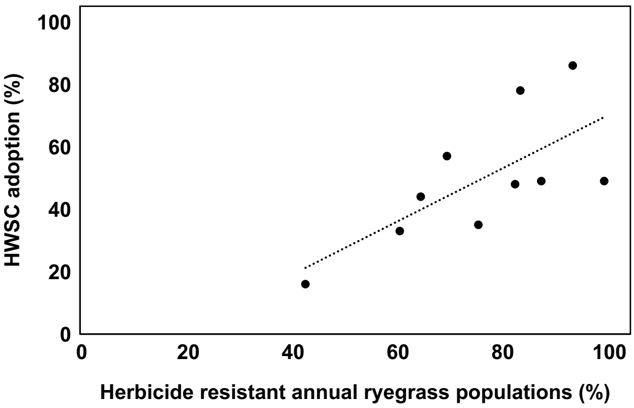

Fig. 1. Relationship between frequency of herbicide resistance in Australian cropping regions and corresponding levels of adoption of harvest weed seed control (HWSC) systems.

to reduce weed seed inputs to the seedbank and, therefore, future weed problems.

The effects of HWSC systems on weed populations will be influenced by the densities and dynamics of the residual seedbank of particular weed species. For example, seeds of annual ryegrass and several other annual grass species have limited soil persistence because most new seeds reaching the soil seedbank germinate in the next growing season (Chauhan *et al.* 2006). However, seed of many weed species can persist for several years in the soil seedbank; consequently, HWSC requires long-term use for the weed-control benefits to be fully realised. The difficulty in managing herbicide-resistant annual ryegrass populations has meant that HWSC systems have often been employed to assist in the management of high-density populations. As indicated in field trials comparing HWSC system effects on annual ryegrass emergence in the following growing season, high seedbank levels reduced the impact of HWSC treatments (Walsh *et al.* 2017*a*). Similarly, in a 16-year study of 25 continuous cropping fields in Western Australia with initially high annual ryegrass populations (>50 plants m^{-2}), 8 years elapsed before the impacts of HWSC were clearly evident (Walsh *et al.* 2018*c*). After this period, annual ryegrass plant densities were consistently lower (<1.0 plant m^{-2}) in the fields where HWSC treatments were included in herbicide-based weed management programs than in fields where herbicides alone were used (5–10 plants m^{-2}) (Fig. 2*a*). The long-term effect of targeting weed seeds is further highlighted by comparing the estimated annual ryegrass seedbank inputs for fields with (<100 seed m^{-2}) or without (1000–2000 seed m^{-2}) the use of HWSC treatments (Fig. 2*b*). These results clearly highlight the potential to drive weed populations to very low levels by including HWSC in weed management programs. In addition to weed management outcomes, low weed densities will likely have broader effects on grain production, and there is an opportunity for researchers to investigate additional agronomic and economic impacts.

Identifying the potential of HWSC in global cropping systems

Weed management with HWSC is effective on weed species in which seed remains attached to mother plants and present at a harvestable height at the time of crop maturity, such that grain harvest can also be weed seed harvest. The potential susceptibility to HWSC of a weed species can be assessed by quantifying the degree of seed retention at crop maturity. An initial study that focused on assessing HWSC potential in Western Australian wheat crops identified high seed retention (HWSC potential) for the major weed species: annual ryegrass (85%), wild radish (*Raphanus raphanistrum* L.) (99%), brome grass (*Bromus* spp.) (77%) and wild oats (*Avena* spp.) (84%) (Walsh and Powles 2014). This geographically wide survey of weed seed retention in commercial wheat crops confirmed that high proportions of the total seed production of these species could potentially be targeted with HWSC systems.

The role of HWSC in enabling Australian growers to manage herbicide-resistant weed populations became noted internationally. Problems with herbicide-resistant weeds in many global cropping regions (Heap 2021) are comparable to those in Australia. Consequently, there is considerable international interest in adopting the Australian-developed HWSC systems. Driving this research interest in HWSC is that the occurrence of weed seed collection during grain harvest has been recognised for many years in many of these cropping regions (Wilson 1970; Howard *et al.* 1991; Balsari *et al.* 1994; Rew *et al.* 1996). Now that HWSC techniques are available, there has recently been a concerted research effort to quantify weed seed retention in order to identify the potential for HWSC to target the dominant, and frequently herbicide-resistant, weed species in several of the world's major cropping systems. These studies (see reviews by Walsh *et al.* 2018*b*; Maity *et al.* 2021) have investigated seed retention at crop maturity of >30 weed species prominent in these grain production systems. Importantly, these studies have identified the opportunity for HWSC to target significant proportions (50–99%) of the seed production of the particularly damaging weeds Palmer amaranth (*Amaranthus palmeri*), water hemp (*Amaranthus tuberculatus*), annual ragweed (*Ambrosia artemisiifolia* L.), Italian ryegrass (*Lolium perenne* subsp. *multiflorum*), charlock (*Sinapis arvensis*) and chickweed (*Stellaria media*) (Bitarafan and Andreasen 2020; San Martín *et al.* 2021; Schwartz-Lazaro *et al.* 2021*a*, 2021*b*).

In the USA and Canada, evaluation of HWSC systems is occurring more rapidly than elsewhere in the world. Within these countries there is a focus on the identification and evaluation of HWSC systems for use in specific crop production systems (Shergill *et al.* 2020*b*) (Table 2). In Canada, where chaff carts originated, the use of these systems was found to reduce the dispersal of wild oat seed

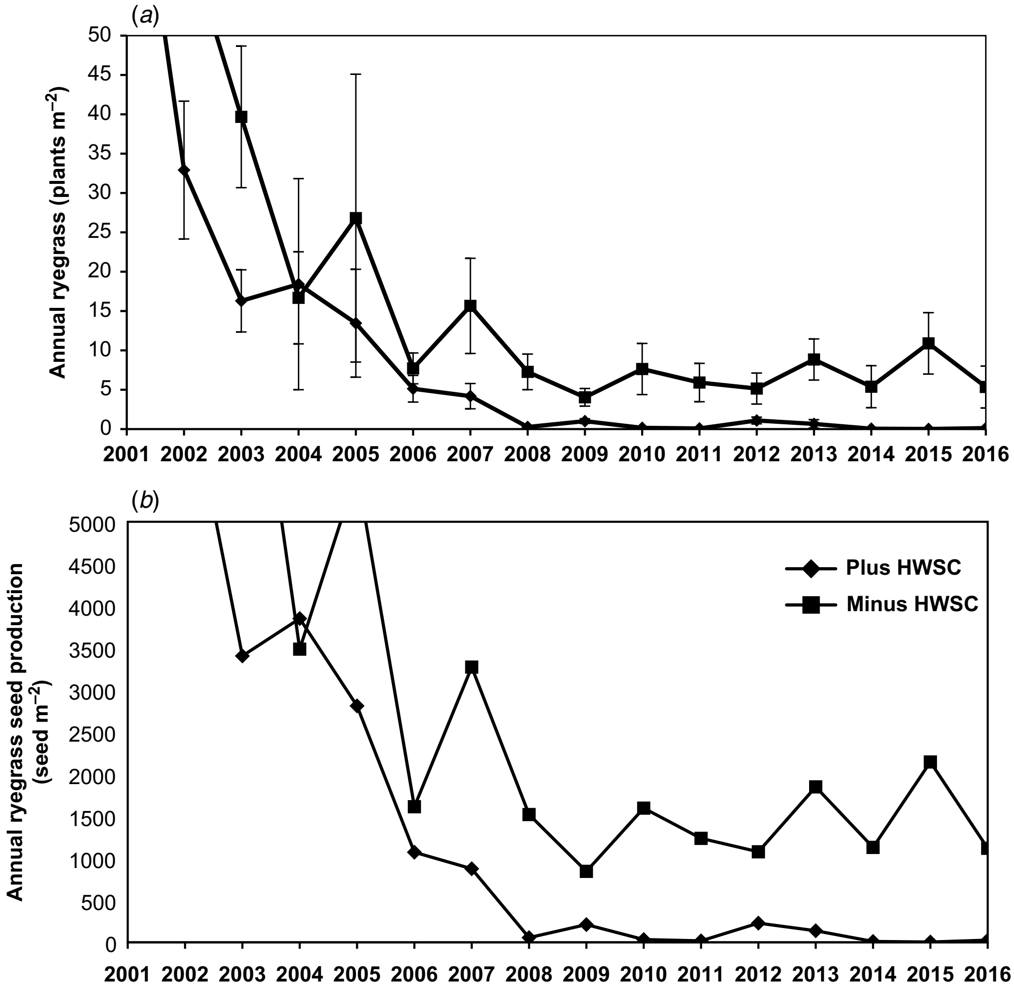

Fig. 2. Influence of herbicide alone and herbicide plus HWSC weed management programs on (*a*) average in-crop annual ryegrass populations and (*b*) predicted seedbank inputs in 25 Western Australian cropping paddocks from 2008 to 2016. Capped bars represent s.e. of the mean of 12 replicates. (Adapted with authors' permission from Walsh *et al.* 2018*c*.)

by 74% during wheat harvest (Shirtliffe and Entz 2005). The inclusion of chaff cart HWSC in weed management programs has been shown to improve the management of glyphosate-resistant Palmer amaranth in soybean (*Glycine max* L.) cropping systems (Norsworthy *et al.* 2016). Beam *et al.* (2019) determined that chaff collection during soybean harvest reduced subsequent emergence of annual ragweed by 22–26%. The study also found that, when used at harvest in wheat, this approach reduced subsequent emergence of Italian ryegrass by 30–69%. Similarly, narrow windrow burning HWSC controlled 100% of Palmer amaranth, Johnson grass (*Sorghum halepense* L.), barnyard grass (*Echinochloa crus-galli* L.) and pitted morning-glory (*Ipomoea lacunosa* L.) seed present in soybean crop residues (Norsworthy *et al.* 2020). Lyon *et al.* (2016) determined that burning narrow windrows of wheat crop residues formed during harvest reduced subsequent emergence of Italian ryegrass by 99%. Impact mill studies have confirmed high rates of weed seed destruction (>95%) of major weed species of soybean (Palmer amaranth and waterhemp), rice (barnyard grass and weedy rice (*Oryza sativa* L.)), oilseed and cereal (Italian ryegrass and wild oats) crops in the USA and Canada (Schwartz-Lazaro *et al.* 2017*b*; Tidemann *et al.* 2017*a*; Shergill *et al.* 2020*a*). It is now apparent that there is substantial research and development of HWSC systems for use in North American cropping systems. Development of HWSC systems for US cropping systems has recently been substantially boosted through support from several funding programs that have prioritised this area of research. As a result, a large multi-state program is currently evaluating 16 HWSC systems in US on-farm commercial trials (Flessner *et al.* 2021).

The introduction of HWSC systems into global cropping systems will require more than just consideration of weed seed retention at crop maturity and assessment of impacts on subsequent weed densities. Crop types, harvest environments and machinery used in many of the world's production

Table 2. Evaluations of HWSC systems at locations across the USA and Canada for their efficacy on weed species commonly occurring in major crops, as recently published.

HWSC system	Location	Crop	Weed species	Reference
Chaff cart	Manitoba, CA	Wheat (*Triticum aestivum* L.)	Wild oat (*Avena fatua* L.)	Shirtliffe and Entz (2005)
Chaff cart	Arkansas, US	Soybean (*Glycine max* L.)	Palmer amaranth (*Amaranthus palmeri* S.)	Norsworthy *et al.* (2016)
Chaff cart	Virginia, US	Wheat	Italian ryegrass (*Lolium perenne* ssp. *multiflorum*)	Beam *et al.* (2019)
Chaff cart	Virginia, US	Soybean	Common ragweed (*Ambrosia artemisiifolia* L.), Palmer amaranth	Beam *et al.* (2019)
Narrow windrow burning	Arkansas, US	Soybean	Palmer amaranth, Johnson grass (*Sorghum halepense* L.), barnyard grass (*Echinochloa crus-galli* L.), pitted morning-glory (*Ipomoea lacunosa* L.)	Norsworthy *et al.* (2020)
Narrow windrow burning	Washington state, US	Wheat	Italian ryegrass	Lyon *et al.* (2016)
Impact mill	Arkansas, US	Soybean	Palmer amaranth, pitted morning-glory, entireleaf morning-glory (*Ipomoea hederacea* Jacq.), common cocklebur (*Xanthium strumarium* L.), Johnson grass, barnyard grass, hemp sesbania (*Sesbania herbacea* Mill.), prickly sida (*Sida spinosa* L.), velvetleaf (*Abutilon theophrasti* Medik.), sicklepod (*Senna obtusifolia* L.), giant ragweed (*Ambrosia trifida* L.), common lambsquarters (*Chenopodium album* L.), weedy rice (*O. sativa*)	Schwartz-Lazaro *et al.* (2017*b*)
Impact mill	Arkansas, US	Rice (*Oryza sativa* L.)	Barnyard grass, weedy rice, hemp sesbania, rice flatsedge (*Cyperus iria* L.), Nealley's sprangletop (*Leptochloa nealleyi* Vasey), waterhemp (*Amaranthus tuberculatus* Moq.), Johnson grass	Schwartz-Lazaro *et al.* (2017b)
Impact mill	Illinois and Maryland, US	Soybean	Waterhemp, common lambsquarters, giant foxtail (*Setaria faberi* Herrm.), velvetleaf, ivyleaf morning-glory (*Ipomoea hederacea* Jacq.), giant ragweed, common cocklebur, smooth pigweed (*Amaranthus hybridus* L.), common ragweed, jimsonweed (*Datura stramonium* L.).	Shergill *et al.* (2020*a*)
Impact mill	Alberta, Ca	Field pea (*Pisum sativum* L.)	Kochia (*Kochia scoparia* L.), green foxtail (*Setaria viridis* L.), false cleavers (*Galium spurium* L.), volunteer canola, wild oat	Tidemann *et al.* (2017*a*)
Impact mill	Alberta, Ca	Barley (*Hordeum vulgare* L.) Canola (*Brassica napus* L.)	Volunteer canola	Tidemann *et al.* (2017*a*)

systems are different from the typical Australian grain crop harvesting conditions for which the current HWSC systems have been developed. For example, Australian grain crops are harvested during hot and dry conditions markedly different from the frequently cold and damp harvest environments often prevailing in large areas of North America and Europe (e.g. maize and soybean crop harvest). There is some evidence that impact mill systems will be less effective when the moisture content of crop residues is higher than the typical 12% limit for Australian grain crops (Schwartz-Lazaro *et al.* 2017*b*; Walsh *et al.* 2018*b*). Similarly, the cooler, damper post-harvest environment conditions for these and other crop production systems, along with strict regulations on smoke hazards, will restrict the use of HWSC systems such as narrow windrow burning and, to some extent, chaff carts that rely on residue burning (Norsworthy *et al.* 2020). Therefore, for these and other regions, production system and environment influences on the type and amount of harvest residues will affect HWSC system efficacy, particularly that achieved with impact mills (Tidemann *et al.* 2017*a*; Walsh *et al.* 2018*b*). In general, the introduction of HWSC systems into many of the world's cropping systems will require region-specific research and development efforts aimed at ensuring their effective implementation.

Influences on the efficacy of HWSC

Weed seed retention at the time of crop harvest defines the potential efficacy of HWSC systems, and large variations in retained seed between and within particular weed species need to be considered when planning the use of HWSC systems. The percentage seed retention of some weed species varies considerably (30–90%) (Walsh and Powles 2014; Borger *et al.* 2020; Schwartz-Lazaro *et al.* 2021*a*, 2021*b*). Where this variability has been noted, environmental conditions (e.g. wind, rain, high temperatures) have been identified as the major influence. In the Western Australian grainbelt, Borger *et al.* (2020) noted that a low-rainfall growing season resulted in less seed retention, of ~40% for brome grass and 90% for barley grass (*Hordeum leporinum* Link), in wheat crops. In the USA, Schwartz-Lazaro *et al.* (2021*b*) identified that seed retention by grass weed species in soybean crops was lower in northern production regions. Similarly, dependent on the weed species, seed retention usually declines as the harvest period progresses. Australian studies with the major weed species wild oats, brome grass and barley grass revealed considerable reductions in seed retention (>50%) over the first 4 weeks of wheat crop harvest (Fig. 3) (Walsh and Powles 2014; Borger *et al.* 2020). Similar weed seed retention studies in US soybean cropping systems identified that average reductions in seed retention as the harvest period progressed were low (10%) for broadleaf weeds, but much higher (42%) for grass weeds (Schwartz-Lazaro *et al.* 2021*a*, 2021*b*). On large grain farms where harvest extends over several weeks, HWSC efficacy will likely progressively decline over this period. Of course, growers can harvest first the particularly weedy crop fields so as to maximise weed seed 'harvest' and thus HWSC efficacy. However, this approach may compromise the need to prioritise harvest of higher quality/yielding crops. Agronomic practices that increase crop competition (e.g. higher crop plant density, narrower row spacing) can be used to increase seed retention height and improve HWSC efficacy.

Many problematic annual weeds of cropping systems are intolerant of shade and elongate to be taller when competing for light in high biomass crops (Morgan *et al.* 2002; Vandenbussche *et al.* 2005). This response to shading was potentially responsible for an increase in seed retention height by annual ryegrass plants in higher biomass yielding wheat crops (Walsh *et al.* 2018*a*). For 70 commercial wheat fields across southern and Western Australia, the proportion

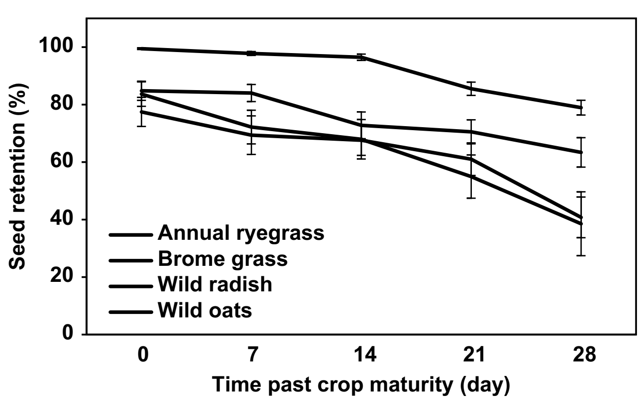

Fig. 3. Seed retention above harvest cutting height for four species averaged across nine sites at wheat crop maturity and at 7-day intervals for 28 days. Capped bars represent s.e. of the mean of three replicates and nine sites. (Modified from Walsh and Powles 2014.)

of annual ryegrass seed retained above 40 cm was increased by ~50% for plants growing in high (>12 t ha^{-1}) compared with low (<7 t ha^{-1}) biomass crops. In a study investigating competition effects due to increasing wheat plant densities, similar increases in the proportion of weed seed retained above 40 cm were observed for annual ryegrass, wild oats, brome grass and wild radish plants (Walsh 2019). In this study, seed retained above 40 cm at crop maturity at a wheat density of 60 plants m^{-2} was 50% for annual ryegrass, 57% for wild oats and 83% for wild radish, whereas for brome grass, it was just 5%. When wheat density was increased to 400 plants m^{-2}, seed retention above 40 cm increased to 93%, 70%, 98% and 70% for annual ryegrass, wild oats, wild radish and brome grass, respectively. The increase in wheat density from 60 to 400 plants m^{-2} also resulted in reductions in total seed production of 74–91% for these weed species. Similar reductions in weed seed production due to crop competition effects have previously been demonstrated for wild oats (Radford *et al.* 1980), wild radish (Eslami *et al.* 2006) and brome grass (Koscelny *et al.* 1990). Clearly, when crop competition is used in combination with HWSC treatments, there is the potential for an additive or even potentially synergistic effect on efficacy of HWSC on weed populations. Further investigations on crop–weed interactions for major weeds in cropping systems will likely identify additional biological attributes that can be exploited to sustain the efficacy and longevity of HWSC.

HWSC and the introduction of in-crop, site-specific weed control (SSWC)

The use of HWSC in concert with other control strategies can result in low in-crop weed densities, which creates the opportunity and momentum for the development and introduction of SSWC technologies. Estimated low in-crop annual ryegrass densities (<1.0 plant m^{-2}) that are now evident across much of Australia's cropping regions are a clear indication of effective and optimised herbicide use plus the impact of the widespread adoption of HWSC systems (Table 3). Although at reduced densities, annual ryegrass populations continue to persist in cropping fields; thus, owing to the highly fecund nature of this species, the potential remains for rapid population growth if control practices are relaxed (Gill 1996). Consequently, growers have been reluctant to scale back in-crop herbicide weed control treatments despite achieving very low weed densities.

The opportunity to implement in-crop, site-specific weed control in Australian cropping systems has been created by the combination of low weed densities and significant advances in automated weed recognition capability. Recent substantial improvements in computational power and machine-learning efficiency have resulted in the

Table 3. Average density of annual ryegrass populations when present in randomly surveyed crop fields across Australian cropping regions.

Cropping region	Annual ryegrass density (no. of plants m^{-2})
South Australia and Victoria[A]	<5.0
Western Australia[B]	<1.0
New South Wales[C]	<1.0
Tasmania[C]	<1.0

[A]Data from P Boutsalis (pers. comm. 2018).
[B]Data from M Owen (pers. comm. 2018).
[C]Data from J Broster (pers. comm. 2020).

development of accessible and low-cost RGB camera based weed-recognition systems (Fernández-Quintanilla *et al.* 2018). These sophisticated systems are well suited to the complex task of accurate in-crop weed recognition, which subsequently enables the in-crop, site-specific delivery of weed control treatments (Wang *et al.* 2019). The availability of suitably accurate in-crop weed recognition creates the opportunity to target specific weeds with non-selective physical and thermal weed control treatments, thereby expanding the options for in-crop weed control. The direct targeting of in-crop weeds with potentially highly effective SSWC treatments removes the need for the field-wide application of weed control treatments. Depending on the weed density, a SSWC approach enables growers to reduce inputs of weed control treatments such as herbicides by up to 90%, and to lower the agronomic and environmental risks associated with some weed control treatments (Timmermann *et al.* 2003). The savings in weed control from the use of SSWC, as well as rewarding diligent weed control, will ensure the enduring aim of reducing weed populations to very low densities.

Securing the long-term use of HWSC systems

The prolonged use of any weed control technology, regardless of how effective, is reliant on utilisation as part of a program with a diversity of tactics and strategies. As for all weed control treatments, the sustainability of HWSC is threatened by the potential for evolution of resistance (Powles and Yu 2010). In the case of 'resistance' to HWSC, this is most likely due to 'avoidance' mechanisms that enable the seed of targeted weeds to evade the HWSC treatment. Early seed shattering (less seed retention at weed maturity), or a more prostrate morphology are two obvious ways in which biotypes of weed species could avoid HWSC. There is, perhaps, already evidence in the results from seed retention studies of the potential for annual weed species to adapt to avoid weed seed targeting systems. Low weed seed retention at crop harvest occurs when there has been seed shedding from seed heads or pods as well as when collapsed or snapped tillers/branches place seed below a harvestable height. Incomplete and often variable seed retention implies genetically linked traits that can be selected by persistent reliance on HWSC. For example, seed shattering is a genetically controlled trait in major crops such as rice, soybean, canola (*Brassica napus* L.) and wheat (reviewed in Dong and Wang 2015), and in important weed species (e.g. *Avena* spp., *Echinochloa colona* and *Alopecurus myosuroides*) (Moss 1983; Barroso *et al.* 2006; Schwartz-Lazaro *et al.* 2017*a*; Tidemann *et al.* 2017*b*). Because there is evidence of adaptation in this trait in response to selection (e.g. weedy rice) (Yao *et al.* 2015), it is possible that continued weed species selection with HWSC will select for increased seed shattering. There is also the potential for species shifts in favour of those species with a more prostrate growth habit (e.g. *Hordeum leporinum*) with seed produced on lateral tillers or branches that are well below a harvestable height. As with all weed control technologies, securing the ongoing efficacy of HWSC systems requires due consideration to the potential for adaptation and avoidance.

The introduction of HWSC systems created the opportunity to use an alternate weed control technology suited to routine use at a novel weed control timing in grain crops grown in conservation cropping systems. Given the success of HWSC in Australian cropping and potential global importance, there is a need to develop an understanding of how best to implement HWSC. Annual ryegrass has been the primary target of HWSC systems for >20 years in Australian cropping, and to date there is no evidence of adaptation for HWSC avoidance in this species (Walsh *et al.* 2018*a*). An important factor in minimising the potential for annual ryegrass to adapt genetically to HWSC is weed population size. Evolution to counter HWSC, as occurred for herbicides, occurs most rapidly when weed numbers are high (Jasieniuk *et al.* 1996). At low weed numbers, evolution of resistance can occur more slowly. As indicated by the Plus HWSC treatment in Fig. 2*a*, the combination of herbicide treatments and HWSC use leads to lower annual ryegrass numbers. Evolution of resistance can be minimised by low weed numbers and maximum diversity in weed control strategies. This finding highlights the importance of effective in-crop herbicide treatments and importantly the need to support the use of herbicides and HWSC treatments with a multi-layered approach to weed management in grain production systems.

HWSC treatments will most likely continue to be used in Australian grain production systems because of the unique timing of this weed control approach, notwithstanding that there is species-specific, incomplete weed seed retention at crop maturity. With the degree of weed seed retention influenced by genetic and environmental factors (Walsh and Powles 2014; Walsh *et al.* 2018*a*; Borger *et al.* 2020; Maity *et al.* 2021), HWSC cannot be solely relied on for weed control, but must be viewed as a supplemental weed control practice. Similarly, because HWSC treatments have an end-of-season timing, their use will continue to be supported by earlier, in-crop weed control treatments (usually herbicides) to minimise weed interference during the growing season. Consequently, HWSC will continue to be implemented as one component of a weed management program and not as a stand-alone weed control practice.

Conclusion

The introduction of HWSC as an alternative, end-of-season weed control treatment has created the opportunity for routine targeting of the seed production of weed species surviving to maturity in Australian grain production systems. In Australia, the widespread use of HWSC has substantially improved the management of herbicide-resistant weed populations and helped to mitigate their adverse impact on crop production systems. The resultant 'improved' weed management programs have reduced weed population densities, as evidenced in the now commonly occurring, low annual ryegrass plant densities in Australia's cropping systems (Table 3). Low weed populations reduce the potential for evolution of resistance to weed control practices, providing some insurance for continuing weed control efficacy. Importantly, reduced weed densities create the opportunity to implement SSWC technologies that specifically target weed plants/patches, allowing considerably reduced weed control treatment inputs and the introduction of additional alternative weed control technologies. There is now considerable evidence identifying the opportunity of HWSC to target many of the problematic weeds of the world's major cropping regions. With the current significant HWSC research and development momentum in these cropping systems, this approach to weed control will likely have significant international adoption in the near future.

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Stephen Powles is Emeritus Professor at the University of Western Australia, following his retirement as long-term Director of the Australian Herbicide Resistance Initiative. He is widely recognised as a global expert in herbicides, herbicide resistance and weed control technologies, with over 300 publications in international journals. Powles is a Fellow of the Australian Academy of Science and the Australian Academy of Technology & Engineering. He is the recipient of the GRDC Seed of Light Award (2010) and in 2021 the coveted GRDC Seed of Gold Award. In addition to R & D in agricultural technology he stays grounded with a 340 hectare cropping farm devoted to wheat, canola and legume production.