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High Levels of Adoption Indicate That Harvest Weed Seed Control Is Now an Established Weed Control Practice in Australian Cropping

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HWSC systems that target weed seed production during harvest have been in use in Australian crop production systems for over 30 years. Until recently, though, grower adoption of these systems has been relatively low. It is now apparent with the introduction of a range of new weed seed targeting systems that there is renewed grower interest in the use of this approach to weed control. With the aim of determining the current adoption and use of HWSC systems, 600 crop producers from throughout Australia's cropping regions were interviewed on their adoption and use of these systems. This survey established that 43% of Australian growers are now routinely using HWSC to target weed seed production during grain harvest. The adoption of narrow-windrow burning (30%) was considerably greater than the other currently available techniques of chaff tramlining (7%), chaff carts (3%), bale-direct system (3%), and the Harrington Seed Destructor (HSD) (<1%). When growers were asked about their future use of these systems 82% indicated that they would be using some form of HWSC within five years. Grower preferences for future HWSC use were primarily for either narrow-windrow burning (42%) or the HSD (29%). This very high level of current and potential HWSC adoption signifies that HWSC is now considered an established weed control practice by Australian growers.
Key words: Bale-direct system, chaff cart, chaff tramlining, Harrington Seed Destructor (HSD), narrow-windrow burning.

The efficacy of harvest weed seed control (HWSC) systems is based on the biological attribute of high seed retention at maturity by annual weed species. For many of Australia's dominant weeds of cropping systems, seed heads remain intact at maturity with high levels of seed production retained at a height that ensures collection during crop harvest: >75% for rigid ryegrass (*Lolium rigidum* Gaudin), wild radish (*Raphanus raphanistrum* L.), wild oat (*Avena fatua* L.), and cheat (*Bromus secalinus* L.) (Walsh and Powles 2014). Collected weed seeds are processed, separated from the grain, and then expelled from the grain harvester, mostly in the chaff fraction, and ironically are redistributed across the crop field, entering the seedbank to become future weed problems. Thus, crop harvest presents an opportunity to exploit high weed seed retention by targeting the collected weed seeds as they pass through the harvester (combine), thereby restricting seedbank inputs. With the major portion (e.g., >95% rigid ryegrass) of collected weed seeds exiting in the chaff fraction, several HWSC systems have been developed specifically to target this material (Walsh et al. 2013).

Although HWSC systems have been in use in Australian cropping for over three decades, it is only recently that their use has become widespread. The first system used in Australia in the late 1980s was chaff carts, introduced from Canada where they were used during harvest to collect chaff material for stock feed (Olfert et al. 1991). Australian growers recognized the potential value of this system in targeting weed seeds during harvest. However, despite their efficacy (Matthews et al. 1996; Walsh and Powles 2007), their adoption has remained low. In a survey of 132 Western Australian (WA) growers in 2000 (Llewellyn et al. 2004), it was determined that 7% were currently using chaff carts, but that 10% had

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used this practice over the previous four years. Despite the slight reduction in adoption, grower recognition of the value of this system remained with 23% expected to be using chaff carts in the next four years.

In the late 1990s, more than a decade after the introduction of chaff carts, WA growers began developing alternate HWSC systems. The first of these was narrow-windrow burning, which was first used in the northern WA cropping zone in the mid-1990s (Walsh and Newman 2007). The adoption of this practice was rapid, and 21% of the growers surveyed by Llewellyn et al. (2004) were using this practice in 2000. Despite the popularity of narrow-windrow burning, additional HWSC systems continued to be developed. The bale-direct system (during-harvest baling of all harvest residues) became commercially available during the mid-2000s. Chaff tramlining (concentration of chaff material on dedicated wheel tracks) was also introduced in WA in the late 2000s, and most recently, the Harrington Seed Destructor (HSD), a cagemill-based chaff processing system, became commercially available in 2012 (Walsh et al. 2012).

As indicated by demand for new HWSC systems and information on their efficacy, it is clear that there is increasing adoption of this approach to weed control. The objective of this paper is to establish the current level of HWSC adoption, as identified in an interview survey of 600 crop producers evenly representing each of Australia's cropping regions.

Materials and Methods

Crop Producer Survey. A grower survey of crop production practices was conducted across the 13 crop production zones of Australia designated by the Grains Research and Development Corporation (GRDC) (Table 1). As part of a larger survey (Llewellyn et al. 2016), specific information was collected on grower adoption and use of HWSC systems.

A total of 602 grain growers were surveyed, beginning in March 2014, with some follow-up interviews completed in July 2014. Interviews were conducted by phone to facilitate a relatively high response rate and ensure a sound representation of grain growers. Participants were offered the chance to win one of ten $50 gift cards. Growers were randomly contacted until the quota for growers meeting the criteria in each cropping zone was met, resulting in 602 complete responses distributed across these zones (Table 1). Respondents needed to be identified as primary cropping decision makers and were screened based on their farm's crop area having been greater than 500 ha, with the exception of the High Rainfall Victoria and Tasmanian zone, where this was later reduced to 250 ha to reflect the commonly smaller farm size in this zone. The completion rate of the survey was 44% of the total number of primary cropping decision makers directly approached for participation. The 602 grower responses represent a total arable area of 2.0 million hectares.

Table 1. The number and proportion of growers surveyed in each cropping region and zone.

Cropping region and zone	Growers surveyed	Percentage of total
		%
Northern Region		
Queensland Central	28	5
New South Wales North-East/ Queensland South-East	45	7
New South Wales North-West/ Queensland South-West	46	8
Southern Region		
New South Wales Central	49	8
New South Wales -Victoria Slopes	52	9
Victoria High Rainfall and Tasmania Grain Zone	51	8
South Australia-Victoria Bordertown-Wimmera	50	8
South Australia-Victoria Mallee	52	9
South Australia Mid-North/Lower Yorke, Eyre	51	8
Western Region		
Western Australia Sandplain-Mallee	46	8
Western Australia Central	45	7
Western Australia Northern	40	7
Western Australia Eastern	47	8

HWSC System Definitions and Questions on Adoption and Use of These Systems. Growers were asked about five harvest weed seed control practices described as follows:

- Chaff cart. A trailing cart attached to the harvester collects the chaff fraction, which is then strategically dumped to be burned, grazed, or removed.
- Bale-direct system. Chaff and straw collected during harvest are baled directly using a baler attached to the harvester.

- Narrow-windrow burning. Chaff and straw are concentrated in narrow windrows (500 to 600 mm wide) at harvest to be later burned to destroy the weed seeds.
- Chaff tramlining. Chaff is concentrated at harvest on dedicated tramlines used in a controlled traffic system.
- HSD. A trailer-mounted chaff processing system attached to the harvester that processes chaff in order to destroy weed seeds.

Q. I am now going to read you out a list of five harvest weed control systems. Can you please tell me which ones you use?

Q1a. Do you use a chaff cart for harvest weed seed control?

Q1a1. In what year did you first start using this practice?

Q1a2. On what percentage of your annual cropped area did you use this practice, as an average, over the past three seasons? *(Or % that will be cropped in the coming crop season if they have not previously used this practice.)*

Q1a3. Do you expect to be using this practice in five years?

Q1b. Do you use a bale-direct system for weed control purposes?

Q1b2. On what percentage of your annual cropped area did you use this practice, as an average, over the past three seasons? *(Or % that will be cropped in the coming crop season if they have not previously used this practice.)*

Q1b3. Do you expect to be using this practice in five years?

Q1c. Do you use narrow-windrow burning for weed control purposes? Narrow-windrow burning is placing chaff in narrow windrows at harvest and later burning them.

Q1c1. In what year did you first start using this practice?

Q1c2. On what percentage of your annual cropped area did you use this practice, as an average, over the past three seasons? *(Or % that will be cropped in the coming crop season if they have not previously used this practice.)*

Q1c3. Do you expect to be using this practice in five years?

Q1d. Do you use chaff tramlining for weed control? Chaff tramlining is concentrating chaff at harvest on dedicated tramlines used in a controlled traffic system.

Q1d2. On what percentage of your annual cropped area did you use this practice, as an average, over the past three seasons*? (Or % that will be cropped in the coming crop season if they have not previously used this practice.)*

Q1d3. Do you expect to be using this practice in five years?

Q1e. Do you use a HSD for weed control?

Q1e2. On what percentage of your annual cropped area did you use this practice, as an average over the past three seasons? *(Or % that will be cropped in the coming crop season if they have not previously used this practice.)*

Q1e3. Do you expect to be using this practice in five years?

Q1f. Which of the five harvest weed seed control systems I just mentioned would you most prefer to be using in five years' time, if you had to select one: 1) chaff cart, 2) bale-direct system, 3) narrow windrow burning, 4) chaff tramlining, or 5) HSD?

Q1g. What are the main reasons you are not using this practice now?

Results and Discussion

National and Regional HWSC Adoption. As evidenced by widespread adoption, HWSC is now an accepted weed control practice for Australia's crop producers. Our survey of producers, representing each Australian grain crop production region, (Table 1) revealed that 43% of growers are currently using HWSC to target weed seeds during crop harvest (Table 2). Narrow-windrow burning (30%) is the most commonly used HWSC technique, with much lower levels of use of other available systems: chaff tramlining (7%), chaff carts (3%), the bale-direct system (3%), and the HSD (<1%). The western region has the highest proportion (63%) of HWSC users, followed by the southern region (39%), with the northern region (19%) having lower but substantial levels of adoption. The high level of adoption in the western region is not surprising given that most of the currently available HWSC systems, narrow-windrow burning, bale-direct, chaff tramlining, and HSD, were developed by western region growers. Additionally, the higher levels of adoption across this and some of the southern cropping regions are a likely response to higher frequencies of

Table 2. Grower adoption of narrow-windrow burning, chaff tramlining, chaff carts, and the bale-direct system, and the crop area on which these harvest weed seed control systems are used on in each of Australia's cropping zones.

Cropping region and zone	Narrow-windrow burning		Chaff tramlining		Chaff cart		Bale-direct system		
	Adoption[a]	Crop area[b]	Adoption	Crop area	Adoption	Crop area	Adoption	Crop area	Total adoption
	%								
Northern	**4**	**23**	**13**	**77**	**1**	**78**	**1**	**15**	19
Qld Central	-	-	18	88	4	78	-	-	22
NSW NE/Qld SE	-	-	18	71	-	-	-	-	18
NSW NW/Qld SW	11	23	4	75	-	-	2	15	17
Southern	**28**	**23**	**6**	**70**	**1**	**63**	**4**	**27**	39
NSW Central	12	30	2	100	-	-	2	10	16
NSW Vic. Slopes	33	29	12	63	-	-	12	14	57
SA Midnorth-Lower Yorke Eyre	31	15	-	-	4	50	-	-	35
SA Vic Bordertown-Wimmera	38	13	2	100	-	-	4	45	44
SA Vic Mallee	21	18	6	39	-	-	6	37	33
Vic. High Rainfall & Tas.	33	34	12	82	2	90	2	60	49
Western	**51**	**30**	**4**	**86**	**7**	**59**	**1**	**13**	63
WA Central	56	25	7	70	13	57	2	5	78
WA Eastern	45	33	4	90	-	-	-	-	49
WA Sandplain-Mallee	33	23	4	100	9	73	2	20	48
WA Northern	75	36	3	100	8	47	-	-	86
National average	**30**	**26**	**7**	**76**	**3**	**61**	**3**	**25**	**43**

[a] Adoption expressed as percentage of all growers in region or zone.

[b] Average percentage of cropping land is the proportion of cropping land receiving this practice over the last three years.

herbicide-resistant weed populations (Boutsalis et al. 2012; Broster et al. 2013; Owen et al. 2014, 2015).

It is apparent that there has been a dramatic increase nationally in the use of HWSC systems over the last five years. The only previously published data on HWSC use by WA growers in 2000 determined that approximately 28% of survey participants were using either of the two available HWSC options at the time, chaff carts (7%) and narrow-windrow burning (21%) (Llewellyn et al. 2004). There were similar results from our survey, in which 30% of western region growers reported that they first started using HWSC in 2008, using either narrow-windrow burning (21%) or chaff carts (9%). It is also estimated that in 2008 HWSC adoption in the northern and southern cropping regions was just 11% and 2%, respectively, with narrow-windrow burning accounting for all northern region HWSC use and 90% of southern region HWSC use. These adoption levels may be a slight underestimate, as they do not include the use of the other HWSC systems available at that time: bale-direct and chaff tramlining. Growers using these systems were not asked when they first started using these systems, and therefore, no historical data on the use of these systems were collected.

Narrow-Windrow Burning. The most commonly used HWSC system in Australian cropping is narrow-windrow burning, with an estimated 30% of Australian crop producers now using this practice. This approach to HWSC control was developed in the WA northern zone and, not surprisingly, 75% of growers in this area are using this approach (Table 2). The western region in general has the highest frequency of adoption of this practice with 50% of growers routinely using narrow windrow burning. Adoption in the southern region is the next highest, with 28%, while only 4% of northern region crop producers use this practice.

Cumulative adoption of narrow windrow burning highlights the earlier and higher level of adoption of this practice by growers in the WA northern cropping zone. Over a period of 13 years, the frequency of this zone's growers using this practice increased from less than 10% in 2000 to 75% in 2013 (Figure 1).

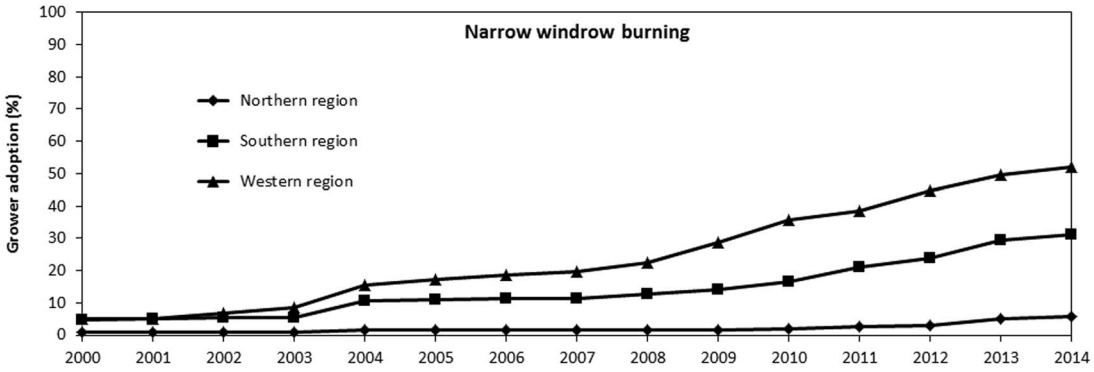

Figure 1. Cumulative adoption of narrow windrow burning in each of Australia's cropping zones.

The rate of adoption of narrow windrow burning across this zone consistently averaged approximately 5% annually over this period. In comparison, the initial adoption of this practice in the southern and northern regions was delayed by 4 to 12 years, respectively. However, once commenced, adoption levels have consistently increased by 5% to 6% annually in these regions as well.

Chaff Tramlining. Although the most recently developed, chaff tramlining is the second most commonly grower-adopted HWSC system. Where adopted, this system is used on a greater proportion of cropped area than other HWSC systems. The advantage of this approach over most of the other options is that residue burning is not required for weed seed control. However, unlike other HWSC systems, weed control efficacy has not yet been documented. The highest level of chaff tramlining adoption has occurred in the northern cropping region, where 13% of growers are using this technique (Table 2). Frequencies of adoption in the western and southern regions are lower at 4% and 6%, respectively. Consistent across all regions is the elevated proportion of the harvested area that chaff tramlining is used on. Where adopted, growers used this system across 77% of their cropped area, a substantially higher area of use than that for narrow-windrow burning (26%), chaff carts (61%), and the bale-direct system (25%).

Chaff Carts. Chaff carts were the initial form of HWSC introduced into Australian cropping, but despite this their adoption has been slow and remains low, with just 3% of Australian producers using this system. Although first introduced over 30 years ago, and with demonstrated high efficacy (Walsh and Powles 2007), the uptake of this technology has been slow (Table 2), probably due to practical limitations with the transfer of chaff to the cart and the burning of collected residues. The highest proportion of chaff cart users are in the WA central cropping zone, with 13% of growers in this zone using this system (Table 2). With growers in this zone reporting that they first began using this system in the early 1990s, the annual uptake then is <1.0% annually. Similarly, low rates of adoption for this system are consistent throughout the cropping zones where chaff cart adoption has occurred.

Future Use of HWSC Systems. The national levels of HWSC adoption are expected to double over the next five years. When surveyed growers were asked about future use of HWSC practices, 82% expected to be using some form of this approach for weed control in the next five years (Table 3). This indicates that, nationally, HWSC adoption is expected to increase by approximately 8% annually over this period. Narrow windrow burning is expected to remain the most commonly used technique, with 46% of growers expecting to be using this system, a 16% increase over the current level of adoption. Chaff tramlining will be the next most frequently used system at 15% adoption, followed by chaff carts at 10%, HSD at 7%, and the bale-direct system at 4%.

Despite the planned use of the HSD being low, almost a third of Australian growers using HWSC would prefer to be using this system. When asked which HWSC system they would prefer to be using in five years' time, the majority of growers chose narrow-windrow burning (42%) and HSD (29%) (Table 4). There were much lower preferences for chaff

Table 3. Harvest weed seed control systems that growers are planning to use in the next five years.[a]

Cropping region and zone	Narrow windrow burning			Chaff tramlining			Chaff cart			Bale direct			HSD		
	Yes	No	Unsure	Yes	No	Unsure	Yes	No	Unsure	Yes	No	Unsure	Yes	No	Unsure
	%														
Northern	**10**	**80**	**10**	**15**	**76**	**8**	**3**	**92**	**6**	**3**	**90**	**8**	**3**	**88**	**9**
Qld Central		89	11	18	71	11	2	93	4		96	4		96	4
NSW NE/Qld SE	4	91	4	20	78	2	2	89	9	2	89	9	2	87	11
NSW NW/Qld SW	22	63	15	9	78	13	4	93	4	4	87	9	4	85	11
Southern	**47**	**43**	**10**	**15**	**75**	**10**	**5**	**84**	**11**	**5**	**88**	**7**	**6**	**85**	**9**
NSW Central	29	63	8	14	78	8	4	88	8	2	96	2	2	94	4
NSW Vic Slopes	50	40	10	15	71	13	2	88	10	12	79	10	4	87	10
SA Midnorth-Lower Yorke Eyre	55	33	12	12	78	10	14	69	18	2	88	10	18	71	12
SA Vic Bordertown-Wimmera	68	20	12	14	68	18	4	82	14	6	84	10	6	80	14
SA Vic Mallee	35	56	10	12	81	8	4	83	13	6	90	4	6	87	8
Vic. High Rainfall & Tas.	47	45	8	25	73	2	4	92	4	4	90	6	2	90	8
Western	**67**	**26**	**7**	**13**	**78**	**9**	**22**	**66**	**12**	**4**	**93**	**3**	**12**	**72**	**15**
WA Central	73	18	9	13	71	16	31	58	11	4	93	2	11	67	22
WA Eastern	64	34	2	15	83	2	11	81	9	4	94	2	11	83	6
WA Sandplain - Mallee	52	33	15	17	70	13	24	63	13	7	87	7	11	70	20
WA Northern	83	18		8	88	5	23	60	18		100		18	70	13
National average	**46**	**45**	**9**	**15**	**76**	**9**	**10**	**80**	**10**	**4**	**90**	**6**	**7**	**82**	**11**

[a] Percentage of growers, expressed as percentage of all growers per region or zone. Growers currently using a harvest weed seed control system are assumed to be future users.

tramlining (9%), chaff cart (12%), and the bale-direct system (8%). In general, these grower preferences of HWSC systems were similar to their reported plans to use these systems (Tables 3 and 4). The exception was planned use of HSD, with only low numbers of growers planning to use this system despite this being a highly preferred option. When growers were asked to provide a reason for not adopting the HSD, the most common responses were the perceived high cost (55%) and unproven technology (24%).

The demand for alternate weed control tactics, such as HWSC, has been driven by high frequencies of herbicide resistance, but the adoption of these systems has likely been facilitated by workshops featuring grower presenters. Survey respondents were not asked to provide information on what influenced their decision to adopt HWSC. It is clear that high frequencies of herbicide resistance are a contributing factor. However, high frequencies of herbicide resistance have been present in Australian cropping systems for almost two decades, and therefore this factor alone does not explain the increased levels of adoption that have occurred recently. Specifically, from 2010 onwards there have been substantial increases in the adoption of narrow windrow burning (Figure 1). It was at this time that we began conducting HWSC workshops, featuring grower presenters, throughout Australia's production regions. The combination of research data and growers' personal experiences with the practical implementation of HWSC systems resonated well with audiences. In particular, it was how these innovative grower presenters had overcome the practical barriers to adoption that was crucial for many. Initial observations were that adoption was immediate and substantial in areas where these workshops were held.

High levels of HWSC adoption by Australian growers clearly signifies that this approach to weed control is now an accepted and routine weed control practice in Australian cropping systems. HWSC systems have been developed because high retention of problematic weeds at crop maturity creates the opportunity to target these weed seeds during harvest (Walsh and Powles 2014). Importantly though, adoption of these systems is being driven by very high frequencies of herbicide-resistant weed populations across many of Australia's cropping regions. The ongoing refinement and development of HWSC systems, as evidenced by the recent introduction of the integrated HSD (iHSD), will continue to drive grower interest in the use of these systems. The challenge now though is to motivate grower adoption as a pre-emptive tactic for herbicide conservation rather than a reactive response to herbicide resistance.

Table 4. Grower preference of harvest weed seed control system if adopting this practice within the next five years.[a]

Cropping region and zone	Narrow windrow burning	Chaff tramlining	Chaff cart	Bale direct	HSD
			%		
Northern region	**40**	**17**	**10**	**9**	**24**
Qld Central	25	29	18	-	29
NSW NE/Qld SE	44	18	9	7	22
NSW NW/Qld SW	46	9	7	17	22
Southern region	**44**	**6**	**9**	**11**	**31**
NSW Central	45	10	16	8	20
NSW Vic Slopes	50	8	2	17	23
SA Midnorth-Lower Yorke Eyre	41	-	14	2	43
SA Vic Bordertown-Wimmera	38	6	2	18	36
SA Vic Mallee	44	4	6	8	38
Victoria High Rainfall & Tasmania Grain	45	6	12	14	24
Western region	**40**	**6**	**18**	**2**	**34**
WA Central	33	9	16	4	38
WA Eastern	51	4	21	-	23
WA Sandplain - Mallee	37	4	20	4	35
WA Northern	40	5	15	-	40
National average	**42**	**9**	**12**	**8**	**29**

[a] Percentage of all growers per region.

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