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www.publish.csiro.au/journals/cp *Crop & Pasture Science*, 2009, **60**, 667–674

Impact of crop-topping and swathing on the viable seed production of wild radish (*Raphanus raphanistrum*)

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Abstract. Crop-topping, the practice of applying non-selective herbicides at crop maturity, has proved to be an effective management technique in preventing the input of seed into the seedbank for some annual weed species of southern Australian crop production systems. However, the efficacy of this practice on the dominant broad-leaf weed of these systems, wild radish, is not well understood. These studies investigated the effect of crop-topping and swathing on the viable seed production of wild radish. Crop-topping with either glyphosate or sprayseed (paraquat 135 g/L + diquat 115 g/L) can provide large reductions of 80–90% in viable seed production of wild radish plants present in crops at the end of the growing season. However, the efficacy of this practice was found to be highly variable and therefore, cannot be relied upon to consistently produce these large reductions in seed numbers. Similarly, swathing also produced large reductions in viable seed production but results from this practice were even less consistent than crop-topping treatments. For all treatments, early application timings of growth stage 6.5 or earlier, were optimum for targeting wild radish seed production. However, these treatment timings also resulted in large crop yield losses of ~30%. To preserve at least 90% of crop yield, crop-topping and swathing treatments need to be delayed until wild radish growth stage 8.5, with expected reductions in seed numbers of up to 70%. However, in high-density infestations the need to preserve grain yield will be less important than preventing substantial inputs of wild radish seed into the seedbank.

Additional keywords: targeting weed seed, wild radish seed production.

Introduction

Wild radish (*Raphanus raphanistrum* L.), originating from the Mediterranean region (Rollins 1981), is a significant weed of many of the world's major cropping zones (Cheam and Code 1995). It is the most problematic dicotyledonous weed of the large (30 Mha) southern Australian dryland cropping region (Alemseged *et al*. 2001). Wild radish is a vigorous competitor, causing substantial yield reductions in wheat (*Triticum aestivum* L.) (Reeves *et al*. 1981; Cousens *et al*. 2001), lupins (*Lupinus angustifolius* L.) (Hashem and Wilkins 2002), and canola (*Brassica napus* L.) (Blackshaw *et al*. 2002). The success of wild radish as a weed is due to its flexible life cycle, lack of specific germination requirements, prolific seed production, and a long-lived seedbank (Cheam and Code 1995). In particular, the considerable genetic diversity (Bhatti 2004; Madhou *et al*. 2005) within this weed species has enabled wild radish to be successful across several agro-ecosystems of the Australian dryland cropping region.

Over the last decade the difficulty in controlling wild radish has been further exacerbated by the widespread evolution of herbicide resistance in populations of this weed. Strong herbicide selection and considerable genetic diversity in wild radish have resulted in the widespread development of resistant populations. A further complication is that most resistant populations have evolved multiple resistance to several in-crop selective herbicides frequently used to control this weed. We have documented *R. raphanistrum* populations with resistance to acetolacetate synthase (ALS)-inhibiting herbicides (Walsh *et al*. 2001), photosystem (PS) II-inhibiting herbicides (Hashem *et al*. 2001; Walsh *et al*. 2004), auxin analogue herbicides, and phytoene desaturase (PDS)-inhibiting herbicides (Walsh *et al*. 2004). A survey of the Western Australian wheatbelt in 2003 revealed very high frequencies of resistance to chlorsulfuron (54%), 2,4-D amine (60%), diflufenican (40%), and atrazine (15%) in randomly collected wild radish populations (Walsh *et al*. 2007). Additionally, over half (58%) of these populations were multiple resistant to two or more of these different mode-of-action herbicides.

In intensive crop production systems, reducing weed seed inputs into the soil seedbank is critical to the effective management of annual weed species such as wild radish. This is particularly important when herbicide resistance is present in populations of this weed. Within wheat crops, wild radish plants can produce over 1000 seeds/plant (Walsh and Minkey 2006), with dense infestations producing 45 000–60 000 seeds/m^2 (Reeves *et al*. 1981; Eslami *et al*. 2006). If this seed rain is not intercepted, the resulting large and viable seedbank will ensure wild radish infestations in crop production for several subsequent growing seasons. Despite the widespread occurrence of herbicide-resistant wild radish populations, there remains the

10.1071/CP08286 1836-0947/09/070667

continual and ubiquitous use of herbicides for wild radish control within cropping systems. Therefore, any seed-producing plants present within crops late in the growing season will most likely have survived one or more herbicide applications and consequently have a very high probability of being herbicide resistant. This further adds to the need for the prevention of seed inputs into the seedbank.

Crop-topping, the late-season, in-crop application of non-selective herbicides targeting weed seed development, is likely to substantially restrict the viable seed production of wild radish plants infesting crops at the end of the growing season. Originally developed in Australia to target the seed production of annual ryegrass (*Lolium rigidum* Gaud.) infesting dicotyledonous crops (Powles and Mathews 1996; Gill and Holmes 1997), crop-topping when successfully implemented, can reduce viable seed production of this weed by up to 90% (Matthews 1996; Steadman *et al*. 2006). This technique has also proved similarly effective in reducing viable seed production of other weed species including *Vulpia bromoides* (Leys *et al*. 1991), *Hordeum glaucum* (Powles 1986), *Bromus* spp. (Dowling and Nicol 1993), *Xanthium strumarium*, *Sesbania exaltata*, *Senna obtusifolia* (Clay and Griffin 2004), and *Cassia obtusifoli* (Ratnayake and Shaw 1992). However, there is limited documented evidence on the efficacy of crop-topping in controlling the seed production of wild radish. Preliminary studies have provided widely varying results on the levels of seed reduction achieved by crop-topping, ranging from 10 to 100% seed control (Cheam *et al*. 2004; Newman and Adam 2006; Walsh and Minkey 2006). These results suggest that due to the prolonged period of seed production (Cheam and Code 1995) of this weed, this practice will be less effective on wild radish than on other weed species with a short period of seed production. Consequently, this study was conducted with the initial aim of quantifying the effectiveness of wild radish seed-set control practices following crop-topping treatments at maturity of wheat, lupins, barley, and canola crops. As canola crops are traditionally swathed (defined here as cut and shaped crop row for drying in preparation for harvest) at this stage to reduce grain shedding (Colton and Sykes 1992), the effects of this practice on wild radish seed production were also investigated. There is some evidence suggesting that the optimum timing for seed-set control of wild radish may occur before the maturity of these crop species (Cheam *et al*. 2004; Walsh and Minkey 2006). Therefore, a subsequent aim was to determine the optimum timing of crop-topping and swathing treatments during the reproductive development phase of wild radish for minimising wild radish seed production.

Materials and methods

Experiment 1: Effect of crop-topping and swathing on wild radish seed production and crop grain yield, 1999 field trial, Goomalling

The efficacy of crop-topping and swathing treatments in reducing the viable seed production of wild radish in wheat, lupins, barley, and canola crops was investigated in field experiments conducted in 1999 at Goomalling (31°12′46.10′S, 116°45′26.79′E), Western Australia (WA). Immediately before crop seeding, a mixture of 270 g/ha paraquat plus 230 g/ha diquat, as Sprayseed® (from this point forward referred to as sprayseed) (Syngenta Crop Protection Australia, PO Box 886, North Ryde, NSW), was applied to control emerged weed seedlings using a vehicle-mounted sprayer with a delivery rate of 60 L/ha. On 8 June 1999, all crops were planted in 2 m wide by 20 m long plots using a tyned plot seeder fitted with knife points and press wheels on a 20-cm row spacing and 4-cm seeding depth. At seeding, fertiliser was incorporated in the soil below the seed at 17.5, 7.6, and 16 kg/ha of N, P, and S, respectively. Wheat (*Triticum aestivum* cv. Westonia), lupins (*Lupinus angustifolius* cv. Belara), canola (*Brassica napus* cv. Karoo), and barley (*Hordeum vulgare* cv. Unicorn) were planted at 75, 75, 100, and 125 kg/ha, respectively. The experimental design was a randomised complete block, with crop-topping and swathing treatments replicated 4 times, once in each block. Crop-topping and swathing treatments were applied on 25 Oct. 1999 when all crops had reached maturity. Crop-topping treatments [glyphosate at 450 g a.i./ha (Glyphosate CT, Nufarm Australia, 103–105 Pipe Road, Laverton North, Vic.) and sprayseed at 376 g a.i./ha] were applied using a vehicle-mounted spray boom equipped with flat-fan nozzles delivering 60 L/ha at 400 kPa. A self-propelled plot swather was used in the swathing treatments where crops and wild radish plants were cut at 10 cm above ground height.

To determine total wild radish seed production at crop maturity, seed was collected from wild radish plants and from the soil surface within a 1.0-m^2 area in each plot immediately before harvest on 11 Nov. 1999. In swathed plots, wild radish plants were counted and collected from a 1.0-m section of swathed row. Collected pod segments were then counted and total pod segment production per plant was determined for each plot. Following the collection of wild radish pods, plots were harvested for grain yield using a small plot harvester. Samples of 100 pod segments were collected from each treatment and hand-dissected to remove intact seeds. Wild radish seed viability was determined by placing seeds on agar plates in a germination cabinet with a 12-h alternating cycle of 25°C/light and 15°C/dark. After 4 weeks, viable seed was counted where germinated and not germinated but not decayed (assumed dormant) were assessed as viable seed. This dormancy assumption is based on evidence that there is a seed coat-imposed dormancy mechanism present in wild radish seeds, which prevents germination of some viable seeds (Young 2001). There were no treatment effects ($P > 0.05$) on seed germination and the average value (87 ± 4%) across all treatments was used to convert pod segment numbers to viable seed number per plant for analysis.

Experiment 2: Effect of crop-topping and swathing timing on wild radish seed production, 2001 pot trial, UWA

The wild radish population (WARR7) used in the pot study was collected in 1999 from a reserve at Yuna (28.34°S, 115.01°E). Following collection, wild radish seeds were removed from their pod segments using a modified gristing mill. Seeds were then stored at 20°C under laboratory conditions until used in subsequent screening studies. In May 2001, wild radish seeds were planted to a depth of 10 mm into 30-cm-diameter pots (5 seeds/pot) lined with 2 cm of gravel and filled with potting mix (25% peat moss, 25% sand, and 50% mulched pine bark). After planting, the pots were placed in the outside plant growth area at the University of Western Australia (UWA), Crawley campus, where they were arranged in a completely randomised design with 5 replicates. Pots were watered as required and fertilised weekly using a complete liquid fertiliser throughout the duration of the experiment. Two weeks after planting, when all seedlings had emerged, they were thinned to 3 plants per pot.

Crop-topping and swathing treatments were applied at 6 growth stages, all of which occurred during wild radish reproductive development (Table 1). Glyphosate at 450 g a.i./ha and sprayseed at 376 g a.i./ha were applied at each of the 6 stages using a dual-nozzle cabinet sprayer with a delivery rate of 98 L/ha at 200 kPa. Control treatments were established for each application time and were similarly moved to and from the treatment application facility. Swathing treatments were applied by cutting the wild radish plant stems 10 cm above the soil surface, then putting the plant material in a woven plastic mesh bag to dry on the soil surface for 3 weeks.

At plant maturity, pods were collected from the three wild radish plants in each pot and counted. Samples of 100 pod segments were collected from each treatment and hand-dissected to remove intact seeds. Wild radish seed viability was determined using the methods describe above. There were no treatment effects ($P > 0.05$) on seed germination, and the average value (82%) across all treatments was used to convert pod segment numbers to viable seed number for analysis.

Experiment 3: Effect of timing of crop-topping and swathing on seed production and crop grain yield, 2001 field trials, York

The efficacy of crop-topping and swathing treatments and the application timing of these treatments in reducing the viable seed production of wild radish were investigated in field experiments conducted at York (31°37′16.05′S, 116°49′22.10′E) in 2001. To control emerged weed seedlings immediately before crop seeding, sprayseed at 376 g a.i./ha was applied using a vehicle-mounted spray boom equipped with flat-fan nozzles delivering 60 L/ha at 400 kPa. The same varieties of wheat, lupins, barley, and canola, and planting procedures as used in the 1999 field trial (Expt 1) were also used in this field trial. The efficacy of two crop-topping treatments, glyphosate 450 g a.i./ha and sprayseed 376 g a.i./ha, as well as swathing, were compared for their effect on viable seed production of wild radish. These treatments were applied at 4 growth stages (Table 2), all timed to occur during reproductive development. Treatments were applied using a vehicle-mounted spray boom equipped with flat-fan nozzles delivering 60 L/ha at 400 kPa. A self-propelled plot swather was used in the swathing treatments where plants were cut 10 cm above the soil surface.

Table 1. Treatment application timings used in pot studies for crop-topping and swathing treatments applied at key wild radish growth stages (Madafiglio *et al.* 1999)

Timing	Growth stage	Description
T1	GS 4.5	Flowering: 50–90% of branches have flowers, no pods
T2	GS 5.5	Flowering and early pod development: 50% branches flowering with small pods present (<1 mm diam.)
T3	GS 6.5	Half of branches with flowers and medium pods (1–2 mm diam., some constrictions between segments)
T4	GS 7.5	Flowering, half of branches with pods >2 mm diam., yellow-brown colour
T5	GS 8.5	Flowering completed, half pods >2 mm diam., definite constrictions between segments
T6	GS 9.5	Senescence, half pods and branches green

Wild radish plant densities were determined by counting all plants in each plot immediately before harvest on 14 Nov. 2001. At this time, seed was collected from wild radish plants and the soil surface from a 1.0-m^2 area in each plot. In swathed plots, wild radish plants were counted and collected from a 1.0-m section of swathed row. Collected pod segments were counted and pod segment production per plant was determined. Seed viability was determined using the procedures described in Expt 1. There were no treatment effects ($P > 0.05$) on seed germination, and the average value (92 ± 5%) across all treatments was used to convert total pod segment numbers to viable seed number per plant for analysis. At crop maturity, all plots were harvested for grain yield using a small plot harvester. However, a hail storm before harvest prevented the collection of any yield data from the lupins plots.

Statistical design and analysis

The 1999 and 2001 field trials (Expts 1 and 3) were arranged in randomised block designs with 4 replicates. Wild radish seed number data were $\log_{10}$-transformed before analysis to improve homogeneity and normality of residuals, with treatment means back-transformed for presentation. There were significant ($P < 0.05$) interaction effects between crop and herbicide treatments only for wild radish seed number and grain yield data from the 1999 and 2001 field trials. Therefore, herbicide treatment effects on wild radish seed number and grain yield were compared in a 1-way ANOVA in randomised blocks for the 1999 field trial. A 2-way ANOVA in randomised blocks was used to compare herbicide treatment and application timing main effects on wild radish seed number and grain yield data from the 2001 field trial. There were significant ($P < 0.05$) interaction effects between application timing and herbicide treatment for the wild radish seed number data from the 2001 pot trial. An l.s.d. test ($\alpha = 0.05$) was used to test statistical differences between treatment means of grain yield and wild radish seed number in all trials. ANOVA and l.s.d. tests were performed using SAS 9.1 (SAS 2002). Treatment effects on wild radish as a percentage of the control are presented to highlight effects of application timing (Figs 1, 3) and crop type (Fig. 2).

Table 2. Application timings for crop-topping and swathing treatments to wild radish at key growth stages for the 2001 York trial (Madafiglio *et al.* 1999)

Timing	Growth stage	Description
T1	GS 6.5	50–90% of branches have flowers
T2	GS 7.5	Half of branches with flowers and medium pods 1–2 mm diam., some constrictions between segments
T3	GS 8.5	Flowering completed, half pods >2 mm diam., definite constrictions between segments
T4	GS 9.5	Senescence, half pods and branches green

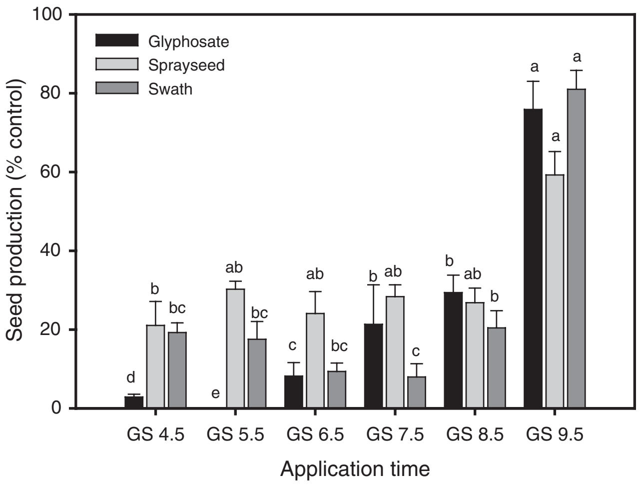

Fig. 1. Seed production of wild radish as a percentage of the untreated control in response to crop-topping and swathing treatments applied at 6 growth stages of wild radish, pot trial 2001. Bars represent standard error values for 4 replicates. The same letters above bars representing the same crop-topping or swathing treatments indicate that there were no differences due to application time ($P = 0.05$).

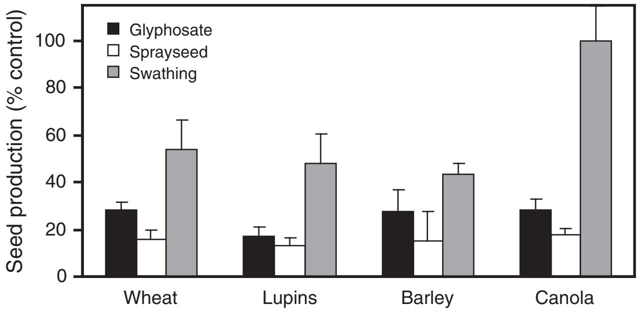

Fig. 2. Effect of crop-topping and swathing treatments on the seed production of wild radish plants growing in wheat, lupins, barley, and canola crops, York 2001. Bars represent standard error values for 4 replicates.

Results

Experiment 1: Effect of crop-topping and swathing on wild radish seed production and crop grain yield, 1999 field trial, Goomalling

Crop-topping treatments reduced wild radish seed production by ~50% when they were applied at maturity of wheat, lupins, barley, and canola crops. The effects of glyphosate and sprayseed crop-topping treatments, averaged over the four crops, were reductions in wild radish seed numbers of 58 and 53%, respectively (Table 3). Glyphosate was the most consistent crop-topping treatment, with reductions in total seed numbers of 47–65% compared with 22–76% reductions for sprayseed treatments. Swathing on average reduced seed production numbers by 42%, with a range of 14–62%. Despite these large effects on wild radish seed production, variability in the efficacy of crop-topping and swathing treatments meant that significant reductions in seed numbers below that of the untreated control only occurred in lupins and barley crops. Crop-topping treatments reduced ($P < 0.05$) wild radish seed numbers in lupin and barley crops, whereas swathing reduced numbers in barley crops only.

Wild radish seed production varied considerably among the four different crops due to differing crop competition effects. Untreated wild radish plants infesting lupins and canola crops produced 2394 ± 1101 and 3114 ± 1208 seeds/plant, respectively, which was approximately double the level of seed produced by plants growing in wheat (1304 ± 260 seeds/plant) and barley (1142 ± 441 seeds/plant) crops (Table 3). It is likely that these crop competition effects were largely responsible for the interaction effects ($P < 0.05$) between crop species and treatments targeting seed production.

Consistent with commercial experience, application of crop-topping treatments after crop maturity had little or no adverse effect on grain yield of any of the four crops. Neither glyphosate nor sprayseed crop-topping treatments applied at crop maturity reduced grain yield of wheat, lupins, barley, or canola crops (Table 4). In contrast, swathing caused yield reductions ($P < 0.05$) of 47, 34, and 48%, respectively, for wheat, lupins, and barley. However, as these crops were mature at the time of swathing it is likely that these reductions are largely due to the difficulty in creating an effective swath in narrow plots (2.0-m wide), which can subsequently be collected by a plot harvester. Swathing did not reduce canola yields.

Experiment 2: Effect of crop-topping and swathing timing on wild radish seed production, 2001 pot trial, UWA

In the 2001 pot experiment where wild radish was grown under highly favourable conditions, crop-topping and swathing treatments resulted in larger reductions in the numbers of viable wild radish seed than those observed in the 1999 field trial. Conducted outdoors during the normal growing season and despite the absence of crop competition, seed production on untreated wild radish plants was similar to untreated plants in the 1999 field trial (Table 5). Averaged over all application timings, glyphosate and sprayseed crop-topping treatments reduced this seed production by 77 and 68%, respectively

Table 3. Effect of crop-topping and swathing treatments on viable seed production (seeds/plant) of wild radish plants infesting wheat, lupins, barley, and canola crops (Goomalling, 1999)

Numbers in columns followed by the same letter are not significantly different at $P = 0.05$

Treatment	Wheat	Lupins	Barley	Canola	Average
Glyphosate	688 ± 165a	856 ± 516b	489 ± 334b	1099 ± 225a	783 ± 311b
Sprayseed	1014 ± 152a	963 ± 314b	270 ± 190b	1419 ± 1052a	916 ± 427b
Swathing	1122 ± 487a	1148 ± 474ab	433 ± 239b	1850 ± 1072a	1138 ± 568ab
Control	1304 ± 260a	2394 ± 1101a	1142 ± 441a	3114 ± 1208a	1988 ± 753a

Table 4. Effect of crop-topping and swathing treatments on grain yield (t/ha) for wheat, lupins, barley, and canola crops (Goomalling, 1999)

Numbers in columns followed by the same letter are not significantly different at $P = 0.05$

Treatment	Wheat	Lupins	Barley	Canola
Glyphosate	2.56 ± 0.23a	0.94 ± 0.08a	1.67 ± 0.14a	1.55 ± 0.13a
Sprayseed	2.51 ± 0.21a	1.08 ± 0.09a	1.55 ± 0.14a	1.26 ± 0.11a
Swathing	1.29 ± 0.11b	0.58 ± 0.05b	0.98 ± 0.07b	1.15 ± 0.09a
Control	2.43 ± 0.22a	0.89 ± 0.05a	1.89 ± 0.13a	1.49 ± 0.16a

(Table 5). However, on average, glyphosate treatments resulted in lower ($P < 0.05$) seed numbers (348 ± 79 seeds/plant) than sprayseed (480 ± 44 seeds/plant). Swathing was similarly as effective as crop-topping treatments, reducing seed production by 75% ($P < 0.05$). These reductions in seed numbers were much larger than those observed in the 1999 field trial, with crop-topping and swathing treatments 50% more effective in this experiment.

The application of crop-topping and swathing treatments during the early stages of wild radish reproductive development resulted in the lowest wild radish seed numbers. These treatments applied at wild radish growth stages 4.5, 5.5, and 6.5, respectively, reduced viable seed production on average by 89, 83, and 87% (Table 5, Fig. 1). Glyphosate treatments applied at the last three application timings (GS 7.5, 8.5, and 9.5) reduced wild radish seed production by 69, 74, and 41%. However, resulting seed numbers for these treatments were higher ($P < 0.05$) than those recorded following the first three timings. Further evidence of the efficacy of glyphosate at earlier application timings was that this treatment produced the lowest levels of seed production of 44 ± 11 and 0 ± 0 seeds/plant following GS 4.5 and 5.5 application timings (Table 3, Fig. 1). Sprayseed and swathing treatments were both less effective ($P < 0.05$) most likely because of the similar wild radish plant responses to these treatments. The action of sprayseed and swathing treatments was to stop seed production immediately following treatment application. However, with neither treatment resulting in plant death, earlier application timings (GS 4.5 and GS 5.5) and favourable growing conditions allowed plant recovery and additional seed production (Fig. 1). Conversely, delaying application of sprayseed and swathing treatments allowed the development of increased numbers of mature seeds that were not affected by these treatments. Although it was not possible in this study to accurately determine the amount of wild radish seed that was produced by sprayseed and swathed plants following regrowth over the period GS 6.5 to GS 9.5, results in Table 3 indicate that an additional 300 seeds/plant developed over this growth period. Consequently, there were fewer differences ($P < 0.05$) in seed production levels between application timings for the sprayseed and swathing treatments.

Experiment 3: Effect of timing of crop-topping and swathing on seed production and crop grain yield, 2001 field trials, York

Wild radish plants surviving to maturity within wheat, lupins, barley, and canola crops in the 2001 field trial had substantially lower seed production levels than those recorded in the 1999 field and 2001 pot trials. The average seed production of untreated wild radish plants across all four crops was 174 ± 88 seeds/plant, which was ~10% of the seed production levels of untreated plants in the 1999 field (1988 ± 753) and 2001 pot trial (1519 ± 80). However, similar to the 1999 field trial, increased crop competition from wheat and barley crops resulted in ~25% lower seed production levels on untreated wild radish plants compared with plants growing in lupins and canola crops (Table 6). As demonstrated by wild radish plant densities, which are a response to in-season crop competition effects, barley was the most competitive crop, causing the largest reductions in both wild radish plant density and seed production per plant. Average wild radish plant density in barley plots was 4.7 plants/m^2 compared with densities of 11.8, 7.4, and 12.8 plants/m^2 for wheat, lupins, and canola plots, respectively.

In the 2001 field experiment, crop-topping treatments consistently resulted in large reductions in the numbers of viable seed produced by wild radish plants growing in wheat, lupins, barley, and canola crops. Glyphosate and sprayseed crop-topping treatments, on average, reduced seed production levels by 75 and 85%, respectively (Table 6, Fig. 2). The effect of these treatments was consist across the four crops, with glyphosate and sprayseed consistently reducing seed production by 72–83% and 82–86%, respectively (Table 6, Fig. 2). In contrast, swathing treatments averaged only a 39% reduction in seed numbers. Additionally, the efficacy of swathing was considerably more variable, reducing wild radish seed production by 0–57%.

Similar to results from the pot experiment, field application of crop-topping and swathing treatments was most effective following the earliest application timings. Crop-topping and swathing treatments all reduced ($P < 0.05$) wild radish seed numbers in all four crops following the earliest application timing (GS 6.5) only (Table 6). Treatments applied at this timing resulted in average reductions in seed numbers of ~80% (Table 6, Fig. 3). At later application timings, reductions in seed numbers were less consistent across all crop species, resulting in generally

Table 5. Effect of crop-topping and swathing treatments applied at 6 wild radish growth stages on seed production (seeds/plant) of wild radish plants (pot trial, 2001)

Numbers in columns followed by the same letter are not significantly different at $P = 0.05$

Treatment	GS 4.5	GS 5.5	GS 6.5	GS 7.5	GS 8.5	GS 9.5	Average
Glyphosate	44 ± 11c	0 ± 0d	124 ± 52c	324 ± 151b	447 ± 67b	1152 ± 109bc	348 ± 79c
Sprayseed	320 ± 92b	459 ± 31b	366 ± 85b	431 ± 46ab	407 ± 56b	900 ± 90c	480 ± 44b
Swathing	252 ± 37b	266 ± 69c	142 ± 33c	121 ± 51c	310 ± 67b	1230 ± 73b	387 ± 74bc
Control	1810 ± 80a	1464 ± 124a	1566 ± 161a	954 ± 144a	1476 ± 196a	1842 ± 206a	1519 ± 80a

Table 6. Viable seed number (seeds/plant) for wild radish plants growing in 4 crops as affected by crop-topping and swathing treatments applied at 4 growth stages of wild radish (York, 2001)

Numbers in columns followed by the same letter are not significantly different at $P = 0.05$

Treatment	GS 6.5	GS 7.5	GS 8.5	GS 9.5	Average
			Wheat		
Glyphosate	36 ± 11b	54 ± 13ab	54 ± 3b	29 ± 6b	44 ± 13c
Sprayseed	23 ± 8b	13 ± 3b	33 ± 11b	29 ± 11b	25 ± 11c
Swathing	57 ± 23b	77 ± 21b	120 ± 38a	82 ± 33ab	84 ± 45b
Control	155 ± 58a	155 ± 58a	155 ± 58a	155 ± 58a	155 ± 95a
			Lupins		
Glyphosate	32 ± 15b	48 ± 8ab	22 ± 7b	32 ± 21b	34 ± 15c
Sprayseed	12 ± 2b	21 ± 8b	21 ± 2b	51 ± 18ab	26 ± 8c
Swathing	22 ± 5b	62 ± 16ab	144 ± 4a	151 ± 45ab	95 ± 27b
Control	198 ± 85a	198 ± 85a	198 ± 85a	198 ± 85a	198 ± 85a
			Barley		
Glyphosate	21 ± 11b	8 ± 3b	69 ± 22ab	64 ± 24ab	40 ± 26b
Sprayseed	4 ± 2b	20 ± 6b	33 ± 13b	29 ± 10b	22 ± 9b
Swathing	8 ± 2b	41 ± 23b	120 ± 30a	82 ± 25ab	63 ± 15b
Control	145 ± 90a	145 ± 90a	145 ± 90a	145 ± 90a	145 ± 90a
			Canola		
Glyphosate	53 ± 26b	15 ± 7b	31 ± 11b	36 ± 8b	55 ± 15b
Sprayseed	74 ± 22b	63 ± 23ab	36 ± 24b	43 ± 14b	34 ± 8b
Swathing	100 ± 33b	299 ± 89a	90 ± 34b	287 ± 43a	194 ± 79a
Control	193 ± 83a	193 ± 83a	193 ± 83a	193 ± 83a	193 ± 83a

higher (10–20%) seed production levels. However, due to variable treatment effects, these higher seed numbers following later application timings were not due to consistently less effective ($P > 0.05$) crop-topping and swathing treatments (Fig. 3).

Crop-topping and swathing treatments consistently reduced the grain yields of wheat and canola crops following all application timings in the 2001 field experiment. Wheat and canola grain yields were reduced ($P < 0.05$) each time glyphosate, sprayseed, and swathing treatments were applied to these crops. Although swathing similarly consistently reduced the yield of barley at every application timing, this is likely due to the difficulty in swathing small plot areas. In contrast, glyphosate and sprayseed treatments only reduced barley yields following the GS 8.5 application timing. When averaged over application time and crop type, glyphosate, sprayseed, and swathing treatments reduced grain yields by 8, 12, and 34%, respectively (Table 7). Yield reductions due to swathing differed among crop species, ranging from 35 and 28% for canola and barley, respectively, to 49% for wheat. In contrast, crop-topping treatments resulted in smaller yield losses for the three crops species. Wheat, barley, and canola yield reductions were 15, 6, and 14% for glyphosate treatments and 20, 6, and 27%, respectively, for sprayseed treatments. The largest reductions ($P < 0.05$) in grain yields for wheat (50%), barley (28%), and canola (38%) occurred following the GS 6.5 application timing.

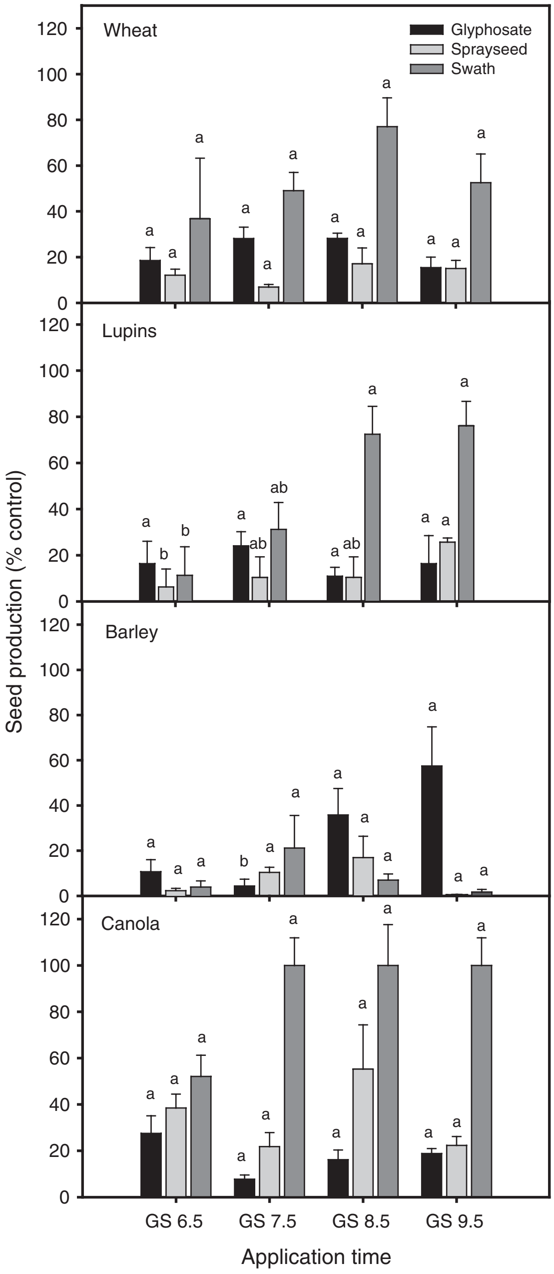

Fig. 3. Effect of treatment application timing averaged over crop-topping and swathing treatments on the seed production of wild radish plants growing in wheat, lupins, barley and canola, York 2001. Bars represent standard error values for 4 replicates. The same letters above bars representing the same crop-topping or swathing treatments indicate that there were no differences due to application time ($P = 0.05$).

Discussion

The application of crop-topping and swathing treatments at the end of the growing season can substantially reduce the production of viable seed by wild radish plants present in southern Australian grain crops. However, as the efficacy of these treatments is greater following earlier application timings the success of this practice will depend on the trade-off between the need for wild radish seed-set reduction and the preservation of crop yield. Results from these field and pot trials indicated that the application of crop-topping and swathing treatments at or before wild radish growth stage 6.5 resulted in 80–85% lower viable seed numbers.

Table 7. Grain yield (t/ha) for wheat, barley, and canola crops as affected by crop-topping and swathing treatments applied at 4 growth stages of wild radish (York, 2001)

Numbers in columns followed by the same letter are not significantly different at $P = 0.05$

Treatment	GS 6.5	GS 7.5	GS 8.5	GS 9.0	Average
			Wheat		
Glyphosate	2.09 ± 0.10a	2.41 ± 0.21a	2.85 ± 0.02a	2.81 ± 0.03a	2.54 ± 0.09b
Sprayseed	2.11 ± 0.03a	1.92 ± 0.16b	2.72 ± 0.06a	2.87 ± 0.08a	2.40 ± 0.08b
Swathing	0.19 ± 0.02b	0.72 ± 0.16c	2.36 ± 0.11b	3.83 ± 0.08a	1.52 ± 0.09c
Control	3.00 ± 0.11a	3.00 ± 0.11a	3.00 ± 0.11a	3.00 ± 0.11a	3.00 ± 0.11a
			Barley		
Glyphosate	3.29 ± 0.28a	3.65 ± 0.10a	3.57 ± 0.16a	3.66 ± 0.06a	3.54 ± 0.15b
Sprayseed	3.38 ± 0.20a	3.65 ± 0.15a	3.36 ± 0.16a	3.89 ± 0.07a	3.57 ± 0.14b
Swathing	1.44 ± 0.05b	2.72 ± 0.15b	3.20 ± 0.25a	3.48 ± 0.18a	2.71 ± 0.16c
Control	3.78 ± 0.06a	3.78 ± 0.06a	3.78 ± 0.06a	3.78 ± 0.06a	3.78 ± 0.06a
			Canola		
Glyphosate	0.40 ± 0.02a	0.49 ± 0.03a	0.46 ± 0.07a	0.41 ± 0.03a	0.44 ± 0.04b
Sprayseed	0.31 ± 0.04ab	0.33 ± 0.04b	0.43 ± 0.06a	0.42 ± 0.04a	0.37 ± 0.04c
Swathing	0.24 ± 0.02b	0.35 ± 0.04b	0.38 ± 0.04a	0.36 ± 0.02a	0.33 ± 0.03c
Control	0.51 ± 0.03a	0.51 ± 0.03a	0.51 ± 0.03a	0.51 ± 0.03a	0.51 ± 0.03a

However, average grain yield losses of over 30% for wheat, barley, and canola following these earlier application timings are prohibitive. Similar levels of wild radish seed reduction and corresponding yield losses in wheat, barley, and lupins following earlier crop-topping timings have been reported previously (Cheam *et al.* 2004; Newman and Adam 2006). These studies indicated that barley was the most tolerant of crop-topping and swathing treatments of the crop species evaluated. However, even for this crop, to prevent more than 10% crop yield loss the application of crop-topping and swathing treatments needed to be delayed until wild radish growth stage 8.5. At this application timing a likely 50–70% reduction in viable wild radish seed numbers can be expected.

The indeterminant nature of wild radish ensures that there will be a significant environmental influence on the efficacy of physical and chemical treatments specifically targeting viable seed production of wild radish populations. Wild radish plants established in annual crops after post-emergence weed control practices have been completed, are frequently large and have a reproductive phase extending over 2–3 months of the growing season (Cheam and Code 1995; Madafiglio *et al.* 1999). With such an extended period for potential seed development, any treatments targeting seed production need to be effective over a long period. In these studies, glyphosate, a translocated herbicide (Grossbard and Atkinson 1985), produced more consistent treatment results than sprayseed, a contact type herbicide (Dodge 1989). However, averaged over all application timings these herbicide treatments produced similar levels of wild radish seed production. In the 2001 pot trial the growing conditions allowed sprayseed and swathing treated plants to regenerate and continue seed production, while in the 2001 field trial where resources were limited, sprayseed in particular was more effective. Therefore, an extended period of efficacy of seed-targeting treatments will be particularly important following early application timings (e.g. GS 6.5). This will be of particular importance in environments where sufficient availability of soil moisture and nutrient resources allows wild radish plants to recover from treatment effects.

Acknowledgments

The authors thank all WAHRI staff and students who were involved in the collection and processing of seed samples, particularly Mr Ryan Duane and Ms Gabrielle Lucchesi. We are grateful to the GRDC for providing the funding for this research.

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Manuscript received 28 August 2008, accepted 21 April 2009