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Eleven years of integrated weed management: long-term impacts of row spacing and harvest weed seed destruction on *Lolium rigidum* control

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Summary

Long-term research aimed to determine whether narrow row spacing and harvest weed seed destruction, in combination with herbicide use, would be sufficient to drive a *Lolium rigidum* population to extinction. A trial was run from 1987 to 2013, with treatments including crop row spacings of 9, 18, 27 or 36 cm and crop residue burning or retention. Herbicides were applied to reflect regional practices. The initial trial design was randomised, but treatments were maintained in each plot over the following years. *Lolium rigidum* seed production at harvest was assessed from 2003 to 2013. Average crop yield was higher in the unburnt plots (1638 kg ha^{-1}) than the burnt plots (1530 kg ha^{-1}) and greater at narrow row spacing, with an average yield of 1658, 1637, 1548 and 1492 kg ha^{-1} in the 9-, 18-, 27- and 36-cm spacings. *Lolium rigidum* seed at harvest was reduced in the burnt plots (57 seeds m^{-2}) compared with the unburnt plots (297 seeds m^{-2}) and was reduced at narrow row spacing, with an average of 58, 78, 223 and 333 seeds m^{-2} in the 9-, 18-, 27- and 36-cm row spacings. By 2013, *L. rigidum* seed production was reduced to an average of 0 seeds m^{-2} in the narrow row spacing, burnt plots.

Keywords: narrow row spacing, chaff cart, residue management, burning, seed production, fecundity.

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Introduction

Integrated weed management (IWM) programmes are advocated for the control of *Lolium rigidum* L. Gaud. (annual ryegrass), Australia's most problematic dryland cropping weed (Pannell *et al*., 2004). Modelling has confirmed that there are clear economic advantages to IWM in the long term, particularly in terms of delaying the development of herbicide resistance or managing the resistant populations (Schmidt & Pannell, 1996; Jones & Medd, 2000; Pannell *et al*., 2004; Jones *et al*., 2005; Jones & Monjardino, 2006). However, IWM programmes are not always popular with growers, as individual IWM techniques can be expensive and labour intensive compared with the herbicide use (Jones & Medd, 2000; Jones & Monjardino, 2006). To ensure the widespread adoption of IWM programmes, the IWM techniques need to be simple to implement and inexpensive (in the short term, as well as the long term).

Examples of simple, inexpensive techniques include reduced crop row spacing and weed seed destruction at

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harvest. If the crop row spaces are reduced (while seeding rate remains constant), then crop density remains constant, but intraspecies competition is reduced. This improves the competitive ability of the crop, thus increasing the density-dependant mortality of weeds or reducing biomass and fecundity of individual weed plants (Zimdahl, 2004; Scott *et al.*, 2013). Further, the reduced intraspecies competition from narrow row spacing increases the yield of wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and oilseed rape (*Brassica napus* L.), regardless of weed density (Scott *et al.*, 2013). This increased crop yield offsets the cost of this technique (from increased fuel usage and a slight increase to the time of sowing), making narrow row spacing economically desirable even in the absence of weeds (Scott *et al.*, 2013). Weed seed destruction at harvest may be achieved using a harvest seed destructor or chaff cart (Walsh *et al.*, 2013). The cost includes an initial investment in machinery, mechanical operation, delayed harvest, fire risk (if burning chaff dumps) and lost nutrients if chaff is removed or burnt (Jones & Monjardino, 2006). Alternatively, weed seeds may be destroyed by burning all residues or burning residue placed into windrows (Walsh & Newman, 2007). The cost of burning residue includes labour, management of the fire risk and lost nutrients, and is inexpensive compared with other methods of weed control utilised in Australia (Storrie, 2014). Up to 85% of *L. rigidum* seed present at harvest time is collected by the harvester, and up to 99% of this seed can be destroyed by burning or mechanical weed seed destruction (Walsh *et al.*, 2013; Walsh & Powles, 2014).

The goal of an IWM programme should be a continuous reduction in the weed seedbank (Jones & Medd, 2000). This cannot usually be achieved through use of herbicides alone, due to the development of herbicide resistance (Jones & Medd, 2000). An IWM programme based on herbicide use, reduced crop row spacing and crop residue burning would be simple and inexpensive to implement, but the long-term impacts on *L. rigidum* seed production are not known. Multiple studies demonstrate that narrow row spacing or residue burning can reduce *L. rigidum* seed production in a single year (Walsh & Newman, 2007; Scott *et al.*, 2013). However, it is not known whether these control techniques are sufficient to ensure a continuous reduction in *L. rigidum* density and seed production, given that a range of environmental factors can ensure poor weed control in individual years under field conditions (Jones & Medd, 2000).

A study was conducted over 27 years, from 1987 to 2013, to determine the long-term impacts of crop row spacing and crop residue burning on yield. Within this trial, herbicides were applied according to regional practices, to control broad-leaved weeds (mainly *Sisymbrium orientale* L., Indian hedge mustard) and *L. rigidum*. A chaff cart collection system was also utilised in some years. While broad-leaved weed control was successful, *L. rigidum* was still found in the trial. This research utilised data from the final 11 years of this trial (2003 to 2013), to determine the long-term impact of crop row spacing and crop residue burning on *L. rigidum* seed production. We hypothesised that *L. rigidum* seed production at the conclusion of the trial would be lowest in the plots with narrow row spacing and crop residue burning.

Materials and methods

A trial was run from 1987 to 2013 at the Department of Agriculture and Food Western Australia Merredin Research Station (31°29′52.32″S, 118°13′36.14″E), in a mottled eutrophic red chromosol soil (Isbell, 2002). Treatments included crop row spacings (9, 18, 27 and 36 cm) and crop residue management (residue burnt prior to crop seeding or unburnt). The trial was established as a randomised block design with six replications (plot size of 5 m by 30 m), but treatments were not re-randomised in each subsequent year. To implement the burnt residue treatment, crop residue from the prior year was burnt over the entire plot in autumn (March–May). This study utilised data from 2003 to 2013. Non-selective herbicides were used to remove weeds that emerged over summer and autumn, and a pre-emergence herbicide was applied directly prior to sowing (Table 1). The crop choice reflected a standard rotation for the region and was sown using a no tillage seeding system (knife points and press wheels). In 2008, the field was not sown to crop and was a chemical fallow (i.e. herbicide used to kill all weeds prior to seed set) due to low rainfall. Throughout the trial, the fertiliser used was Agras® (16.1,9.1,14.3,0.5,0.06% N, P,S,Ca,Zn), Double Phos® (17.7,16.2,3.6,0.08,0.08% P, Ca,S,Zn,Cu) or Double Super® (17.7,16.2,3.6,0.08,0.08% P,Ca,S,Zn,Cu). There was no fertiliser applied in 2008 (fallow year) or those years where soil analysis indicated that fertiliser was not necessary to ensure healthy crop growth (fertiliser from CSBP Ltd., Merredin, WA, Australia). Selective herbicides were applied in crop to control *L. rigidum* (Table 1) and *S. orientale*. Broad-leaved weed herbicides were not listed in Table 1 because the herbicides were successful in removing *S. orientale* and did not affect the growth of the crop or *L. rigidum*. Herbicides were bulk sprayed, with a 10-m boom, 1 m off the ground, with nozzle spacing of 50 cm. Nozzle type, water rate and spray pressure were altered for each herbicide

Table 1 The sowing date, crop cultivar, sowing rate, herbicide use for *L. rigidum* control, annual rainfall for the Merredin Research Station and growing season (May to October) rainfall, from 2003 to 2013. Note that + is used to indicate two herbicide products that were combined into a single tank mixture at the time of application

Sowing date, crop (and sowing rate)	Herbicide and date of application	Annual rainfall/ growing season rainfall (mm)
4/6/03: wheat cv. Wyalkatchem (99 kg ha^{-1})	1/5/03: glyphosate 450 g a.i. ha^{-1} (RoundupCT® Extra, 450 g a.i. L^{-1}, SC, Nufarm Ltd.) 28/5/03: glyphosate 900 g a.i. ha^{-1} 4/6/03: trifluralin 480 g a.i. ha^{-1} (TriflurX®, 480 g a.i. L^{-1}, EC, Nufarm Ltd.) + paraquat/diquat 270/230 g a.i. ha^{-1} (Spray.Seed®, 135/115 g a.i. L^{-1}, SL, Syngenta Pty. Ltd.) 29/7/03: diclofop-methyl/fenoxaprop-p-ethyl 375/19.5 g a.i. ha^{-1} (Spear®, 250/13 g a.i. L^{-1}, EC, Bayer Crop Science)	356/278
3/6/04: wheat cv. Westonia (101 kg ha^{-1})	2/6/04: trifluralin 960 g a.i. ha^{-1} + paraquat/diquat 270/230 g a.i. ha^{-1} 20/7/04: diclofop-methyl/fenoxaprop-p-ethyl 375/19.5 g a.i. ha^{-1}	279/210
2/6/05: field pea (*Pisum sativum* L.) cv. Kaspa (160 kg ha^{-1})	15/4/05: paraquat/diquat 270/230 g a.i. ha^{-1} 2/6/05: paraquat/diquat 270/230 g a.i. ha^{-1} + trifluralin 480 g a.i. ha^{-1} 25/7/05: clethodim 60 g a.i. ha^{-1} (Select®, 240 g a.i. L^{-1}, EC, Sumitomo Chemical Australia Pty. Ltd.)	305/240
8/6/06: wheat cv. Bonnie Rock (100 kg ha^{-1})	25/1/06: carfentrazone-ethyl 7.2 g a.i. ha^{-1} (Hammer® 400EC, 400 g a.i. L^{-1}, EC, FMC Australasia Pty. Ltd.) + glyphosate 450 g a.i. ha^{-1} 10/5/06: carfentrazone-ethyl 7.2 g a.i. ha^{-1} + glyphosate 450 g a.i. ha^{-1} 8/6/06: trifluralin 480 g a.i. ha^{-1} + paraquat/diquat 270/230 g a.i. ha^{-1} + s-metolachlor 192 g a.i. ha^{-1} (DualGold®, 960 g a.i. L^{-1}, EC, Syngenta Australia Pty. Ltd.) 21/8/06: diclofop-methyl/sethoxydim 200/20 g a.i. ha^{-1} (Decision®, 200/20 g a.i. L^{-1}, EC, Bayer Crop Science)	330/154
26/6/07: barley cv. Hamlin (101 kg ha^{-1})	26/6/07: trifluralin 480 g a.i. ha^{-1} + paraquat/diquat 270/230 g a.i. ha^{-1} 13/8/07: diclofop-methyl/sethoxydim 200/20 g a.i. ha^{-1}	230/163
5/5/08: chemical fallow	5/5/08: paraquat/diquat 270/230 g a.i. ha^{-1}	313/212
15/6/09: oilseed rape cv. Tanami (5.3 kg ha^{-1})	15/6/09: paraquat/diquat 270/230 g a.i. ha^{-1} + trifluralin 480 g a.i. ha^{-1}	290/195
3/6/10: wheat cv. Mace (75 kg ha^{-1})	3/6/10: paraquat/diquat 270/230 g a.i. ha^{-1} + trifluralin 480 g a.i. ha^{-1} 2/8/10: tralkoxydim 152 g a.i. ha^{-1} (Achieve® WG, 400 g a.i. kg^{-1}, WG, Crop Care Australasia)	168/139
7/7/11: wheat cv. Magenta (72 kg ha^{-1})	7/7/11: glyphosate 1080 g a.i. ha^{-1} (Roundup® PowerMAX, 540 g a.i. L^{-1}, AC, Monsanto Australia Ltd.) + prosulfocarb/s-metolachlor 1920/288 g a.i. ha^{-1} (Boxer Gold®, 800/120 g a.i. L^{-1}, EC, Syngenta Australia Pty. Ltd.) g a.i. ha^{-1} + carfentrazone-ethyl 6 g a.i. ha^{-1} 26/7/11: tralkoxydim 152 g a.i. ha^{-1}	400/255
18/6/12: chickpea (*Cicer arietinum* L.) cv. Slasher (136 kg ha^{-1})	15/6/12: paraquat/diquat 135/115 g a.i. ha^{-1} + simazine 600 g a.i. ha^{-1} (Simazine Hi-Load® 600, 600 g a.i. L^{-1}, SC, Crop Care Australasia Pty. Ltd.) 24/7/12: clethodim 60 g a.i. ha^{-1} (Select®, 240 g a.i. L^{-1}, EC, Sumitomo Chemical Australia Pty. Ltd.)	290/136
28/5/13: wheat cv. Mace (97 kg ha^{-1})	13/5/13: glyphosate 1140 g a.i. ha^{-1} (Roundup® Attack™, 570 g a.i. L^{-1}, SL, Nufarm Australia Ltd.) 28/5/13: paraquat/diquat 270/230 g a.i. ha^{-1} + pyroxasulfone 102 g a.i. ha^{-1} (Sakura® 850WG, 850 g a.i. kg^{-1}, WG, Bayer Crop Science Pty. Ltd.)	353/224

according to label requirements for optimal performance. Herbicide control of *L. rigidum* was inadequate, and by 2003, there was dense *L. rigidum* in the trial, particularly in the wide row spacing, unburnt plots. Harvests were conducted in November or December, using crop lifters (to improve harvest of the short crops in the dry seasons and to capture the maximum number of *L. rigidum* heads). The crop lifters were custom designed for the harvester by G Riethmuller and were attached to extend the harvest platform and lift the crop into the front of the harvester. A Rytec™ chaff system (Weed Seed Collection System, Harvestaire Pty. Ltd., Perth, WA, Australia) was utilised at harvest in all plots in the trial from

2003 to 2006, in response to the very high *L. rigidum* density in the wide row spacing plots.

Measurements

Crop plant density was measured using two 46-cm-by-108-cm quadrats per plot, 4–6 weeks after crop emergence. Crop yield was assessed by harvesting the centre of each plot (1.62 m by 30 m). A grain sample was removed from the bulk-harvested grain from each plot and cleaned (using a Sample Cleaner Model SLN3, Pfeuffer GmbH, Kitzingen, Germany) to remove the *L. rigidum* seeds. The number of *L. rigidum* seeds per kg of grain within this sample was compared with the total yield per plot to estimate *L. rigidum* seed m^{-2} captured by the harvester.

Total *L. rigidum* seeds m^{-2} were estimated for each year, although the method of estimation varied between years. From 2003 to 2006, *L. rigidum* seed was captured in the chaff cart. The *L. rigidum* seed from the chaff cart was manually counted, and the total seed number was divided by plot area to determine seed captured by the chaff cart m^{-2}. From 2003 to 2006, when the chaff cart was used, the crops included wheat and field peas (Table 1). Matthews *et al.* (1996) determined that the *L. rigidum* seed captured by a chaff cart and harvester is 71% of the total *L. rigidum* seeds in a wheat crop and 20% of the seeds in a field pea crop. Using these data, the *L. rigidum* seeds captured in the chaff cart and harvester from 2003 to 2006 were used to estimate total *L. rigidum* seeds m^{-2}. From 2011 to 2013, above-ground *L. rigidum* biomass was harvested directly prior to crop harvest (from quadrats of 23 cm by 108 cm or 46 cm by 108 cm), dried for 3 days at 40°C, weighed, threshed and put through a splitter (a stainless steel automatic divider to divide threshed material into multiple streams, to generate a representative sample). The subsample generated by the splitter was weighed, and *Lolium rigidum* seeds were manually counted. The number of seeds in the subsample and weight of the subsample compared with the weight of the initial biomass sample were used to estimate total *L. rigidum* seed number m^{-2}. In wheat crops in 2011 and 2013, the number of seeds m^{-2} estimated from the biomass samples was compared with the number of seeds m^{-2} captured by the harvester. In both years, the harvester captured 4% of the total *L. rigidum* seed in the wheat crop. In 2007 to 2010, the crops included wheat, barley and oilseed rape (no crop in 2008). Barley and oilseed rape are a similar height to wheat, and the *L. rigidum* in all years was at a similar developmental stage at harvest (i.e. the *L. rigidum* had senesced). Therefore, it was assumed that 4% of the total *L. rigidum* seed would be captured in the harvested grain sample of the crops grown from 2007 to 2010, as for those wheat crops grown in 2011 and 2013.

Rainfall data were obtained from the Department of Agriculture and Food Western Australia Merredin Research Station (weather station number 010093) (Table 1, Bureau of Meteorology, 2014). The average rainfall at this site was 312 mm (calculated from 1911 to 2013), and the average growing season rainfall (i.e. rainfall from May to October) was 211 mm (Bureau of Meteorology, 2014).

Statistical analysis

The crop density, crop yield and *L. rigidum* seed production variates were analysed with a linear mixed model for the repeated measurements (REML procedure, GenStat 16th edition, VSN International, 2012). The variates were taken from each year a crop was produced (i.e. set to exclude 2008 where the field was fallow). The fixed model terms included year, crop residue (residue) and row spacing (spacing). The random model terms included block, the eight combinations of residue and row spacing treatments (residue spacing) and year. Variance components were constrained to positive values. The covariance structure included block by residue spacing by year. A power correlation model was used, and the model allowed heterogeneity over time (due to the varying crop choice and seasonal conditions in each year). Significant factors were identified by Wald tests, and means were separated using the standard error of the difference (SED). Least significant difference (LSD) was used to separate means (Welham *et al.*, 2015). A square root transformation was applied to the *L. rigidum* seed data (after adding one to each value to remove zero values) (Welham *et al.*, 2015). The *L. rigidum* data in the results are presented as both back-transformed and transformed means (note that transformed means are presented in parenthesis, and the SED and LSD values are presented for the transformed means). To clarify the analysis, the GenStat input is included as Annex 1, using the analysis of the *L. rigidum* seed variate as an example.

Results

Crop plant density and yield

Crop density varied significantly among years, as different crops were sown at different rates, but was not affected by residue or spacing (data not presented). Average yield was greater in the unburnt plots (1638 and 1530 kg ha^{-1} in the unburnt and burnt plots, $P < 0.001$, SED: 20.7, LSD: 41.7). This was due to increased yield in the unburnt plots in 2003, 2007, 2011 and 2013, although yield was reduced in the unburnt plots in 2005 (Table 2). Average yield also significantly increased at narrower row spacing, although the relationship was not linear in every year (1658, 1637, 1548 and 1492 kg ha^{-1} in the 9-, 18-, 27- and 36-cm row spacing treatments, $P < 0.001$, SED: 29.2, LSD: 59.0). Exceptions to this trend included 2012 and 2013, where the difference was not significant from 9 to 36 cm. The interaction between crop residue and row spacing treatments, and the interaction between residue, spacing and year, were not significant.

Lolium rigidum seed density

The average *L. rigidum* seed density was significantly different between years (data not presented). Seed density was lower in the burnt plots compared with the unburnt plots, with 56 and 296 seeds m^{-2} in the burnt plots and unburnt plots (transformed means of 7.6 and 17.2 seeds m^{-2}, $P = 0.005$, SED: 1.2, LSD: 6.1). Seed density was greater in the wide row spacing treatments, with 57, 77, 222 and 332 seeds m^{-2} in the 9-, 18-, 27- and 36-cm row spacing treatments (transformed means of 7.6, 8.8, 15.0 and 18.2 seeds m^{-2}, $P = 0.014$, SED: 1.7, LSD: 4.3). There was a significant interaction between year, crop residue and row spacing. The *L. rigidum* seed density was generally greater in wide row spacing treatments, although the relationship between seed density and row spacing was not linear in every year (Table 3). However, in the burnt plots, there was no significant difference between row spacing treatments by 2010 as the seed density was uniformly low.

Table 2 Average crop yield (kg ha^{-1}) in the burnt and unburnt residue treatments ($P < 0.001$, SED: 46.2, LSD: 92.0) and the row spacing treatments ($P < 0.001$, SED: 65.9, LSD: 130.4), from 2003 to 2013

	Crop residue		Row spacing			
Year	Burnt	Unburnt	9 cm	18 cm	27 cm	36 cm
2003	2901	3436	3210	3317	3099	3049
2004	1759	1725	1823	1825	1760	1560
2005	1944	1802	1995	2024	1761	1710
2006	2468	2427	2585	2631	2358	2216
2007	335	458	366	385	394	441
2009	858	849	929	887	832	766
2010	1085	1100	1273	1077	988	1031
2011	1892	2178	2140	2058	1969	1975
2012	155	137	176	148	119	141
2013	1898	2269	2083	2021	2196	2035

Discussion

Burning stubble was a highly effective method of weed control, reducing *L. rigidum* seed production to close to zero by the end of the 11-year management period. It is relatively easy to destroy *L. rigidum* seeds on the soil surface through residue burning, as the seeds have a very thin seed coat (Walsh & Newman, 2007). Removing the crop residue through burning is also likely to have improved the efficiency of the pre-emergence herbicide. Where crop residue is left on the soil surface, the pre-emergence herbicide may bind to the residue, and the minimal soil disturbance in the no tillage system ensures that the residue and herbicide are not fully incorporated into the soil (reviewed by Chauhan *et al.*, 2006b). As stated in the methods, burning was performed over the entire plot area. This has the advantage of improving the ease of sowing by clearing crop residue, but it is environmentally unfriendly and can be detrimental to soil structure (Bronick & Lal, 2005; Cao *et al.*, 2008). Wheat was the most common crop in the rotation, and burning wheat residue has a high emission factor of particulate matter and other gaseous pollutants, compared with other types of crop

Table 3 *Lolium rigidum* seeds (m^{-2}) as back-transformed values (and the transformed means), in the burnt and unburnt treatments, at a row spacing of 9–36 cm, from 2003 to 2013 ($P < 0.001$, SED: 4.6, LSD: 9.3, where the SED and the LSD are presented for the transformed data)

	Burnt				Unburnt			
Year	9 cm	18 cm	27 cm	36 cm	9 cm	18 cm	27 cm	36 cm
2003	120 (11.0)	117 (10.9)	170 (13.1)	141 (11.9)	324 (18.0)	296 (17.2)	702 (26.5)	382 (19.6)
2004	42 (6.6)	117 (10.9)	213 (14.6)	313 (17.7)	318 (17.9)	312 (17.7)	757 (27.5)	1001 (31.7)
2005	147 (12.2)	221 (14.9)	354 (18.8)	1101 (33.2)	375 (19.4)	558 (23.7)	1930 (43.9)	1581 (39.8)
2006	5 (2.4)	5 (2.5)	22 (4.8)	13 (3.8)	14 (3.9)	18 (4.3)	29 (5.5)	27 (5.3)
2007	6 (2.7)	23 (4.9)	28 (5.4)	105 (10.3)	25 (5.1)	54 (7.4)	424 (20.6)	789 (28.1)
2009	55 (7.5)	152 (12.4)	159 (12.7)	622 (25.0)	140 (11.9)	319 (17.9)	3056 (55.3)	3468 (58.9)
2010	3 (2.0)	1 (1.5)	6 (2.7)	17 (4.3)	17 (4.3)	24 (5.0)	36 (6.1)	173 (13.2)
2011	2 (1.9)	0 (1.0)	0 (1.0)	17 (4.3)	159 (12.6)	162 (12.8)	334 (18.3)	552 (23.5)
2012	3 (2.0)	0 (1.0)	4 (2.2)	10 (3.4)	60 (7.8)	50 (7.1)	135 (11.7)	287 (17.0)
2013	0 (1.0)	5 (2.4)	0 (1.0)	0 (1.0)	2 (1.7)	1 (1.3)	51 (7.2)	171 (13.1)

residue (Cao *et al.*, 2008). An alternative is to use a chute attached to the harvester to concentrate the crop residue in a band to be burnt (windrow burning). This method ensures that a small proportion of the field is burnt and may destroy weed seeds more effectively as a concentrated windrow of residue can burn at a hotter temperature than residue scattered over the field (Walsh & Newman, 2007).

Burning crop residue reduced average crop yield, in spite of the fact that the crop probably had less competition from *L. rigidum* than crop in the unburnt plots. The reduced *L. rigidum* seed production in the burnt plots indicates that there was lower *L. rigidum* density or smaller plants (Zimdahl, 2004). Residue management impacts crop yield by affecting soil moisture retention, soil structure, nutrient availability, soil erosion, etc. (Bronick & Lal, 2005; Cao *et al.*, 2008; D'Emden *et al.*, 2008). None of these factors were examined in the current research, so possible reasons for the reduced yield will not be speculated upon in detail. However, if burning is undesirable in a farming system (due to reduced yield or detrimental environmental impacts), a range of other methods for weed seed destruction at harvest can be used as an alternative to burning (Walsh *et al.*, 2013). In the current study, a chaff cart was used from 2003 to 2006 in all plots to remove weed seeds at harvest. The chaff cart was introduced because *L. rigidum* density was increasing in spite of herbicide use (particularly in the wide row spacing, unburnt plots). As *L. rigidum* seed at harvest was reduced over 2003 to 2006 in both the burnt and unburnt plots, it is reasonable to conclude that the chaff cart was a highly effective part of the weed management programme. It is clear that some methods of harvest weed seed destruction should be included in an integrated weed management programme to reduce *L. rigidum* density.

This research demonstrates the long-term benefits of narrow row spacing to reduce *L. rigidum* seed production. While narrow row spacing is generally accepted as a method to increase the competitive ability of crops and suppress weed growth, the benefits of narrow row spacing have not been demonstrated in all studies (reviewed by Scott *et al.*, 2013). For example, Champion *et al.* (1998) and Lemerle *et al.* (2002) found no impact of row spacing on weed biomass in a range of crops, whereas Drews *et al.* (2009) and Borger *et al.* (2010) noted a reduction in weed biomass at narrow row spacing. However, prior research on row spacing has generally been conducted in trials over a single year, established on sites with an evenly distributed *L. rigidum* population (Scott *et al.*, 2013). The problem with this method is that if wide row spacing leads to greater weed seed production, then wide row crops will have a greater initial weed burden than narrow row crops (Zimdahl, 2004; Scott *et al.*, 2013). The major difference in the current study is that the row spacing treatments had been established for 16 years prior to 2003 when *L. rigidum* seed production was first assessed. The trial demonstrates that higher weed seed production occurs in the wide row spacing plots, leading to a higher weed seedbank in the sequential years. Further, prior studies have often focused on row spacing in a single crop (Scott *et al.*, 2013). The current study establishes that narrow row spacing reduces *L. rigidum* seed production in a range of different crop species. The reduction in weed seed at narrow row spacing likely resulted from the improved crop competition (Peltzer *et al.*, 2009; Scott *et al.*, 2013). However, narrow row spacing would also result in increased soil disturbance at seeding compared to wide row spacing, which would improve the performance of pre-emergent herbicides (Chauhan *et al.*, 2006b, 2007).

Crop density was not affected by row spacing, although prior research has indicated that wide row spacing may lead to lower crop density (Amjad & Anderson, 2006; Scott *et al.*, 2013). However, this depends on seeding and fertiliser rates (Scott *et al.*, 2013). Crop yield was reliably increased at narrow row spacing. This would be partially due to reduced weed competition, but narrow row spacing increases crop yield in the absence of weeds, due to canopy closure at an earlier stage, increased light interception, reduced evaporation and reduced intraspecies competition for resources (Doyle, 1988; Zimdahl, 2004; Eberbach & Pala, 2005; Scott *et al.*, 2013). Prior research has indicated that crops with wide row spacing may have more soil moisture available at maturity and so have higher yields in dry seasons (Blackwell *et al.*, 2006; Scott *et al.*, 2013). In the current trial, a significant yield increase was not observed in the dry years (notably 2007 and 2010). However, the increased *L. rigidum* density in the wide rows may have negated any advantage of increased soil moisture, as the weeds would compete with the crop and utilise stored soil moisture prior to crop maturity. Narrow row spacing is not always viable in high-yielding areas, where the resulting crop residue is difficult to manage during the subsequent seeding operation. However, this technique is economically desirable where feasible in the broadscale, rain-fed grain cropping regions of Southern Australia (Scott *et al.*, 2013). Where narrow row spacing is not practical, a range of other techniques can be used to increase crop competition, including increased crop density, choice of competitive cultivar and use of appropriate crop orientation (Lemerle *et al.*, 2004, 2006; Zimdahl, 2004; Paynter & Hills, 2009; Borger *et al.*, 2010).

A weakness of this research is that *L. rigidum* seed production at harvest was estimated using differing methods over the 11-year span. The data from 2003 to 2010 may not be as accurate as the data from 2011 to 2013 (where *L. rigidum* seed production was assessed from *L. rigidum* biomass samples). This makes it difficult to compare *L. rigidum* density between seasons. Generally, 84–96% of *L. rigidum* seed germinates during the year following the seed production (Chauhan *et al*., 2006a). Seed may persist for at least 4 years, but annual decline in viability is 70–80% (Storrie, 2014). Therefore, if the population was successfully controlled in 1 year, there should not be much dormant seed to rejuvenate the population in the following years. This was generally observed in the current experiment. There was particularly high seed production in 2009, as no grass-selective herbicides were applied in the oilseed rape crop. However, 2010 had good weed control, particularly in the narrow row spacing or burnt plots, and in the following years, *L. rigidum* seed production remained low, indicating that there was not a large dormant seedbank following the 2009 season. In spite of potential inaccuracies in data from individual years (due to the varied methods of estimation of seed production), it is clear that *L. rigidum* seed production has declined over the entire period. It is also clear that the decline has been more rapid in the burnt plots compared to the unburnt plots and the narrow rather than wide row spacing plots. We recommend that future long-term research should aim to directly measure *L. rigidum* seed production in every year.

Conclusions

Herbicides alone were not sufficient to eliminate *L. rigidum*, even with the additional use of a chaff cart from 2003 to 2006. Use of narrow row spacing within this system was a highly effective weed control method. Use of narrow row spacing combined with residue burning was sufficient to reduce *L. rigidum* seed production at harvest to 0–3 seeds m^{-2} in the final 4 years of the trial. It is clear that improved crop agronomy, through increased crop competition and physical weed control, through weed seed destruction at harvest, should be used to develop effective and inexpensive IWM programmes (Zimdahl, 2004; Scott *et al*., 2013; Walsh *et al*., 2013).

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Annex 1

Genstat code:

```
variate [values=2003...2007,2009...2013] realyears
calc sqrt_annual_ryegrass_seeds=sqrt
(annual_ryegrass_seeds+1)
vcomp [fixed=year*residue*spacing] replication/
residue_spacing/year;con=pos
vstructure
[terms=replication.residue_spacing.year]
coord=realyears;model=power;factor=year;
hetero=outside
reml  [print=model,wald,dev,comp,mean;
mvinclude=yvar;maxcycle=1000]
sqrt_annual_ryegrass_seeds
```