Weed Technology

www.cambridge.org/wet

Influence of chaff and chaff lines on weed seed survival and seedling emergence in Australian cropping systems

Michael J. Walsh[1], Annie E. Rayner[2], Annie Ruttledge[3] and John C. Broster[4]

[1]Associate Professor, Sydney Institute of Agriculture, University of Sydney, New South Wales, Australia; [2]Undergraduate Student, University of Sydney, New South Wales, Australia; [3]Research Scientist, Department of Agriculture and Fisheries, Leslie Research Facility, Toowoomba, Queensland, Australia and [4]Senior Technical Officer, Graham Centre for Agricultural Innovation (Charles Sturt University and NSW Department of Primary Industries), Charles Sturt University, New South Wales, Australia

Research Article

Cite this article: Walsh MJ, Rayner AE, Ruttledge A, Broster JC (2021) Influence of chaff and chaff lines on weed seed survival and seedling emergence in Australian cropping systems. Weed Technol. **35**: 515–521. doi: 10.1017/wet.2020.142

Received: 31 October 2020
Revised: 10 December 2020
Accepted: 15 December 2020
First published online: 23 December 2020

Associate Editor:
Drew Lyon, Washington State University

Nomenclature:
Annual sowthistle; *Sonchus oleraceus* L.; rigid ryegrass; *Lolium rigidum* Gaud.; turnip weed; *Rapistrum rugosum* (L.) All.; wild oat *Avena fatua* L.; barley; *Hordeum vulgare* L.; canola; *Brassica napus* L.; lupin; *Lupinus angustifolius* L.; wheat; *Triticum aestivum* L.

Keywords:
Chaff lining; chaff tramlining; harvest weed seed control

Author for correspondence:
Michael J. Walsh, University of Sydney, 380 Werombi Road, Brown Hill, NSW 2570, Australia
Email: m.j.walsh@sydney.edu.au

Abstract

Chaff lining and chaff tramlining are harvest weed seed control (HWSC) systems that involve the concentration of chaff material containing weed seed into narrow (20 to 30 cm) rows between or on the harvester wheel tracks during harvest. These lines of chaff are left intact in the fields through subsequent cropping seasons in the assumption that the chaff environment is unfavorable for weed seed survival. The chaff row environment effect on weed seed survival was examined in field studies, and chaff response studies determined the influence of increasing amounts of chaff on weed seedling emergence. The objectives of these studies were to determine the influences of (1) chaff lines on the summer–autumn seed survival of selected weed species and (2) chaff type and amount on rigid ryegrass seedling emergence. There was frequently no difference ($P > 0.05$) in seed survival of four weed species (rigid ryegrass, wild oat, annual sowthistle, and turnip weed) when seeds were placed beneath or beside chaff lines. In one instance, wild oat seed survival was increased ($P < 0.05$) when seed were placed beneath compared to beside a chaff line. The pot studies determined that increasing amounts of chaff consistently resulted in decreasing numbers of rigid ryegrass seedlings emerging through chaff material. The suppression of emergence broadly followed a linear relationship in which there was approximately a 2.0% reduction in emergence with every 1,000 kg ha^{-1} increase in chaff material. This relationship was consistent across wheat, barley, canola, and lupin chaff types, indicating that the physical presence of the chaff was more important than chaff type. These studies suggested that chaff lines may not affect the survival over summer–autumn of the contained weed seeds but that the subsequent emergence of weed seedlings will be restricted by high amounts of chaff (>40,000 kg ha^{-1}).

Introduction

The loss of herbicide efficacy due to the widespread evolution of herbicide resistance in dominant weed populations throughout Australian cropping regions has created the demand for alternate weed control technologies. High frequencies of multiple herbicide resistance (Boutsalis et al. 2012; Broster et al. 2019; Owen et al. 2014) and a lack of new herbicide modes of action (Duke 2012; Peters and Strek 2018) have combined to severely deplete herbicide availability for Australian growers. This loss of herbicide resources is compounded by increasing public concerns over herbicide use. The demand is now greater than ever for the development of alternative weed control technologies that are suitable for routine use in conservation cropping systems (Walsh et al. 2019).

High seed retention at crop maturity by weeds of Australian cropping systems led to the development of HWSC systems that target these seed during harvest. The retention of high proportions of total seed production (>60%) by rigid ryegrass, *Bromus* spp., and wild oat is due to the weed seed–bearing tillers remaining upright and intact at maturity and at a height that enables collection during harvest (Walsh and Powles 2014). In a conventional harvest operation, collected weed seeds are redistributed back across the field by the residue-spreading systems fitted to the rear of combines. Realizing the opportunity to target these weed seeds as they exited the combine to prevent the process of "weed reseeding" led Australian growers to develop a number of HWSC systems: chaff carts, narrow windrow burning, bale direct, impact mills (e.g., iHSD, seed terminator), chaff lining, and chaff tramlining.

In Australia, HWSC is now established as an effective weed control practice, with several options used routinely in crop production. In a survey of Australian grain growers in 2014, it was estimated that nearly 50% of Australian growers were regularly using some form of HWSC to target their crop weed problems (Walsh et al. 2017b). Several similarly effective weed

A B


Figure 1. Harvest weed seed control systems that concentrate the weed-containing chaff fractions into narrow rows (20 cm) during harvest. (A) Chaff lining and (B) chaff tramlining.

seed targeting systems are available for growers to choose from, and this choice is frequently based on cost and grower's preference (Walsh et al. 2017a). The most commonly used HWSC system has been narrow windrow burning, with the 2014 survey determining that 30% of growers were using this approach. The preference for this approach is based on ease of use and low cost of implementation (Walsh and Newman 2007). However, given the risks associated with windrow burning and the loss of crop residues that are essential to conservation cropping systems, there is a need for an alternative.

The concentration of the weed seed–containing chaff material into narrow rows offers a simple-to-use, low-cost approach to targeting weed seeds that is an ideal entry-level option for growers adopting the HWSC approach. There are two HWSC systems that concentrate the weed seed–containing chaff fraction into narrow rows during harvest: chaff tramlining, wherein chaff material is concentrated in two rows on harvester wheel tracks; and chaff lining, wherein this material is concentrated in a single narrow row between the wheel tracks (Figure 1). These practices focus on the chaff fraction of harvest residues, as this material contains the majority (>95%) of weed seed exiting the harvester (Broster et al. 2016). This also allows the much-needed straw residue to be spread and thus retained on the field. Chaff tramlining and chaff lining have the potential for widespread adoption, as they are low-cost HWSC options that, similar to narrow windrow burning, require a simple low-cost chute fitted to the rear of the combine. A further simplification is that no post-harvest operations are required, as the chaff lines are left in place through subsequent seasons. Although Australian growers have been using these systems for over a decade, the weed control efficacy and factors that might influence this efficacy have not been evaluated. The objectives of this research were to determine the influence of (1) chaff lines on the summer–autumn seed survival of selected weed species and (2) chaff type and amount on weed seedling emergence.

Materials and Methods

Field studies investigated the influence on weed seed survival of chaff lines made during harvest (November 2017) by chaff lining or chaff tramlining systems (Figure 1) over summer–autumn (˜5 mo), between crop harvest in 2017 and crop planting in 2018. The survival of four weed species (rigid ryegrass, wild oat, annual sowthistle, and turnip weed) was evaluated following their placement beneath chaff lines or on the soil surface beside chaff lines. Fourteen field sites were established across three locations: Marrar, NSW (34.82° S, 147.35° E) (wheat and barley stubble sites), Narrabri, NSW (30.31°S, 149.83°E) (one wheat stubble site), and Mt Tyson, QLD (27.58°S, 151.57°E) (two barley stubble sites) (Table 1). Weed seed lots used at each of the sites were freshly collected from within the field site area or in adjacent fields, except for rigid ryegrass, which was from a fresh seed lot grown in a field location on Charles Sturt University campus, Wagga Wagga (approximately 30 km south of Marrar). At each of the field sites used in the study, weed seed in 0.5-mm plastic mesh bags (10 by 10 cm) were placed beneath and beside chaff lines immediately after harvest (Table 2).

Seed Viability Testing

Prior to the start of the field and pot studies, the seed viability for each weed species was established for each seed lot used in the study. To test germinability, weed seeds were placed on 0.6% (w/v) agar solidified in Petri dishes that were kept in the dark in a temperature-controlled laboratory at ˜ 20 C. Over 28 d, germinating seeds were counted and removed. Seeds were classified as viable if they germinated and viable but dormant if they did not germinate but remained firm and not decayed. Germination alone was used to calculate seed survival for annual sowthistle, because of the small seed size. The resulting seed viability levels were used to adjust the seed numbers placed in the plastic mesh bags at the commencement of the study and to assess seed survival at each time of collection.

Influence of Chaff Lines on Weed Seed Survival

In November 2017, after crop harvest, seed bags containing an estimated 100 viable weed seeds were placed beneath the chaff lines by carefully lifting these lines with a spade and sliding the bags under the chaff. Seed bags were also placed on the soil surface adjacent to the chaff lines, where they were anchored with wooden skewers. Seed bags for each weed species were placed beneath and beside

https://doi.org/10.1017/wet.2020.142 Published online by Cambridge University Press

Table 1. Monthly rainfall and mean daily temperatures for the weed seed survival field trial locations over the 2017 to 2018 summer–autumn period.

Month	Rainfall			Mean daily temperature		
	Mt Tyson	Narrabri	Marrar	Mt Tyson	Narrabri	Marrar
	mm			C		
November	16	70	48	23.7	21.9	21.3
December	74	36	132	26.6	27.3	23.5
January	32	19	65	25.6	29.3	26.3
February	84	55	21	24.6	27	24.1
March	43	12	52	22.6	25.6	21.8
April	7	3	2	19.7	22.2	19.1
Total	256	195	273			

Table 2. Influence of chaff type on the seed viability of four weed species located beneath and beside chaff concentrated in narrow rows over the summer–autumn period 2017 to 2018.

Species	Location	Chaff line		Seed survival[a]	
				Beneath chaff	Beside chaff
		Type	kg ha^{-1}	%	
Rigid ryegrass	Marrar	Wheat	23,000	86.7	93.3
	Marrar	Barley	5,300	93.0	95.6
	Narrabri	Wheat	8,100	78	88
	Mt Tyson	Barley	1,500	34.4	23.8
	Mt Tyson	Barley	1,300	41.2	31.1
Wild oat	Marrar	Wheat	23,000	22.3	15.0
	Marrar	Barley	5,300	25.3	21.9
	Narrabri	Wheat	8,100	84.3 a	24.6 b
	Mt Tyson	Barley	1,500	91.3	83.7
	Mt Tyson	Barley	1,300	6.0	0.3
Annual sowthistle	Mt Tyson	Barley	1,500	10.0	4.2
	Mt Tyson	Barley	1,300	22.8	15.6
Turnip weed	Mt Tyson	Barley	1,500	12.2	5.7
	Mt Tyson	Barley	1,300	16.5	38.6

[a]Comparisons of weed seed survival are not significant ($P > 0.05$) except when numbers are followed by letters.

chaff lines at four locations (replicates) that were spaced at 50- to 100-cm intervals along a chaff line.

For each field study, seed bags were collected the following autumn (April 2018) just prior to crop seeding. During collection, it was noted that many of the seed bags had been disturbed and even broken or chewed. Collected seed bags were cut open, and seeds were removed for germination testing and the establishment of viability. During this process, decayed and shriveled shoots and roots were observed in many of the seed bags. Where possible, the recently germinated seedlings were recorded as viable seed. In many instances the seedlings had disintegrated, making it impossible to identify individual seedlings. Seed viability testing was conducted on intact seed using the procedures described above. The number of viable seed remaining were converted to a percentage seed survival of the initial seed lot total, with missing seed assumed to be seed lost (nonsurvival) as a result of failed germination, degradation, or predation.

Chaff Suppression of Weed Seedling Emergence

During the 2018 winter growing season, pot studies investigated the effects of chaff amount and type on weed seedling emergence. These studies were conducted at three locations: shade house (Wagga Wagga), outdoor netted area (Narrabri), and glasshouse (Toowoomba). At each location, pot studies examined the influence of increasing amounts of wheat chaff on the emergence of rigid ryegrass seedlings. The wheat chaff rates (0, 3,000, 6,000, 12,000, 18,000 24,000 30,000, and 42,000 kg ha^{-1}) chosen for use in the pot studies are those that can be expected to be produced during the harvest of wheat crops with yields ranging from 250 to 3,500 kg ha^{-1}. Chaff rates (x) were calculated using the following equation (Equation 1):

$$x = 0.3ywz \quad [1]$$

where 0.3 is the ratio of chaff production per 1,000 kg of wheat grain yield (y) (Broster et al. 2016), w is harvest width, and z is chaff line width.

At each location, 100 viable rigid ryegrass seeds from the same seed lot were spread across the surface of pots (17 cm diam; Toowoomba) or trays (30 by 33 cm; Narrabri and Wagga Wagga) filled with potting mix (50% sand and 50% peat moss). Wheat chaff collected during harvest at Marrar was used in all pot studies. Chaff was spread evenly across the surface of the potting mix, with four replicates of each chaff treatment arranged in a randomized complete block design. Wire mesh (1.0-cm square) was placed around the pots and trays to contain the chaff material at the two highest rates, 30,000 and 42,000 kg ha^{-1}. Once the chaff was evenly spread across the surface of the pots and trays, they were watered thoroughly and maintained at or near field capacity for 28 d. During this period, weed seedlings were counted and carefully removed to minimize chaff disturbance. Weed seedling emergence data were converted to a percentage of the emergence from the chaff-free control treatment for analysis and presentation.

To examine the influence of chaff type on weed seedling emergence, the chaff of four crop species was used in pot studies conducted during the winter growing seasons at Wagga Wagga in 2018 and repeated in 2019. Using the same procedures described above, rigid ryegrass seed was spread on the surface of potting mix–filled trays (30 by 33 cm), and trays were then covered with increasing amounts of chaff (0, 3,000, 6,000, 12,000, 18,000, 24,000, 30,000, and 42,000 kg ha^{-1}). Wheat, canola, barley, and lupin chaff used in these repeat studies was collected during the 2017 and 2018 harvests, respectively.

Statistical Analysis

Two-way ANOVA (Genstat, version 18) (VSN International, Hemel Hempstead, UK) compared the effects of field site and weed seed placement (beneath or beside chaff) on seed viability of each weed species. There was a significant effect ($P < 0.05$) of field site on seed survival for each weed species, so one-way ANOVAs were performed for each site to test for differences in weed seed placement (beneath or beside chaff) for each species. Pairwise comparisons of weed seed location effect on seed viability were made for each weed species–by–site combination using Fischer's protected LSD with statistical significance set at $P = 0.05$.

Effects of increasing wheat chaff amounts on rigid ryegrass seedling emergence was examined in separate regression analyses conducted for each pot trial location. Simple linear regression analyses using Sigmaplot® (SigmaPlot software v. 14.0 Systat, San Jose, CA) were used to develop equations for this relationship. Simple linear regression analyses examined the relationship between increasing amounts of chaff on rigid ryegrass seedling

https://doi.org/10.1017/wet.2020.142 Published online by Cambridge University Press

emergence data from the Wagga Wagga pot studies. Linear relationships were developed for each of the four chaff types with adjusted R^2 values used to indicate the suitability of fit.

Results and Discussion

Influence of Chaff Lines on Weed Seed Survival

Chaff lines created by the concentration of chaff material into narrow lines during harvest did not result in an environment that consistently reduced weed seed survival over the summer–autumn period. Across the field studies, it was evident that the placement of weed seed beneath chaff lines did not adversely influence their survival over the approximately 5-mo period between harvest and the start of the next growing season (Table 2). Frequently, the survival of rigid ryegrass, wild oat, annual sowthistle, and turnip weed seed beneath chaff lines was similar to or higher than the survival of seed exposed on the soil surface. However, only at the Narrabri site was this increase statistically significant ($P < 0.05$). In this instance, wild oat seed survival was increased by 60% for seed beneath wheat chaff compared to seed on the soil surface. At the remainder of the sites, there were no differences ($P > 0.05$) in seed survival between beneath and beside chaff treatments, indicating that the presence of chaff, regardless of type or amount, had little or no effect on weed seed survival.

The survival of rigid ryegrass seed exposed on the soil surface over the summer–autumn period was considerably higher than expected at several sites. High levels of survival (88% to 96%) were recorded for rigid ryegrass seed exposed on the soil surface over summer–autumn at the two Marrar sites and the Narrabri site (Table 2). These values were considerably higher than the 24% to 31% seed survival recorded at the two Mt Tyson sites and the previously documented over summer–autumn survival values of 20% to 30% (Chauhan et al. 2006c).

There was typically low over summer–autumn survival of seed on the soil surface for wild oat, turnip weed, and annual sowthistle. The low soil surface survival of wild oat seed (0.3% to 25%) observed at most sites was similar to previously reported results (Boyd and Van Acker 2003; Somody et al. 1984) (Table 2). As expected, annual sowthistle (4% to 16%) seed survival levels were low; the fragile seed of this species is known to have low levels of persistence (Chauhan et al. 2006a; Widderick et al. 2010). The survival of turnip weed seed (6% to 39%) was also expectedly low, as these seed have poor persistence once they are removed from the pericarp (Chauhan et al. 2006b; Ohadi et al. 2011).

Chaff amount and type, as well as the rainfall patterns over summer–autumn appear to have influenced weed seed survival in these field studies, although it is likely that combinations of these and other factors were responsible for determining survival levels. The sites where there was increased ($P < 0.05$) survival for weed seed beneath chaff occurred with generally higher chaff levels (> 8,000 kg ha^{-1}) (Table 2). However, weed seed survival was not increased in chaff lines at the Marrar site, where the highest amount of chaff was present in the chaff lines. Varying rainfall patterns across the trial sites were likely responsible for the generally lower levels of seed persistence at the Mt Tyson sites compared to the Marrar and Narrabri sites. These differences between locations may be due to the higher levels of autumn rainfall at Mt Tyson compared to the other sites (Table 1). Rainfall can potentially influence weed seed survival by changing seed dormancy levels and stimulating out-of-season fatal germination events (Cheam and Code 1995; Goggin et al. 2012). Weed seed loss has been shown to occur through soil microbe–facilitated decay (Chee-Sanford 2008; Kennedy et al. 1991; Kremer 1993; Pollard 2018), and higher soil moisture levels can increase this microbial activity (Davis et al. 2016; Mickelson and Grey 2006). Weed seeds are also prone to predation by vertebrates and invertebrates, with crop residue levels influencing this form of seed loss (Baraibar et al. 2012; Kulkarni et al. 2015; Spafford Jacob et al. 2006). It is likely that the overall effect of chaff on weed seed survival at any field location will be the result of a combination of positive (e.g., dry, insulated, protected environment) and negative (e.g., predator refuge, concentration of allelochemicals, and microbial activity) effects. With a myriad of potential influences on weed seed survival, it is difficult to predict what the effect of concentrating chaff on weed seed survival will be in any particular field situation.

Chaff Suppression of Weed Seedling Emergence

A substantial reduction in rigid ryegrass seedling emergence (>80%) through wheat chaff was only achieved when large quantities (~40,000 kg ha^{-1}) of this material were present. In pot studies conducted at Wagga Wagga, Narrabri, and Toowoomba in 2018, increasing chaff rates from 3,000 to 12,000 kg ha^{-1} resulted in minor (3% to 8%) reductions in rigid ryegrass seedling emergence (Figure 2). The subsequent 6,000 kg ha^{-1} chaff increases to 18,000 and 24,000 kg ha^{-1} reduced emergence in all trials by 6% to 16%. Further increasing the chaff amount to 30,000 kg ha^{-1} resulted in a consistent 20% to 25% reduction in emergence across all three sites. It was only at the highest chaff rate of 42,000 kg ha^{-1} that rigid ryegrass seedling emergence was substantially reduced (80% to 90%). Based on the assumptions of harvest and chaff line widths used to estimate chaff rate treatments, as well as the documented grain yield–to–chaff ratio of wheat (3:1) (Broster et al. 2016), this level of wheat chaff concentrated in a chaff line can be achieved when yields are >3,000 kg ha^{-1}. In areas where average wheat yields are lower than 3,000 kg ha^{-1}, which consistently occurs across most of the Australian grain production region (ABARES 2020), growers will need to be prepared for high levels of rigid ryegrass seedling emergence in chaff lines.

Large temperature differences between the Wagga Wagga site and the Toowoomba and Narrabri sites during the period when the pot trials were conducted are likely responsible for the consistent differences in rigid ryegrass seedling emergence between these sites. Despite the same chaff sample and rigid ryegrass seed lot being used in the three pot studies, there were differences ($P < 0.05$) in rigid ryegrass seedling emergence patterns between the three pot studies (Figure 2). In particular, emergence was consistently lower (20% to 30%) at Wagga Wagga for all treatments except at the highest chaff rate used. This reduced emergence may be due to the cooler growing conditions over the respective periods for these pot studies at the Wagga Wagga site compared to those at Narrabri and Toowoomba. There were a number of frost events within the shade house environment at Wagga Wagga, and the mean daily temperature was an average 9 C lower at Wagga Wagga than at Narrabri (BOM 2020). The Toowoomba pot study was conducted in a glasshouse, where temperatures were similar to those at Narrabri. Regardless of the reduced rigid ryegrass seedling emergence in the Wagga Wagga study, the response to increasing chaff amounts was consistent across all three sites.

Rigid ryegrass seedling emergence was similarly suppressed by increasing amounts of wheat, barley, canola, and lupin chaff. In pot studies conducted at Wagga Wagga, chaff amount rather than chaff type had more influence on rigid ryegrass seedling emergence

https://doi.org/10.1017/wet.2020.142 Published online by Cambridge University Press

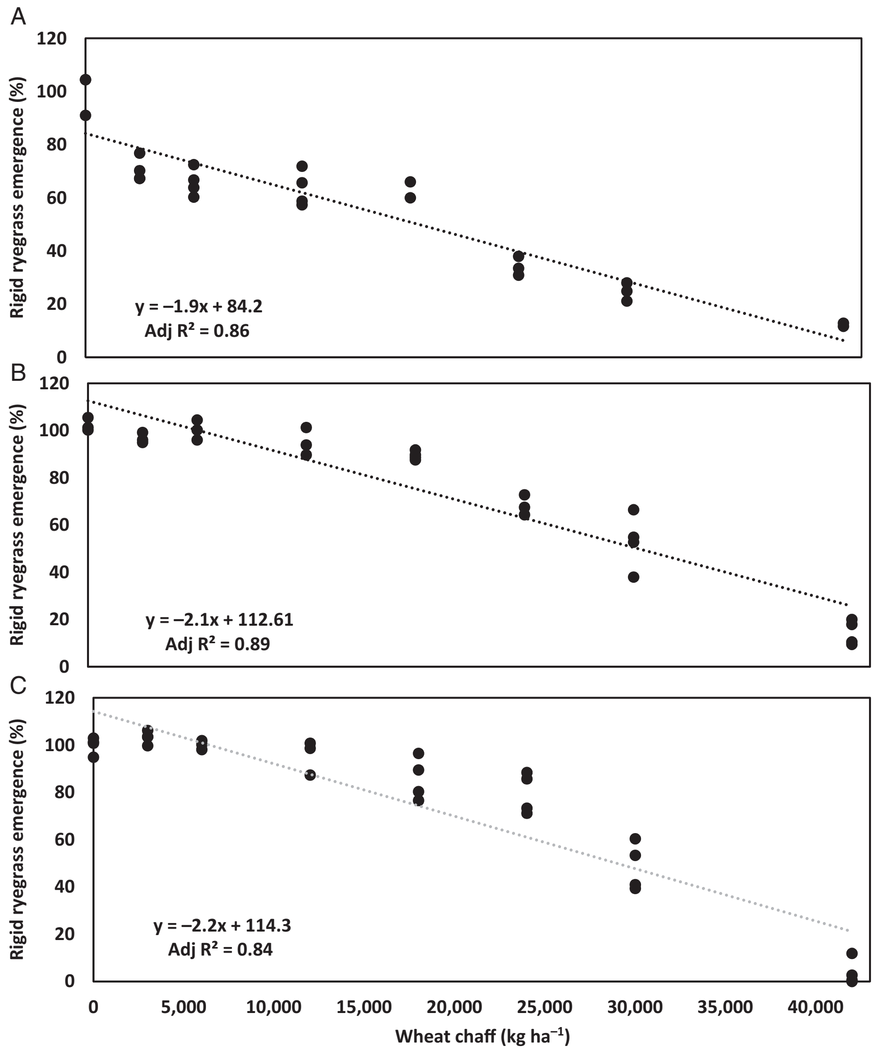

Figure 2. Rigid ryegrass seedling emergence in response to increasing amounts of wheat chaff in pot trials conducted at (A) Wagga Wagga, (B) Narrabri, and (C) Toowoomba during the 2018 winter cropping season. Dotted lines indicate linear relationship between chaff amount and rigid ryegrass seedling emergence.

(Figure 3). There were relatively similar linear relationships for rigid ryegrass seedling emergence in response to increasing amounts of wheat, barley, canola, and lupin chaff types. The slopes for these relationships were approximately –2.0, indicating that for every 1,000 kg ha^{-1} increase in chaff there was a 2% reduction in rigid ryegrass seedling emergence. Thus, for all chaff types, only at the highest chaff amounts was there a suitably high level (>80%) of suppression of rigid ryegrass seedling emergence. These studies focused on the influence of chaff residues on rigid ryegrass seedling emergence. Although this effect has not previously been reported, numerous studies report reduced crop or weed seedling emergence due to the physical presence of crop residues (Chauhan and Abugho 2013; Morris et al. 2009; Rebetzke et al. 2005; Williams et al. 1998; Wuest et al. 2000). The combined effects of residue amount and allelopathic chemical release from wheat, barley, and canola crop stubbles have been indicated to be responsible for the suppression of flaxleaf fleabane [*Conyza bonariensis* (L.) Cronquist] and witchgrass (*Panicum capillare* L.) emergence (Mwendwa et al. 2018). The indications were that allelochemicals released during the decay of canola residues (Weston 2005) resulted in higher levels of weed suppression than those released from wheat and barley residues. The pot study results suggest that an allelochemical effect, if present, was consistent across all species. In field studies of longer duration there will likely be increased chaff decay and greater release of allelochemicals.

The concentration of the weed seed–containing chaff in chaff lining or chaff tramlining treatments during harvest places weed seeds in an environment that is potentially favorable for seed survival but with the potential to restrict weed seedling emergence. When concentrated within a large quantity of chaff material, weed seeds are insulated from factors that contribute to seed losses, such as microbial degradation and failed germination. Seed losses may increase over time with the widespread and repeated use of chaff lines and chaff tramlines; macro- and microfauna may adapt to these systems, potentially resulting in enhanced predation and degradation of weed seeds. The concentration of large quantities of chaff material provides a major physical impediment for emerging weed seedlings that can lead to substantial reductions (>80%) in emergence. Ultimately, weed seedling emergence from chaff lines is an excellent indicator of weed seed collection during harvest and

https://doi.org/10.1017/wet.2020.142 Published online by Cambridge University Press

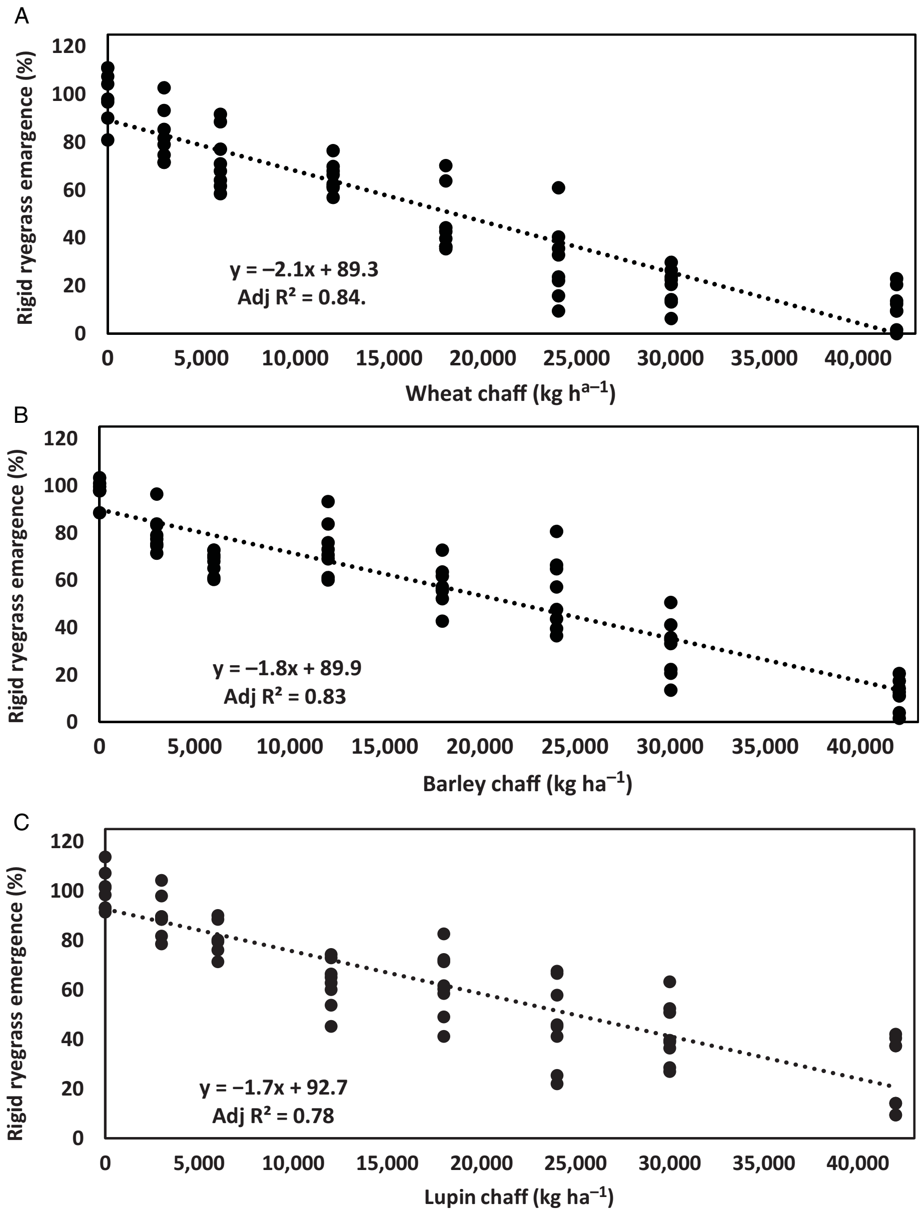

Figure 3. Rigid ryegrass seedling emergence in response to increasing amounts of (A) wheat, (B) barley, (C) lupin, and (D) canola chaff in pot trials conducted at Wagga Wagga during the 2018 and 2019 winter growing seasons. Dotted lines indicate linear relationship between chaff amount and rigid ryegrass seedling emergence.

thus HWSC potential. Chaff lining and chaff tramlining systems are easy and inexpensive to install on combines and are therefore ideal as the initial HWSC systems for growers to adopt.

Acknowledgments. The authors are grateful to David Fox, David Thompson, Peter Bach, and their families for providing trial site areas and their cooperation in the conduct of the field research. We also acknowledge the support we have received from technical officers at the Department of Agriculture and Fisheries (Leslie Research Centre, Toowoomba), Charles Sturt University (Wagga Wagga), and the Sydney Institute of Agriculture (Narrabri). This work was funded by a grant from the Grains Research and Development Corporation (through grain-grower levies). No conflicts of interest have been declared.

References

ABARES (2020) Australian Commodity Statistics. https://www.agriculture.gov.au/abares. Accessed: August 20, 2020

Baraibar B, Daedlow D, De Mol F, Gerowitt B (2012) Density dependence of weed seed predation by invertebrates and vertebrates in winter wheat. Weed Res 52:79–87

BOM (2020) Bureau of Meteorology Weather and Climate Statistics. http://www.bom.gov.au. Accessed: August 20, 2020

Boutsalis P, Gill GS, Preston C (2012) Incidence of herbicide resistance in rigid ryegrass (*Lolium rigidum*) across Southeastern Australia. Weed Technol 26:391–398

Boyd NS, Van Acker RC (2003) The effects of depth and fluctuating soil moisture on the emergence of eight annual and six perennial plant species. Weed Sci 51:725–730

Broster JC, Pratley JE, Ip RHL, Ang L, Seng KP (2019) A quarter of a century of monitoring herbicide resistance in *Lolium rigidum* in Australia. Crop Pasture Sci 70:283–293

Broster JC, Walsh MJ, Chambers AJ (2016) Harvest weed seed control: the influence of harvester set up and speed on efficacy in south-eastern Australia wheat crops. Pages 38–41 *in* Randall R, Lloyd S, Borger C, eds.

20th Australasian Weeds Conference. Perth, Western Australia: Weeds Society of Western Australia
Chauhan BS, Abugho SB (2013) Effect of crop residue on seedling emergence and growth of selected weed species in a sprinkler-irrigated zero-till dry-seeded rice system. Weed Sci 61:403–409
Chauhan BS, Gill G, Preston C (2006a) Factors affecting seed germination of annual sowthistle (*Sonchus oleraceus*) in southern Australia. Weed Sci 54:854–860
Chauhan BS, Gill G, Preston C (2006b) Factors affecting turnipweed (*Rapistrum rugosum*) seed germination in southern Australia. Weed Sci 54:1032–1036
Chauhan BS, Gill G, Preston C (2006c) Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (*Lolium rigidum*) seed bank. Weed Sci 54:669–676
Cheam AH, Code GR (1995) The biology of Australian weeds. 24. *Raphanus raphanistrum* L. Plant Prot Quart 10:2–13
Chee-Sanford JC (2008) Weed seeds as nutritional resources for soil Ascomycota and characterization of specific associations between plant and fungal species. Biol Fertility Soils 44:763–771
Davis AS, Fu X, Schutte BJ, Berhow MA, Dalling JW (2016) Interspecific variation in persistence of buried weed seeds follows trade-offs among physiological, chemical, and physical seed defenses. Ecol Evol 6:6836–6845
Duke SO (2012) Why have no new herbicide modes of action appeared in recent years? Pest Manage Sci 68:505–512
Goggin DE, Powles SB, Steadman KJ (2012) Understanding *Lolium rigidum* seeds: The key to managing a problem weed? Agronomy 2:222
Kennedy AC, Young FL, Elliott LF, Douglas CL (1991) Rhizobacteria suppressive to the weed downy brome. Soil Sci Soc Am J 55:722–727
Kremer RJ (1993) Management of weed seed banks with microorganisms. Ecol Appl 3:42–52
Kulkarni SS, Dosdall LM, Willenborg CJ (2015) The role of ground beetles (Coleoptera: Carabidae) in weed seed consumption: a review. Weed Sci 63:355–376
Mickelson JA, Grey WE (2006) Effect of soil water content on wild oat (*Avena fatua*) seed mortality and seedling emergence. Weed Sci 54:255–262
Morris NL, Miller PCH, Orson JH, Froud-Williams RJ (2009) The effect of wheat straw residue on the emergence and early growth of sugar beet (*Beta vulgaris*) and oilseed rape (*Brassica napus*). Eur J Agron 30:151–162
Mwendwa JM, Brown WB, Wu H, Weston PA, Weidenhamer JD, Quinn JC, Weston LA (2018) The weed suppressive ability of selected Australian grain crops; case studies from the Riverina region in New South Wales. Crop Protect 103:9–19
Ohadi S, Mashhadi HR, Tavakol-Afshari R (2011) Effects of storage and burial on germination responses of encapsulated and naked seeds of turnipweed (*Rapistrum rugosum*) to light. Weed Sci 59:483–488
Owen MJ, Martinez NJ, Powles SB (2014) Multiple herbicide-resistant *Lolium rigidum* (annual ryegrass) now dominates across the Western Australian grain belt. Weed Res 54:314–324
Peters B, Strek HJ (2018) Herbicide discovery in light of rapidly spreading resistance and ever-increasing regulatory hurdles. Pest Manage Sci 74:2211–2215
Pollard AT (2018) Seeds vs fungi: an enzymatic battle in the soil seedbank. Seed Sci Res 28:197–214
Rebetzke GJ, Bruce SE, Kirkegaard JA (2005) Longer coleoptiles improve emergence through crop residues to increase seedling number and biomass in wheat (*Triticum aestivum* L.). Plant Soil 272:87
Somody CN, Nalewaja JD, Miller SD (1984) Wild oat (*Avena fatua*) seed environment and germination. Weed Sci 32:502–507
Spafford Jacob HS, Minkey DM, Borger C, Gallagher RH (2006) Variation in post-dispersal weed seed predation in a crop field. Weed Sci 54: 148–155
Walsh MJ, Aves C, Powles SB (2017a) Harvest weed seed control systems are similarly effective on rigid ryegrass. Weed Technol 31:178–183
Walsh MJ, Broster J, Chauhan B, Rebetzke G, Pratley J (2019) Weed control in cropping systems—past lessons and future opportunities. Pages 153–173 *in* Pratley J, Kirkegaard J, eds. Australian Agriculture in 2020: From Conservation to Automation. Wagga Wagga: Agronomy Australia and Charles Sturt University
Walsh MJ, Newman P (2007) Burning narrow windrows for weed seed destruction. Field Crops Res 104:24–40
Walsh MJ, Ouzman J, Newman P, Powles SB, Llewellyn R (2017b) High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. Weed Technol 31:1–7
Walsh MJ, Powles SB (2014) High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. Weed Technol 28:486–493
Weston LA (2005) History and current trends in the use of allelopathy for weed management. Hort Technol 15:529–534
Widderick MJ, Walker SR, Sindel BM, Bell KL (2010) Germination, emergence, and persistence of *Sonchus oleraceus*, a major crop weed in subtropical Australia. Weed Biol Manage 10:102–112
Williams MM, Mortensen DA, Doran JW (1998) Assessment of weed and crop fitness in cover crop residues for integrated weed management. Weed Sci 46:595–603
Wuest SB, Albrecht SL, Skirvin KW (2000) Crop residue position and interference with wheat seedling development. Soil Till Res 55:175–182

https://doi.org/10.1017/wet.2020.142 Published online by Cambridge University Press