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Herbicidal control of *Solanum elaeagnifolium* Cav. in Australia

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ABSTRACT

Solanum elaeagnifolium Cav. is considered as one of the worst weeds of crop and pasture systems in temperate Australia. Effective long-term control is difficult due to the extensive root system. Field experiments were conducted at two locations in south-eastern Australia between 2006 and 2008 to examine a range of herbicides for control of *S. elaeagnifolium* on seed production and root regrowth. Herbicide performance was affected by herbicide, weed growth stage and environmental factors. Pyridine herbicides, such as pre-packed mixtures of aminopyralid + fluroxypyr and triclopyr + picloram + aminopyralid were the most effective and consistently reduced within-season aerial growth by 60–90% in both seasons. Overall control using glyphosate-based treatments was generally reduced due to emergence of new stems following herbicide application. Three picloram-based treatments provided the best and most consistent long-term control on root regrowth after two seasons, reducing stem emergence by 45–88%, especially with a late application of herbicides. The efficacy of residual herbicides such as atrazine or imazapic + imazapyr depends on rainfall conditions. Seedset control was best achieved with herbicides applied at the start of flowering stage, with no viable seed produced following treatments of 2,4-D amine + picloram and triclopyr + picloram + aminopyralid. These two treatments also significantly reduced viable seed production when applied at the early berry stage. The results indicate that an application at early flowering followed by a late application in autumn is necessary to effectively control the seedset (seedbank) and the root regrowth (rootbank) of *S. elaeagnifolium*.

1. Introduction

Solanum elaeagnifolium Cav. is considered one of the most invasive weeds worldwide. It is highly problematic in Australia, Greece, Morocco, South Africa and the USA, and it has also spread into many Asian, European, Mediterranean and Middle East countries (Mekki, 2007; Brunel, 2011; FAO, 2011; Qasem, 2014; Travlos, 2013). *S. elaeagnifolium* is a deep-rooted, summer-growing perennial weed of the Solanaceae family thought to be native to south-western USA and northern Mexico (Eleftherohorinos et al., 1993). Once established, the extensive root system is difficult to control and the lateral roots are capable of producing new stems up to 2.0 m from the parent stem (Stanton et al., 2009). Root fragments as little as 1 cm can regenerate into new shoots (Stanton et al., 2011). *S. elaeagnifolium* also spreads by seeds. Fruit berries contain 38-89 seeds per berry and each stem produces 1814 to 2945 seeds, depending on the locations and seasons (Stanton et al., 2012).

S. elaeagnifolium arrived in Australia in the early 1900's as a contaminant of grain and fodder (Parsons and Cuthbertson, 2001). Isolated patches of the weed spread slowly (Stanton et al., 2009) until rapid expansion in the 1960's made *S. elaeagnifolium* an important weed. *S. elaeagnifolium* has been listed as one of the Weeds of National Significance in Australia (Australian Weeds Committee, 2012), infesting at least 350,000 ha in Australia, with the potential to infest 400 million ha (Feuerherdt, 2009).

S. elaeagnifolium infestations can cause important economic losses in cotton, grain sorghum, wheat and lucerne (Boyd and Murray, 1982; Lemerle and Leys, 1991). Grain yield losses of 12% were reported from Australia as a result of an infestation of 9 plants/m^2 (Leys and Cuthbertson, 1977). Yields from North American cotton crops were less affected by *S. elaeagnifolium* under irrigation, suggesting that competition for moisture is a significant

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factor (Green et al., 1988).

Potential toxicity and low palatability restrict the usefulness of grazing to control *S. elaeagnifolium*. *S. elaeagnifolium* contains glycoalkaoids which can be hydrolyzed in the gut to form nerve toxins such as alkalids or alkamines (Boyd et al., 1984). Cattle that consume 0.1–0.3% of their body weight in ripe berries display moderate poisoning symptoms, while sheep are more resistant to the toxins and goats are unaffected (Boyd et al., 1984). Mellado et al. (2008) reported that increasing percentages of *S. elaeagnifolium* in the diet led to decreased dry matter intake and body weight gain in goats when *S. elaeagnifolium* contributed more than 25% of the daily dry matter intake.

S. elaeagnifolium has an extensive root system. Cultivation is therefore not a useful tool for management as it can break the roots into fragments and foster the further spread of the weed. Under dry conditions, deep cultivation may reduce but not eradicate an infestation (Parsons and Cuthbertson, 1992). Repeated cultivation has resulted in 14-fold increased in stem numbers of *S. elaeagnifolium* over three years (Choudhary and Bordovsky, 2006). The reproductive capacity of *S. elaeagnifolium* root fragments and the potential for fragments to be relocated to new fields are the major problems with using cultivation (Stanton et al., 2011). Combining mechanical control with application of 2,4-D or picloram/2,4-D did not provide any synergistic benefits (McKenzie, 1980).

To date, no effective and economic herbicide treatments for *S. elaeagnifolium* control have been developed, mainly due to the presence of an extensive root system. Chemical control has generally aimed to reduce spread of large infestations, with eradication of smaller patches and colonies sometimes achieved (Cuthberston et al., 1976). Glyphosate has been reported as providing variable control (Chalghaf et al., 2007), while the use of ammonium sulphate can improve control (Baye, 2007). Baye et al. (2007) reported that herbicides such as imazapyr and bromacil may be a viable alternative for use in non-arable situations. Reliance on herbicide mixtures containing picloram can cause injury to establishing clover pastures the following year due to the residual nature of picloram, making this approach problematic on large infestations (Beeler et al., 2004).

Qasem (2014) found that many herbicides, such as 2,4-D, triclopyr and glyphosate, were effective in suppressing the growth and seed production of *S. elaeagnifolium*, however, no treatments effectively prevented the regrowth of the weed. Choudhary and Bordovsky (2006) reported that one application of glyphosate with early or late within a cotton growing season gave poor control of *S. elaeagnifolium*, however multiple applications of glyphosate effectively reduced stem numbers over three seasons. Wassermann et al. (1988) reported that when picloram was applied to *S. elaeagnifolium* at rates above 264 g ai ha^{-1}, more effective control was achieved in autumn than in summer. Translocation of the herbicide glyphosate within *S. elaeagnifolium* is much greater in spring and autumn compared to summer (Greenfield, 2003), suggesting that time of application is critical for successful herbicide control of the rootbank. The objectives of this study were to determine the efficacy of various herbicides and mixtures and their timing of application on the control of *S. elaeagnifolium*, targeting a) seedset within a season, and b) root regrowth between seasons over several growing seasons.

2. Materials and methods

Field experiments were conducted in 2006/2007 and 2007/2008 at two field sites in southern New South Wales on natural infestations of *S. elaeagnifolium* with uniform densities of 7–10 stems/m^2. One site was located near Leeton (S: 34° 25′ 0.61″, E: 146° 22′ 10.57″) on a clay soil in a field formerly used for cropping under flood irrigation, and the second site was located near Culcairn (S: 35° 35′ 36.51″, E: 147° 10′ 5.28″) on a hillside opportunistically sown to dryland crops or pastures. Monthly rainfall data for each site are summarised in Table 1, with the average annual rainfall of 587 mm for Culcairn and 432 mm for Leeton.

The experimental design was a randomised complete block design with three replicates per site using plots measuring 4 × 10 m. Due to the potential of lateral roots penetrating between plots, measures were not taken within 1 m of the plot boundaries.

Unless otherwise stated, herbicide treatments in both experiments were applied using a shielded 4-m boom fitted with Lechler IDK 120-015 low pressure air induction nozzles operated at 250 kPa to provide 100 L ha^{-1} spray volume. Uptake spray oil at 1% v/v was included as a standard adjuvant.

Herbicide active ingredients and application rates are indicated in Table 2. Early applications (E) of herbicides were applied when the majority of plants were at the start of flowering stage (defined as early flowering) in mid December 2006 and in late November 2007. A late application (L) of either glyphosate or 2,4-D amine was applied in early March 2007 and in late March 2008 to plots that had received the E application of glyphosate at 1080 g ai ha^{-1} to examine the effectiveness of an E application followed by (fb) a L application (E fb L). Treatments 2 and 19 were sprayed E only in 2006/2007 summer season, but received E fb L application of the nominated herbicides in 2007/2008 season. Glyphosate was applied as required during winter for control of annual winter weeds while the *S. elaeagnifolium* was senescent.

Seedset control was evaluated in the summer of 2007 at both field sites for six treatments (2,4-D amine, 2,4-D amine + picloram, fluroxypyr, glyphosate, triclopyr + picloram + aminopyralid and untreated control) by tagging three individual flowers and three green berries in each plot when the early herbicide treatments were applied. Mature berries for each growth stage were collected separately after six weeks and the number of seeds formed counted. For each growth stage, 50 seeds per plot were incubated at 25/15 °C with a 12 h photoperiod corresponding to the higher temperature for 21 days and numbers of seeds germinated recorded. Ungerminated seeds were tested for viability based on a modified method described by Stanton et al. (2012). Briefly, seeds were placed in a petri dish, cutting in half and treating with 5 ml of 0.5% triphenyltetrazolium chloride solution and incubating at 30 °C for 5 h in the dark. All seeds were tested for viability where less than 50 seeds were produced.

S. elaeagnifolium densities were recorded using a 1-m^2 quadrat placed on the centreline 3 m from each end of the plots. Markers were used to allow measurements to be taken from the same location each recording period between years. Stem density and growth stage were recorded prior to the E application of herbicides and the percent control was assessed six weeks after treatment to evaluate within season control. Percent control within season was calculated by dividing the number of dead stems by the total number of dead and live stems present approximately six weeks post E herbicide application. The long-term control between seasons was determined by comparing the stem density measured in November 2006 and in November 2008 using the following formula:

$$\text{Change } 06/08 = [(2008 \text{ count} - 2006 \text{ count})/2006 \text{ count}]*100\% \quad [1]$$

Homogeneity of variance was not improved by transformation, therefore analyses were performed on raw stem densities. Data variance was visually inspected by plotting residuals to confirm homogeneity of variance before statistical analysis. There were no

Table 1
Seasonal rainfall (millimetres) in 2006, 2007, 2008 and long term average for Leeton and Culcairn, NSW.

Month	Leeton				Culcairn			
	2006	2007	2008	30 yr average	2006	2007	2008	30 yr average
January	16	18	35	32	0	26	97	36
February	5	36	20	31	6	31	11	38
March	19	30	15	33	18	44	25	27
April	11	25	16	35	21	33	10	36
May	2	52	6	39	14	78	15	49
June	24	21	62	40	45	21	31	64
July	52	44	49	37	46	77	70	65
August	6	22	23	41	21	10	37	64
September	23	6	22	37	23	10	22	59
October	0	17	27	45	1	12	20	48
November	22	74	22	31	50	89	54	60
December	12	86	37	31	1	104	65	40
TOTAL	191	429	333	432	245	534	458	587
% of yearly average	44%	99%	77%	–	42%	91%	78%	–

Table 2
Percentage control of *S. elaeagnifolium* aerial growth within season after the early herbicide application at early flowering.[a]

	Treatment	Timing	Rate (g a.i./ha)	Within season control (%)	
				2006/07	2007/08
T1	2,4-D amine	E	937.5	39.8	41.8
T2	2,4-D + picloram[b]	E in 06/07, E fb L in 07/08	900 + 225	65.8	63.6
T3	2,4-D + picloram + metsulfuron methyl	E	900 + 225 + 9	90.2	90.3
T4	Aminopyralid + fluroxypyr	E	15 + 210	67.8	77.3
T5	Amitrole	E	500	43	0
T6	Atrazine	E	2000	54.7	8.7
T7	Atrazine + paraquat + diquat	E	2000 + 324 + 276	27.5	6.7
T8	Dicamba	E	2000	38.8	57
T9	Fluroxypyr	E	200	55.7	78.7
T10	Fluroxypyr + 2,4-D amine	E	200 + 937.5	60.7	64.7
T11	Glyphosate	E	1080	22.5	7.3
T12	Glyphosate fb glyphosate	E fb L	1080 fb 1080	46.7	14.5
T13	Glyphosate fb 2,4-D amine	E fb L	1080 fb 937.5	64.2	16.8
T14	Glyphosate + 2,4-D amine	E	1080 fb 937.5	54.8	61.8
T15	Glyphosate + imazapic + imazapyr	E	1080 + 21 + 7	28.8	4.8
T16	Glyphosate + metsulfuron methyl + oxyfluorfen	E	1080 + 9 + 19.2	59	6.7
T17	Glyphosate + metsulfuron methyl	E	1080 + 9	61.8	11.8
T18	Glyphosate + oxyfluorfen	E	1080 + 19.2	37.3	5.7
T19	Triclopyr + picloram + aminopyralid[b]	E in 06/07, E fb L in 07/08	900 + 300 + 24	76.3	83.2
T20	Untreated control	–	–	0	0
	LSD (0.05)			*22.9*	*19.8*

[a] Combined data from the Leeton and Culcairn site due to no significant site interactions. Stem numbers were assessed six weeks after the early herbicide application but before the late herbicide application.
[b] E application only in 2006/2007 season, E fb L in 2007/2008 season.

significant interactions between herbicides and experimental sites for with-season control of stem density and for seedset control, therefore data from the two field sites were combined for analyses. However, the long-term control over two seasons differed significantly between Leeton and Culcairn sites. These data were separately analysed and presented. Data were analysed using analysis of variance and Fisher's Protected LSD at 5% level of significance used to separate treatment means.

3. Results and discussion

3.1. Short-term control of aerial growth within a season

No significant differences occurred between sites, therefore combined data are presented (Table 2). The E application of the mixture of 2,4-D at 900 g ai ha^{-1} + picloram at 225 g ai ha^{-1} + metsulfuron methyl at 9 g ai ha^{-1} (T3) gave the best level of control (90%) of aerial growth within season in both 2006/2007 and 2007/2008. The other four pyridine-based herbicides also provided consistent within season aerial control (60–83%) in both seasons (Table 2). These treatments include the E application of a mixture 2,4-D at 900 g ai ha^{-1} + picloram at 225 g ai ha^{-1} (T2), a prepacked mixture of aminopyralid at 15 g ai ha^{-1} + fluroxypyr at 210 g ai ha^{-1} (T4), a mixture of fluroxypyr at 200 g ai ha^{-1} + 2,4-D amine at 937.5 g ai ha^{-1} (T10) and a prepacked mixture triclopyr at 900 g ai ha^{-1} + picloram at 300 g ai ha^{-1} + aminopyralid at 24 g ai ha^{-1} (T19). Glyphosate alone applied at E or E fb L did not provide acceptable control (7–47%), while some glyphosate mixtures with other herbicides improved control slightly. The E application of glyphosate + 2,4-D amine (T14) provided the best control (55–62%) among the glyphosate-based treatments.

No new stems emerged within season in the untreated control plots between the two observation periods, however up to 2.3 stems/m^2 emerged in plots treated with glyphosate. It appears that new stem emergence was stimulated as a result of the herbicidal removal of aerial parts. The efficacy of glyphosate on emerged stems would therefore have been slightly higher than the overall level of control reported. The least number of new stems was observed in plots treated with picloram or atrazine, where the residual action of the herbicides would have impacted on successful

emergence on new stems.

3.2. Long-term control on root regrowth between two growing seasons

There were significant differences between the two field sites, therefore these data are presented separately. *S. elaeagnifolium* emergence in the untreated control plots at the Leeton field site in 2007 was lower (6 stems/m^2) than in 2006 and 2008, even though stem densities were recorded from the same quadrats at a similar time each season. This could be a result of the limited rainfall (6 mm) received in September 2007 prior to the onset of stem emergence, which was only 16% of the long-term average (Table 1). The *S. elaeagnifolium* stem density in the untreated control plots at Culcairn site in 2008 was lower than in 2007, which is possibly due to the competition of greater levels of annual winter weed biomass residue.

Consistent long-term control of *S. elaeagnifolium* emergence after two seasons of herbicide application was achieved when picloram had been applied. The three picloram based treatments, 2,4-D + picloram (T2), 2,4-D + picloram + metsulfuron methyl (T3) and triclopyr + picloram + aminopyralid (T19), caused stem reduction ranging from 68% to 88% at the Culcairn site and from 45% to 58% at the Leeton site between 2006 and 2008, respectively (Table 3). Other treatments had variable results between the two sites, in particular for those treatments containing residual herbicides. For example, The E application of atrazine at 2000 g ai ha^{-1} reduced stem emergence by 82% at Culcairn site, while a 130% increase in stem numbers was found at Leeton site. Similarly, E applications of atrazine + a prepacked mixture of paraquat and diquat (T7), glyphosate + a prepacked mixture of imazapic and imazapyr (T15), glyphosate + metsulfuron methyl (T16), and glyphosate + metsulfuron methyl + oxyfluorfen (T17) increased weed stem density by 16–59% at Leeton site between 2006 and 2008, while these treatments reduced weed stem density by 24–50% at Culcairn site during the same period. Higher rainfall at Culcairn site might have contributed to the better residual activities due to improved incorporation of herbicides. The annual rainfall at Culcairn site in 2006, 2007 and 2008 was 28.3%, 24.5% and 37.5% higher than Leeton site, respectively (see Table 4).

Three glyphosate based treatments (T11–T13), such as E application of glyphosate, E glyphosate fb L glyphosate, E glyphosate fb L 2,4-D amine, also had suppressive effects on stem emergence, with the change of stem density ranging from −18% to −84%. However, two other glyphosate based treatments (T14 and T18), E applications of glyphosate + 2,4-D amine or oxyfluorfen had inconsistent results between the two field sites. Greenfield (2003) indicated that an antagonistic effect occurred between glyphosate and 2,4-D amine, reducing the translocation of glyphosate into the roots of *S. elaeagnifolium*.

3.3. Seedset control

Seed production was influenced more by stage of maturity at spraying ($P < 0.01$) than by herbicide ($P < 0.05$), although both factors were important (Table 4). Herbicides applied at the early flowering stage were more effective on seedset control than at the early berry stage. On average across the five herbicide treatments, herbicides applied at the early flowering stage produced 5.6 seeds per berry, with a seed viability of 7.5%, while herbicides applied at the early berry stage had 58.1 seeds per berry, with a seed viability of 55.4%.

Compared to the untreated control, seed production was significantly reduced when any herbicide was applied at the early flowering stage, with only 3% of the treated flowers producing berries and 0–2.5 viable seeds per berry being produced. Complete seedset control was achieved with the treatments of 2,4-D amine + picloram, and triclopyr + picloram + aminopyralid when applied at the early flowering stage. However, herbicides applied at the early berry stage resulted in more than 75% of the treated berries producing seeds. The two herbicide treatments containing picloram again provided the best sterilising effects on seed viability, with each berry producing as few as 12 and 22 seeds, while the untreated control produced an average of 84 seeds per berry. Seed production was least affected within the 2,4-D amine, fluroxypyr and glyphosate treatments, with all berries producing high number of viable seeds (42–48 seeds per berry).

Under laboratory conditions, a mixture of glyphosate and 2,4-D amine reduced the translocation of glyphosate within *S. elaeagnifolium* plants, suggesting that such a mixture was not conducive to root control (Greenfield, 2003). The results reported here show that under field conditions the use of 2,4-D amine as a mixing partner with either glyphosate or fluroxypyr generally reduced long term root control when compared to the glyphosate or fluroxypyr alone treatments, with the exception of glyphosate + 2,4-D amine at Leeton site. However, within season control of aerial growth was generally better when 2,4-D amine was used as a mix partner, presumably due to the herbicide not being translocated away from the leaves.

Picloram based products were the most effective treatments on *S. elaeagnifolium*, providing high and consistent aerial control within season as well as regrowth control (stem numbers) between seasons. Such effective long-term impacts of picloram treatments on the roots have also been reported previously (McKenzie, 1980; Molnar, 1982; Wassermann et al., 1988). Gorrell et al. (1988) determined that picloram was more effective than dicamba or triclopyr for the control of *Solanum carolinense* L. Similar amounts of all three herbicides were translocated to untreated shoots and roots, and it was concluded that the difference in control was attributable to the comparative potency of the active ingredients. Similarly, in this work dicamba was less effective than picloram for long term control of *S. elaeagnifolium*, however as triclopyr was only applied in a commercial formulation that also contained picloram, it is not possible to comment on the efficacy of triclopyr alone for *S. elaeagnifolium* control.

The cost of picloram based products, and the land use limitations imposed by the residual nature of picloram, detract from the suitability of this treatment over wide areas. However, the effectiveness of the treatment would suggest this is a suitable management tactic for isolated plants or populations, particularly if they are on areas such as roadways or fencelines where the residual nature of the product will have limited impact on the use of the land.

This study also shows that some glyphosate based treatments E application of glyphosate, E glyphosate fb L application of glyphosate, E glyphosate fb L 2,4-D amine for two consecutive seasons reduced the stem emergence by 22–38% at Leeton site and by 71–88% at Culcairn site. The results indicate that although these treatments were not as effective as the picloram based products on root regrowth control, they could be suitable economic options for large and heavy infestations of *S. elaeagnifolium* to gradually decrease weed populations overtime.

Our previous study has showed that *S. elaeagnifolium* in Australia started to develop fruit berries in December and peaked in March, suggesting that an early management action is required before December to control seed set (Zhu et al., 2013). The present study here further confirms that it is critical to apply suitable herbicides at the early flowering stage to achieve 100% seedset control. However, herbicide applications such as glyphosate at the early flowering stage often stimulate new stem emergence (regrowth) in

Table 3
Long-term effect of herbicide treatments on *S. elaeagnifolium* stem emergence at Leeton and Culcairn field sites.[a]

Treatment		Stem emergence (stems/m^2 ± s.e.)[b]			Change in stem density (%)[c]
		2006	2007	2008	06–08
Leeton					
T1	2,4-D amine	11.8 ± 1.7	8.2 ± 1.5	13.5 ± 2.9	14
T2	2,4-D + picloram	9.5 ± 3.8	1.3 ± 1.3	4.8 ± 1.4	−49
T3	2,4-D + picloram + metsulfuron methyl	14.2 ± 2.9	4.2 ± 0.3	7.8 ± 1.2	−45
T4	Aminopyralid + fluroxypyr	4.2 ± 1.3	1.3 ± 0.6	4.5 ± 1.3	7
T5	Amitrole	9.3 ± 1.3	4.7 ± 2.7	11.2 ± 1.9	20
T6	Atrazine	3.7 ± 0.4	1.7 ± 0.9	8.5 ± 1.4	130
T7	Atrazine + paraquat + diquat	7.5 ± 0.9	5.5 ± 1.4	10.7 ± 4.2	43
T8	Dicamba	11.2 ± 3.7	4.2 ± 1.2	7.8 ± 0.7	−30
T9	Fluroxypyr	9.2 ± 0.7	4.3 ± 1.3	7.5 ± 0.6	−18
T10	Fluroxypyr + 2,4-D amine	7.7 ± 3.3	5 ± 1.5	7.3 ± 3.2	−5
T11	Glyphosate	12 ± 2.4	5.2 ± 1.3	7.5 ± 1.5	−38
T12	Glyphosate fb glyphosate	11.8 ± 3.7	1.8 ± 0.8	9.2 ± 3.2	−22
T13	Glyphosate fb 2,4-D amine	16.3 ± 3.1	4.5 ± 1.3	12 ± 1.9	−26
T14	Glyphosate + 2,4-D amine	12.2 ± 1.2	6.2 ± 1.6	5 ± 2	−59
T15	Glyphosate + imazapic + imazapyr	9.8 ± 2.2	3.7 ± 1.7	13 ± 1	33
T16	Glyphosate + metsulfuron methyl	7.3 ± 5.6	2.8 ± 1.7	8.5 ± 4.3	16
T17	Glyphosate + metsulfuron methyl + oxyfluorfen	8.8 ± 4.5	2 ± 1.2	14 ± 1.5	59
T18	Glyphosate + oxyfluorfen	7.2 ± 2.2	1.5 ± 0.3	8.8 ± 1.5	22
T19	Triclopyr + picloram + aminopyralid	9 ± 1.8	2.8 ± 1.5	3.8 ± 1.5	−58
T20	Untreated control	12.8 ± 3.5	5.8 ± 1.3	15.3 ± 1.7	20
	LDS0.05	n.s.	n.s.	5.9	
Culcairn					
T1	2,4-D amine	6.5 ± 2.1	4.5 ± 0.8	5.3 ± 1.8	−18
T2	2,4-D + picloram	6.7 ± 2.5	11.7 ± 5.4	0.8 ± 0.4	−88
T3	2,4-D + picloram + metsulfuron methyl	3.7 ± 1.5	3.3 ± 2.1	1.2 ± 0.4	−68
T4	Aminopyralid + fluroxypyr	8.8 ± 3.8	12.3 ± 4.5	2.7 ± 0.7	−69
T5	Amitrole	9 ± 1	10.5 ± 5.7	8 ± 2.9	−11
T6	Atrazine	4.5 ± 1.7	5.3 ± 1.7	0.8 ± 0.3	−82
T7	Atrazine + paraquat + diquat	8.2 ± 1.2	14 ± 2.5	6.2 ± 3.7	−24
T8	Dicamba	4.3 ± 2.2	5.5 ± 1.9	3.8 ± 2.4	−12
T9	Fluroxypyr	4.3 ± 1.8	4.3 ± 1.9	1.7 ± 0.7	−60
T10	Fluroxypyr + 2,4-D amine	4 ± 1.7	4.5 ± 0.3	2.5 ± 0.5	−38
T11	Glyphosate	14.3 ± 9.9	17 ± 10.8	2 ± 0.6	−86
T12	Glyphosate fb glyphosate	10.2 ± 5.7	4.5 ± 0.8	3 ± 0.3	−71
T13	Glyphosate fb 2,4-D amine	15.2 ± 12.9	10.2 ± 6.7	2.5 ± 1.2	−84
T14	Glyphosate + 2,4-D amine	6.5 ± 1.7	8.5 ± 3.9	7.3 ± 3.1	12
T15	Glyphosate + imazapic + imazapyr	5 ± 1.5	8.8 ± 3.2	2.5 ± 0.3	−50
T16	Glyphosate + metsulfuron methyl	5 ± 2	7.2 ± 3.2	4 ± 1.6	−20
T17	Glyphosate + metsulfuron methyl + oxyfluorfen	7 ± 3.3	6 ± 1.2	3.7 ± 1.6	−47
T18	Glyphosate + oxyfluorfen	10 ± 6.4	10.2 ± 3.9	4.7 ± 1.6	−53
T19	Triclopyr + picloram + aminopyralid	6.3 ± 2.7	5.7 ± 1.2	1.3 ± 0.2	−79
T20	Untreated control	8.3 ± 2.1	10.3 ± 2.4	6 ± 3.3	−28
	LDS (0.05)	n.s.	n.s.	n.s.	

[a] Early applications (E) of herbicides were applied in mid December 2006 and in late November 2007 and a follow-up late application (L) in T12, T13 was applied in early March 2007 and in late March 2008. A late application of two picloram treatments (T2 and T19) was also imposed in late March 2008.
[b] Mean ± s.e.
[c] Negative numbers indicate a decrease in population density over the two growing seasons.

Table 4
Effect of herbicide and growth stage at spraying on *S. elaeagnifolium* seed production and viability.

Treatment	Seeds per berry	Seed viability (%)	No. viable seeds per berry
Flowering stage			
2,4-D amine	9.3^{a}	5.0^{a}	0.5^{a}
2,4-D amine + picloram	0.0^{a}	0.0^{a}	0.0^{a}
Fluroxypyr	2.3^{a}	16.7^{a}	0.4^{a}
Glyphosate	16.3^{a}	15.7^{a}	2.6^{a}
Triclopyr + picloram + aminopyralid	0.0^{a}	0.0^{a}	0.0^{a}
Untreated control	56.0^{b}	77.3^{b}	44.3^{b}
Early berry stage			
2,4-D amine	54.7^{a,b}	75.6^{a,b}	41.7^{a}
2,4-D amine + picloram	64.5^{a,b}	33.7^{c}	21.7^{b}
Fluroxypyr	73.5^{a}	65.7^{a,b,c}	48.3^{a}
Glyphosate	63.8^{a,b}	66.0^{a,b,c}	42.1^{a}
Triclopyr + picloram + aminopyralid	34.0^{b}	36.0^{b,c}	12.2^{b}
Untreated control	84.7^{a}	99.0^{a}	83.4^{c}

For each weed growth stage, different letters within the same column indicate significant difference at $p < 0.05$.

the same season. This regrowth characteristics within the season has also been reported by McKenzie (1980), highlighting the need for a follow-up late herbicide application to control the regrowth in autumn. Choudhary and Bordovsky (2006) documented that multiple applications of glyphosate within a cotton growing season caused greater reduction in stem numbers of *S. elaeagnifolium* between seasons as compared to one application of glyphosate.

These studies show that herbicide management of *S. elaeagnifolium* needs to be revised to enable effective seedbank and rootbank control to be achieved. Current herbicide recommendations (Kidston et al., 2007; Ensbey, 2009) suggest herbicide application at flowering or early berry set. While this time of application can provide good control of aerial growth and seed set within the season, it is not the optimum time of application to control the rootbank. Greenfield (2003) reported that a greater herbicide translocation was achieved in spring and autumn compared to summer, which coincides with the findings that picloram application was more effective on *S. elaeagnifolium* control in autumn than in summer (Wassermann et al., 1988). It is therefore important to combine a late herbicide application in autumn, particularly with picloram based products, to achieve better herbicide translocation into the root system and to effectively target the rootbank to achieve long term control of *S. elaeagnifolium* infestations.

S. elaeagnifolium propagates by seeds, root segments, and creeping lateral roots (Cuthberston et al., 1976), suggesting that effective management of *S. elaeagnifolium* needs to target the seedset (seedbank) as well as the root system (rootbank). A *S. elaeagnifolium* management guide is currently available, highlighting a "Dual Action" approach for effective management of *S. elaeagnifolium* (Anonymous, 2010). The "Dual Action" approach consists of an early action at the early flowering stage to achieve effective seedset control, followed by a late action in autumn (before plant senescence) to target rootbank as well as the regrowth after the early action. For large and dense infestations of *S. elaeagnifolium*, glyphosate alone or in combination with a suitable mixing partner could initially be the viable options as the early and late applications to gradually run down the populations of *S. elaeagnifolium*. Once the infestation is reduced to isolated plants or patches, picloram based products could then be jointly used as the late application to rapidly damage the root system due to its residual potency and improved translocation in autumn. The use of appropriate residual herbicides could also been considered for rootbank control if there is sufficient rainfall after application to activate the residual activities.

In conclusion, the effective management of *S. elaeagnifolium* with herbicides requires a combination of both short-term control of seed production and the reduction in seedbank, as well a longer-term plan to reduce root growth and the spread of the rootbank. The adoption of no-till cropping will facilitate the containment of *S. elaeagnifolium* infestations by reducing cultivation as a means of weed spread. Environmental conditions strongly influence herbicide performance, and while costly in the short-term, herbicides are essential for long-term reductions in weed infestations, spread and impact. Two leaf-feeding chrysomelid beetles, *Leptinotarsa texana* and *Leptinotarsa defecta* have been successfully released for *S. elaeagnifolium* control in South Africa in 1990's, and the L. texana was identified as the preferred biological control agent (Hoffmann et al., 1998). The L. texana is currently being evaluated as the potential biological control agent of *S. elaeagnifolium* in Australia. Further research is also required to examine its integration with effective herbicides. In addition, to ensure adoption of sustainable management of *S. elaeagnifolium*, it is essential to work with farmers in the early evaluation of new control technologies to ensure they are cost-effective and fit within farming systems.

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