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Harvest Weed Seed Control Systems are Similarly Effective on Rigid Ryegrass

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Harvest weed seed control (HWSC) systems have been developed to exploit the high proportions of seed retained at maturity by the annual weeds rigid ryegrass, wild radish, bromegrass, and wild oats. To evaluate the efficacy of HWSC systems on rigid ryegrass populations, three systems, the Harrington Seed Destructor (HSD), chaff carts, and narrow-windrow burning were compared at 24 sites across the western and southern wheat production regions of Australia. HWSC treatments were established at harvest (Nov. – Dec.) in wheat crops with low to moderate rigid ryegrass densities (1 to 26 plants m^{-2}). Rigid ryegrass counts at the commencement of the next growing season (Apr. – May) determined that HWSC treatments were similarly effective in reducing emergence. Chaff carts, narrow-windrow burning, or HSD systems act similarly on rigid ryegrass seed collected during harvest to deliver substantial reductions in subsequent rigid ryegrass populations by restricting seedbank inputs. On average, population densities were reduced by 60%, but there was considerable variation between sites (37 to 90%) as influenced by seed production and the residual seedbank. Given the observed high rigid ryegrass seed production levels at crop maturity it is clear that HWSC has a vital role in preventing seedbank inputs in Australian conservation cropping systems.
Nomenclature: Bromegrass, *Bromus* spp. Roth BRODI; rigid ryegrass, *Lolium rigidum* Gaudin LOLRI; wild oat, *Avena fatua* L. AVEFA; wild radish, *Raphanus raphanistrum* L. RAPRA; wheat, *Triticum aestivum* L.
Key words: Physical weed control, weed seed production.

Los sistemas de control de semilla durante la cosecha (HWSC) han sido desarrollados para explotar las altas proporciones de semilla retenida en la madurez por las malezas anuales *Lolium rigidum*, *Raphanus raphanistrum*, *Bromus* spp., y *Avena fatua*. Para evaluar la eficacia de los sistemas HWSC sobre poblaciones de *L. rigidum*, se compararon tres sistemas: el destructor de semilla Harrington (HSD), carretas de captura de paja, y quema de residuos acumulados en hileras, en 24 sitios a lo largo del oeste y el sur de las regiones productoras de trigo de Australia. Los tratamientos HWSC fueron establecidos durante la cosecha (Nov. – Dec.) en cultivos de trigo con densidades de plantas de *L. rigidum* de bajas a moderadas (1 a 26 plantas m^{-2}). Los conteos de *L. rigidum* al inicio de la siguiente temporada de crecimiento (Abr. – Mayo) determinaron que los tratamientos HWSC fueron similarmente efectivos para reducir la emergencia. Las carretas de captura de paja, la quema de residuos en hileras, o HSD actuaron en forma similar al colectar la semilla de *L. rigidum* durante la cosecha y para generar reducciones sustanciales en las poblaciones subsiguientes, al restringir el ingreso de semilla nueva al banco de semillas. En promedio, la densidad de las poblaciones se redujo en 60%, pero hubo una variación considerable entre sitios (37 a 90%) dependiendo de la producción de semilla y del banco de semillas residual. Con base en los altos niveles de producción de semilla de *L. rigidum* observados al momento de la madurez del cultivo, es claro que HWSC juega un rol vital para prevenir el ingreso de semillas al banco de semillas en los sistemas de cultivos de conservación Australianos.

In cropping systems, annual weed species infestations are completely dependent on the maintenance of a viable seed bank, and so there is widespread understanding that weed seed production must be prevented and/or targeted wherever feasible. The now widely adopted conservation cropping systems (Llewellyn et al. 2012) are based on reduced soil disturbance, resulting in weed seed banks being constricted to the upper soil layer (0 to 5 cm). In Australian cropping systems, shallow seed banks do not persist owing to predation (Spafford Jacob et al. 2006), fatal germinations, and high rates of seed

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decay (Chauhan et al. 2006b) that reduce seed bank life. Thus, in these systems seed bank decline will be more rapid for the dominant weed species: rigid ryegrass, wild radish, bromegrass, and wild oats (Chauhan et al. 2006b; Kleemann and Gill 2009; Martin and Felton 1993; Reeves et al. 1981). With seedbank life already somewhat restricted in conservation cropping systems, the opportunity should be taken to further exploit this situation by preventing seed bank inputs.

The retention of high proportions of total seed production at maturity has been identified as a key biological attribute (weakness) of problematic annual weed species of Australian cropping. Rigid ryegrass, wild radish, bromegrass, and wild oats all retain significant proportions of total seed production at crop maturity (Walsh and Powles 2014). Thus, during crop harvest these seeds are collected, threshed, separated from the grain, and expelled from the harvester in the chaff fraction. Modern grain harvesters are typically fitted with straw and chaff residue spreading systems that redistribute this material back across the harvest swath. Ironically, it is this process that results in collected weed seeds being evenly distributed across the field and back into the seedbank (Barroso et al. 2006; Blanco-Moreno et al. 2004).

In Australia, for three decades now the harvest operation has also been recognized as a weed control opportunity (Gill 1996; Matthews et al. 1996), representing the last chance during the growing season to restrict seed bank inputs of annual weed species. Importantly, annual weeds surviving to maturity in Australian cropping systems are likely to be herbicide resistant (Boutsalis et al. 2012; Broster et al. 2013; Broster and Pratley 2006; Owen et al. 2014; Owen et al. 2015). Subsequently, a number of harvest weed seed control (HWSC) systems have been developed for the specific purpose of targeting the seed production of these surviving weeds to restrict contributions to the seed bank (Walsh et al. 2012; Walsh and Newman 2007; Walsh et al. 2013).

There are now a number of approaches used to target the weed seed–bearing chaff fraction: collection and burning (chaff cart), concentration in a narrow windrow with straw residues for burning (narrow-windrow burning), collection in bales along with straw residues (bale direct system), and mechanical destruction during harvest using the Harrington Seed Destructor (HSD). Previous studies on some of these systems have determined that high (>90%) levels of rigid ryegrass seed control can be achieved at harvest (Walsh et al. 2012; Walsh and Newman 2007; Walsh and Powles 2007). The aim of this study was to establish the general efficacy of harvest weed seed control systems by comparing the impact of HSD, chaff cart, and narrow-windrow burning systems on rigid ryegrass populations across a range of western and southern Australian wheat belt region environments.

Materials and Methods

To evaluate the efficacy of HWSC systems across a range of crop production environments, a commercial harvester (9650 John Deere®) was used to establish 24 trial sites across the western and southern Australian crop production regions during the 2010 and 2011 harvests, respectively. To coincide with crop maturity, trial site establishment commenced in the northern Western Australia (WA) crop production region on November 8, then proceeded south and east through the region over a 6-wk period (Figure 1). Similarly, in 2011 the same harvester was used to establish 13 trial sites in the southern Australian cropping region. Commencing in the westernmost area of this region on December 2, trial sites were established while traveling east and north through the region. At each site, treatments were established under commercial harvest conditions in wheat crops with uniform low to moderate rigid ryegrass infestations (Table 1). The establishment and management of HWSC treatments was conducted as per standard commercial practices for the use of these techniques (Walsh et al. 2013). A chute was fitted to the rear of the harvester to concentrate chaff and straw residues into a narrow (500 mm) windrow during harvest. A trailing HSD system processed chaff material as it exited the harvester, establishing the HSD treatments. The same harvester was used to establish control (conventional harvest), narrow windrow burning, and HSD treatments. Chaff cart treatments, in which a harvester with a trailing cart was used to collect and remove chaff material from the plot areas, were established with equipment provided by a local farmer.

Prior to harvest, rigid ryegrass plants were counted and seed heads above harvester cutting height (15 cm) were collected from 1- to 10-m^2 quadrat

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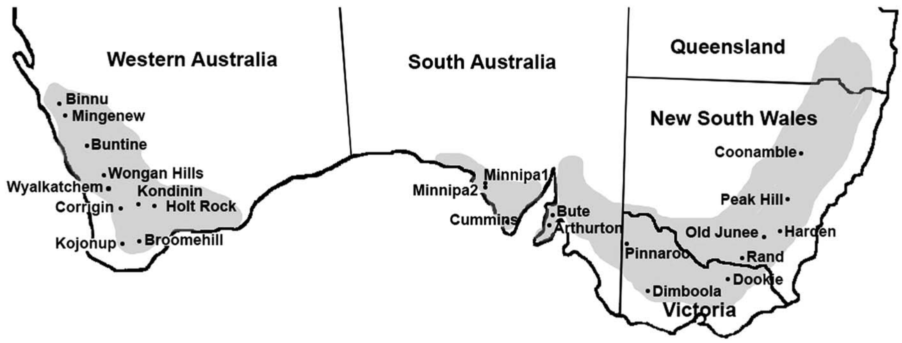

Figure 1. Harvest weed seed control trial sites established at 24 locations across the Australian wheat belt (shaded area) during the 2010 and 2011 wheat harvest period.

areas across the trial site. Seed heads from each quadrat were bulked and subsequently threshed, and the collected seed counts provided a site average annual ryegrass plant seed production. HWSC treatments were established in 11 by 50 m strips in a randomized complete block design with four replicates. Chaff collected in the chaff cart treatment was dumped for burning in a location away from the plot area. At the start of the next growing season (April to May), when burning restrictions had been lifted, chaff heaps and narrow windrows were burned. Standard burning practices were used to ensure a complete burn of these residues, and therefore the destruction of collected weed seed.

As the major proportion of rigid ryegrass emergence results from the previous season's seed production (Monaghan 1980; Reeves and Smith 1975), the density of annual ryegrass that emerged the following growing season was used to assess HWSC efficacy. After the season-opening rains and prior to any herbicide treatments, rigid ryegrass emergence counts were conducted at each site to assess HWSC treatment effects. Rigid ryegrass plant densities were determined in each plot by counting plants in 0.1- to 20-m^2 quadrats. An analysis of variance using SAS® statistical software (SAS Institute Inc., Cary, NC 27513) was performed on rigid ryegrass plant emergence counts. Due to site differences ($P < 0.05$), analyses comparing HWSC treatments were performed individually for each location.

Table 1. Rigid ryegrass plant density and seed production above harvester cutting height (15 cm) in wheat crops immediately prior to harvest at 24 locations. Numbers in parentheses represent standard errors of the mean for four replicates.

Location	Rigid ryegrass		
	plants m^{-2}	seeds m^{-2}	seeds $plant^{-1}$
Arthurton, SA	1 (1)	28	28
Binnu, WA	21 (5)	4410	210
Broomehill, WA	8 (2)	1792	224
Buntine, WA	23 (3)	3680	160
Bute, SA	5 (2)	591	118
Coonamble, NSW	10 (1)	796	80
Corrigin, WA	4 (2)	1216	304
Cummins, SA	5 (1)	1039	208
Dimboola, Vic.	2 (1)	138	69
Dookie, Vic.	15 (3)	2509	167
Harden, NSW	11 (2)	4017	365
Holt Rock, WA	14 (3)	5320	380
Kojonuop, WA	6 (2)	2520	420
Kondinin, WA	26 (3)	4576	176
Mingenew, WA	26 (4)	4524	174
Minnipa1, SA	3 (1)	522	174
Minnipa2, SA	6 (1)	1675	279
Old Junee, NSW	1 (1)	286	286
Peak Hill, NSW	8 (1)	2879	360
Pinnaroo, SA	6 (2)	356	59
Rand, NSW	5 (1)	2127	425
Tenindewa, WA	16 (3)	2000	125
Wongan Hills, WA	8 (2)	1792	224
Wyalkatchem, WA	15 (3)	2175	145
Average	**10 (2)**	**2041**	**209**

Results and Discussion

The high number of rigid ryegrass seeds retained at harvest highlights the fecundity of this species, but more importantly, the potential impact of HWSC on seed bank replenishment. Pre-harvest counts determined that the average rigid ryegrass plant density present at harvest across the 24 trial sites was 10 plants m^{-2}, ranging from 1 to 26 plants m^{-2} (Table 1). These infestations have persisted through typical commercial weed control treatments during the growing season to mature with the wheat crop. With an average production of 209 seeds per plant, over 2000 seeds m^{-2} were retained above the low harvest height of 15 cm. Given that seed retained above this height represents approximately 85% of total seed production (Walsh and Powles 2014), these seed production levels are similar to previously recorded values for rigid ryegrass plants maturing in Australian wheat crops (Reeves 1976).

HWSC treatments were similarly effective in reducing the rigid ryegrass population emerging the following growing season. Across all 24 sites, chaff cart, narrow windrow burning, and HSD treatments each reduced ($P < 0.05$) rigid ryegrass emergence compared to the untreated control (conventional harvest treatment) (Table 2). This is not surprising, as HWSC systems all target the weed seed–bearing chaff fraction exiting the harvester. Therefore, if chaff destruction operations of burning (chaff cart and narrow windrow) and mill processing (HSD) are conducted effectively (Walsh et al. 2012; Walsh and Newman 2007), then it is expected that these systems will deliver similar effects on rigid ryegrass populations.

HWSC treatments had a substantial impact on subsequent rigid ryegrass emergence, and that impact was more pronounced when population densities, and most likely seed bank levels, were lower. When averaged across 24 sites, HWSC treatments reduced the emergence of rigid ryegrass by 60% (Table 2). Given the number and distribution of trial sites across the Australian wheat belt, this value represents the expected result from the use of HWSC. There was considerable variation in HWSC efficacy between sites, with large reductions in rigid ryegrass emergence (70% to 90%) at Arthurton, Corrigin, and Old Junee, contrasting with lower reductions (30% to 40%) at Rand and Minnipa1. Emergence reflects both seed bank carryover and the previous season's inputs; thus the observed results in the field

Table 2. Rigid ryegrass plant densities in response to harvest weed seed control treatments conducted during wheat harvest at 24 sites during 2010 and 2011. Treatment means followed by the same letter within each site are not different at LSD $P \leq 0.05$.

Location	Control	Chaff cart	Narrow-windrow burn	Harrington seed destructor	Reduction in emergence
	Rigid ryegrass (plants m^{-2})				(%)
Arthurton, SA	12 a	2 ab	1 b	1 b	90
Binnu, WA	21 a	8 b	6 b	7 b	66
Broomehill, WA	20 a	8 b	6 b	9 b	61
Buntine, WA	264 a	131 b	103 b	78 b	61
Bute, SA	89 a	42 b	41 b	38 b	55
Coonamble, NSW	208 a	-	98 b	104 b	51
Corrigin, WA	11 a	3 b	3 b	4 b	69
Cummins, SA	294 a	147 b	146 b	162 b	48
Dimboola, Vic.	13 a	4 b	4 b	5 b	68
Dookie, Vic.	5164 a	-	2146 b	2376 b	61
Harden, NSW	5442 a	-	2862 b	2855 b	51
Holt Rock, WA	321 a	112 b	128 b	104 b	64
Kojonuop, WA	143 a	81 b	-	56 b	52
Kondinin, WA	200 a	92 b	112 b	101 b	49
Mingenew, WA	39 a	20 b	22 b	20 b	45
Minnipa1, SA	413 a	229 b	233 b	229 b	37
Minnipa2, SA	234 a	-	78 b	62 b	62
Old Junee, NSW	12 a	-	4 b	3 b	72
Peak Hill, NSW	358 a	-	186 b	126 b	56
Pinnaroo, SA	181 a	74 b	55 b	55 b	66
Rand, NSW	262 a	159 b	169 b	148 b	42
Tenindewa, WA	52 a	-	17 b	21 b	64
Wongan Hills, WA	24 a	9 b	9 b	11 b	60
Wyalkatchem, WA	117 a	51 b	45 b	64 b	55
Average	**554**				**60**

- Treatment not established at this site

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are impacted by the residual seed bank despite the proven high efficacy (>90% seed kill) of HWSC treatments (Walsh et al. 2012; Walsh and Newman 2007). Therefore, the average level of HWSC effect of 60% indicates that residual seed bank levels are having a significant influence on the efficacy of these systems. For example, lower reductions in emergence at some sites were likely due to a large seed bank; this is clearly indicated at sites where emergence was higher than the previous season's seed production (e.g., Harden, Dookie). Seed bank persistence of rigid ryegrass is approximately 3 yr, but varies from 1 to 4 yr (Kleemann et al. 2016; McGowan 1970; Peltzer and Matson 2002). Therefore, the observed impact of HWSC over time on rigid ryegrass populations will vary according to seed bank persistence, generally increasing as seed bank levels decline.

It is only with reduced seed bank inputs that annual weed populations can be controlled. The level of seed production from the average rigid ryegrass plant density in these studies resulted in the production of approximately 2000 seeds m^{-2}. During a typical commercial harvest, this seed is evenly spread (seeded) across the field by the residue distribution systems of modern harvesters. Ironically, this seeding rate of 2000 seeds m^{-2} is more than double that recommended for rigid ryegrass pasture establishment (Launders et al. 2010; Venuto et al. 2004). Even with a 20% to 30% loss of viable seed resulting from predation, fatal germination, and decay (Chauhan et al. 2006a), as well as seed bank retention due to dormancy, this seed bank recruitment will likely realize the establishment of >100 rigid ryegrass seedlings m^{-2} in the following growing season. Thus, not only is there a real opportunity, but an obvious need to intercept weed seed production at harvest using HWSC systems.

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