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Diego J. Bentivegna [a] & Reid J. Smeda [a]

[a] Division Plant Sciences, University of Missouri, Columbia, MO, 65211, USA

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Integrated management of cutleaf teasel (*Dipsacus laciniatus*) along roadsides in Missouri, USA

Diego J. Bentivegna* and Reid J. Smeda

Division Plant Sciences, University of Missouri, Columbia, MO 65211, USA

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Cutleaf teasel is a biennial, invasive weed found along roadsides throughout much of the central USA. Long-term management should, ideally, integrate chemical and cultural practices. Research in Missouri along Interstate Highway 70 was initiated to combine chemical applications with overseeding perennial grasses. A field experiment was carried out with a split-plot design (four replications), where the main plot factor was herbicide applied, and the sub-plot factor was grass species overseeded. Herbicide treatments comprised dicamba + diflufenzopyr, aminopyralid, triclopyr, and metsulfuron. Grass species included tall fescue + buffalograss or Canada wildrye + buffalograss. Cutleaf teasel coverage was reduced from 79% to 93% for all herbicide treatments except triclopyr, 5 months after the last herbicide application. Seedling counts of cutleaf teasel were lowest for aminopyralid by 6 months after the last herbicide application. The herbicide programme that provided > 90% cutleaf teasel control and resulted in at least 65% grass establishment resulted in up to a 93% reduction in cutleaf teasel emergence by 363 days after initial herbicide application. Integration of applications of herbicides and desirable seeding grasses are needed over a long period to exclude cutleaf teasel in roadside areas.

Keywords: Cutleaf teasel; *Dipsacus laciniatus*; grass seeding; herbicide; IPM; invasive weed; roadside

1. Introduction

Cutleaf teasel (*Dipsacus laciniatus*) is an aggressive weed (Solecki 1993) occurring along roadsides and highway corridors in the USA, and is found from New York state to Oregon state. Introduced into East Coast states around 1840, teasel was initially grown as a crop for aligning wool fibre in the textile industry (Terres and Ratcliffe 1979), but was later discarded. According to Solecki (1993), geographical spread was facilitated by the interstate highway system.

Teasel is a biennial plant that grows during the first year as a rosette and bolts during reproduction the second year, reaching a height of 2 m (Werner 1975b). Both its emergence and its growth characteristics allow teasel to continuously dominate areas where the species has become established. Each plant produces more than 33,000 seeds, and seedlings emerge in both the fall and spring (Bentivegna and Smeda 2011); seed persists up to five years (Robert 1986). Rosettes form a dense concentration of leaves (leaf area index > 3) (Bentivegna 2006), allowing plants to crowd out adjacent species (Werner 1975a). Natural seed dispersal occurs in areas near the parent plant, resulting in discrete patches of teasel (Werner 1975a).

Management of cutleaf teasel involves strategies aimed at reducing rosette densities and preventing seed production. Predominant control practices involve mowing or herbicide application (Glass 1991). Because teasel has a deep taproot, multiple mowings of rosettes are necessary to prevent seed production. The time of mowing is critical for reducing seed production. If plants are mown only once in early summer, regrowth occurs and the plants produce viable seed (Cheesman 1998; Solecki 1993). Cutleaf teasel flowers in July in Missouri; plants mown once in late summer (August) are capable of producing viable seeds by the time mowing occurs (Bentivegna and Smeda 2011). Mowing mature plants contributes significantly to the spread of infestations.

A number of post-emergence herbicides can eliminate rosette and seedling plants (Bentivegna and Smeda 2008). Although herbicides initially eliminate cutleaf teasel from treated areas, the lack of competitive species to fill niches left by teasel permits the establishment of new seedlings (Werner 1977). Establishment of desirable plants following weed removal can minimize weed reinfestations (Jacobs et al. 1999; O'Donnell and Adkins 2005). Teasel seedlings are sensitive to competition for light, and establishment of perennial grasses can reduce teasel emergence (Werner 1975c, 1977). Both cool-season grasses such as tall fescue (*Festuca arundinacea* Schreb.) and Canada wildrye (*Elymus canadensis L.*) as well as warm season grasses such as buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.) may present an effective barrier against teasel germination and establishment.

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*Corresponding author. Email: dbentive@criba.edu.ar
Current address: CERZOS CCT- Bahía Blanca, Camino de la Carrindanga Km 7, Bahía Blanca, 8000 Argentina.

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According to Jacobs et al. (1999) the continuous use of resources by desirable plants can reduce infestation by undesirable species.

Cutleaf teasel was declared a noxious weed in Missouri in 2000. The Missouri Department of Transportation (MoDOT) reported that a significant area along roadsides was infested with cutleaf teasel (Mr Rand Swanigan, Head of Roadside Management and Maintenance for MoDOT). Currently, MoDOT employs a combination of mowing and herbicide application to manage populations, but infested areas continue to expand. An integrated management strategy for cutleaf teasel along rights-of-way may be more effective. To date, there have been no published reports assessing long-term removal of cutleaf teasel and replacement with a mixture of desirable species. The aim of this research was to identify an effective management programme for to the removal of cutleaf teasel from established areas along a highway environment in Missouri.

2. Material and methods

2.1. *Control of cutleaf teasel rosettes*

Research plots were established along selected areas of Interstate Highway 70 near Boonville, Missouri (38°56′07″N, 92°58′48″W); each plot was 200 m^2 and consisted of greater than 50% cutleaf teasel by area. Plots were mown mechanically with a string trimmer in fall (18 October, 2006) to 10 cm in height. Five different herbicide programmes were initiated (Table 1) in 20 plots (four replications); applications were made on 3 November, 2006 and 31 May, 2007. Treatments were applied with a CO_2-pressurized backpack sprayer equipped with XR 8001 VS Teejet nozzles (TeeJet XR Spraying Systems CO., North Ave, Wheaton, IL 60188), calibrated to deliver a spray solution of 140 L ha^{-1}, with an application velocity of 2.4 km h^{-1}. Weather conditions at each application time included air temperatures between 12°C and 23°C, with relative humidity ranging between 35% and 70%. Visual evaluation of herbicide effectiveness was recorded at various times; 18 to 636 days after initial application (DAIA). A scale of 0 to 100 was used for evaluations, where 0 indicated no visible effect and 100 indicated plant death. The rating days were: 21 November 2006; 20 March, 31 May, 14 June, 3 July, and 1 November 2007; 5 August 2008. Data from the different herbicide programmes were analysed within each rating date.

2.2. *Grass establishment*

Tall fescue (*Festuca arundinacea* Schreb.), Canada wildrye (*Elymus Canadensis* L.) and buffalograss (*Buchloe dactyloides* Nutt.) were seeded into plots using a rotary spreader to preclude teasel re-establishment. Tall fescue and Canada wildrye are cool-season grasses with optimal growth in spring and fall under Missouri conditions. In contrast, buffalograss is a warm-season species with optimal growth in summer under Missouri conditions. These grasses are sown by the MoDOT. Following the herbicide programme (Table 1), tall fescue and Canada wildrye were spread randomly over half of each plot on 8 November, 2006 and 10 May, 2007, with buffalograss spread over each entire plot on 10 May, 2007. Seeding rates were: 9.8 g m^{-2} for tall fescue, 4.4 g m^{-2} for Canada wildrye, and 3 g m^{-2} for buffalograss. Packed seed germination rates were 85, 80 and 80% for tall fescue, Canada wildrye and buffalograss, respectively. Total grass cover in each half of the plot was evaluated visually using a scale of 0–100%. The design of this experiment was split-plot, with herbicide treatment considered the variable for the whole plot, and grass establishment was considered the sub-plot variable.

2.3. *Seedling cutleaf teasel re-infestation*

In November 2007, 1 year after management of Cutleaf Teasel had been initiated, emerged seedlings of Cutleaf Teasel were counted randomly in eight, 1-m^2 areas within each plot. In August 2008, teasel density was

Table 1. Herbicide programmes and application timings for cutleaf teasel control along Interstate Highway 70 from mile markers 89 to 93 in Cooper County, Missouri.

Herbicide programme	Active ingredient (a.i.)	Time	Rate (kg a.i./ha)	Adjuvant (% v/v)
1	Aminopyralid	Fall 2006	0.18	NIS 0.5%
	Aminopyralid	Spring 2007	0.18	NIS 0.5%
2	Dicamba + diflufenzopyr	Fall 2006	0.23 + 0.09	NIS 0.25% + UAN 1.25%
	Dicamba + diflufenzopyr	Spring 2007	0.23 + 0.09	NIS 0.25% + UAN 1.25%
3	Metsulfuron	Fall 2006	0.02 0.02	NIS 0.5%
	Metsulfuron	Spring 2007		NIS 0.5%
4	Metsulfuron	Fall 2006	0.0175	NIS 0.5%
	Dicamba + diflufenzopyr	Spring 2007	0.23 + 0.09	NIS 0.25% + UAN 1.25%
5	Triclopyr	Fall 2006	3.36	NIS 0.5%
	Triclopyr	Spring 2007	3.36	NIS 0.5%

NIS, non-ionic surfactant; UAN, urea–ammonium nitrate.

recorded for six, 1-m^2 areas. Plants that ranged from cotyledon to six true leaves were considered to be seedlings. In addition to visual assessment of herbicide effectiveness, digital pictures (7.2 megapixels) were taken at a height of 1.5 m above 1 m^2, 1 year after the first herbicide treatment. Six pictures were taken of each half of the plot to assess the extent of grass versus teasel establishment. Using each photo, a remote-sensing software program (Environment for Visualizing Images – ENVI 4.3, ENVI ITT Industries, Inc., USA.) was utilized to identify four classes of interest: teasel, grass, bare soil, and other broadleaf species. The number of pixels for each class was recorded and the percentage of cover was determined for each individual picture. All data were subjected to analysis of variance (ANOVA) using PROC GLM of SAS (2003).

The residuals were plotted to test homogeneity of variance, and the UNIVARATE procedure of SAS was used to assess normality.

Grass establishment and cutleaf teasel seedling counts were analysed as a split-plot design (four replications). The main plot factor included the particular herbicide programme to reduce teasel incidence the sub-plot factor was the particular combination of overseeded grass species. Cutleaf teasel emergence data were transformed logarithmically prior to analysis to meet ANOVA assumptions. Means of significant main effects were separated using Fisher's Protected LSD (SAS 2003).

3. Results

3.1. *Control of cutleaf teasel rosettes*

Eighteen days after applications in the fall (i.e. autumn) of 2006, cutleaf teasel control ranged from 30% (triclopyr) to 45% (dicamba) (Table 2). Control increased from 69% (triclopyr) to 98% (aminopyralid) by March 2007 (137 DAIA), with no appreciable change through May 31 (209 DAIA). By July 2007 (242 DAIA), which was 33 d after the second application date, four of the five herbicide programmes resulted in 99% control. However, two applications of triclopyr resulted in only 31% control (Table 2). By 1 November, 2007 (363 DAIA), visible control of teasel ranged from 79% to 94% for all treatments except triclopyr, which remained poor at 25%. At the last evaluation date in August 2008 (640 DAIA), cutleaf teasel control ranged from 56% to 73% for four of the five treatments (Table 2). Control with triclopyr was almost negligible (8.1%). Repeated applications of aminopyralid, dicamba + diflufenzopyr, and metsulfuron resulted in the most effective herbicide programmes over the duration of the research. However, emergence of new cutleaf teasel seedlings indicates additional applications would be necessary to maintain high levels of control.

Approximately one year after initial herbicide applications and 5 months after the last herbicide application (November 2007), digital pictures revealed that grasses were the dominant soil coverage class in each herbicide programme (Figure 1).

Aminopyralid, dicamba + diplufenzopyr, and metsulfuron were the most effective herbicide programmes for cutleaf teasel control ($P < 0.05$); however, plots treated with aminopyralid resulted in highest grass establishment ($P < 0.05$) (Figure 1). Triclopyr application not only resulted in the lowest level of cutleaf teasel control, but also resulted in the lowest incidence of grasses establishment (Figure 1). Plots treated with metsulfuron or dicamba contained from 67% to 80% grass, with 5–25% of the remaining area covered by other species: Common milkweed (*Asclepias syriaca* L.), common ragweed (*Ambrosia artemisiifolia* L.), horsenettle (*Solanum carolinense* L.), and Chinese bush clover (*Lespedeza cuneata* (Dum. Cours.) G. Don. Unfortunately, use of metsulfuron or dicamba resulted in 5–12% of plot areas being devoid of vegetation (bare ground), which potentially allowed re-infestation by teasel (Figure 1).

Table 2. Effect of fall (i.e. autumn) and spring applied herbicides on visual control of cutleaf teasel along Interstate Highway 70 in Cooper County, Missouri.[a,b]

Evaluation Date (DAIA)[d]	Herbicide programme[c]				
	1	2	3	4	5
18	40 ± 4 A	45 ± 8 A	43 ± 29 A	36 ± 17 A	30 ± 9 A
137	98 ± 5 A	93 ± 7 A	92 ± 12 A	86 ± 13 AB	69 ± 23 B
209	99 ± 3 A	95 ± 3 A	93 ± 4 A	97 ± 4 A	64 ± 16 B
223	100 ± 0 A	99 ± 3 A	99 ± 3 A	96 ± 4 A	58 ± 13 B
242	100 ± 0 A	100 ± 1 A	100 ± 0 A	100 ± 1 A	31 ± 13 B
363	93 ± 9 A	79 ± 27 A	80 ± 35 A	88 ± 14 A	25 ± 27 B
636	73 ± 12 A	56 ± 32 A	63 ± 25 A	60 ± 41 A	8 ± 10 B

[a] Control estimated as 0 = no effect and 100 = plant death. The standard deviation for cutleaf control follows the estimated mean.

[b] Means followed by the same letter within of each rating date are not significantly different according to Fisher Protected LSD at $P \leq 0.05$.

[c] Herbicide applications made on 3 November 3, 2006 and 31 May, 2007.

[d] DAIA, days after initial application.

3.2. *Grass establishment*

Grass establishment was monitored in July 2007, November 2007 and August 2008, which corresponded to 242, 363 and 636 DAIA, respectively (Table 3). At all three evaluation dates, there were some numerical differences in grass establishment, but neither herbicide treatment, grass mixture, nor the interaction of these factors was significant (see Table 5). Coverage by Canada wildrye + buffalograss ranged from 65% to 84.8% for the five herbicide programmes in July 2007 and ranged from 47.5% to 71.3% by November 2007 (Table 3). Tall Fescue + buffalograss coverage ranged from 66.3% to 84.8% for the five herbicide programmes in July 2007 (Table 3). Grass coverage in all treatments was 45–73.8% by November 2007, with tall fescue + buffalograss establishment highest for aminopyralid. By August 2008, chemical programmes employing metsulfuron or dicamba resulted in 61.3–65% grass coverage. However, coverage with Canada wildrye + buffalograss was only 31.3% and 48.8% for triclopyr and aminopyralid, respectively. In August 2008, tall fescue + buffalograss coverage was 57.5–68% for all chemical programmes except triclopyr (32.5%).

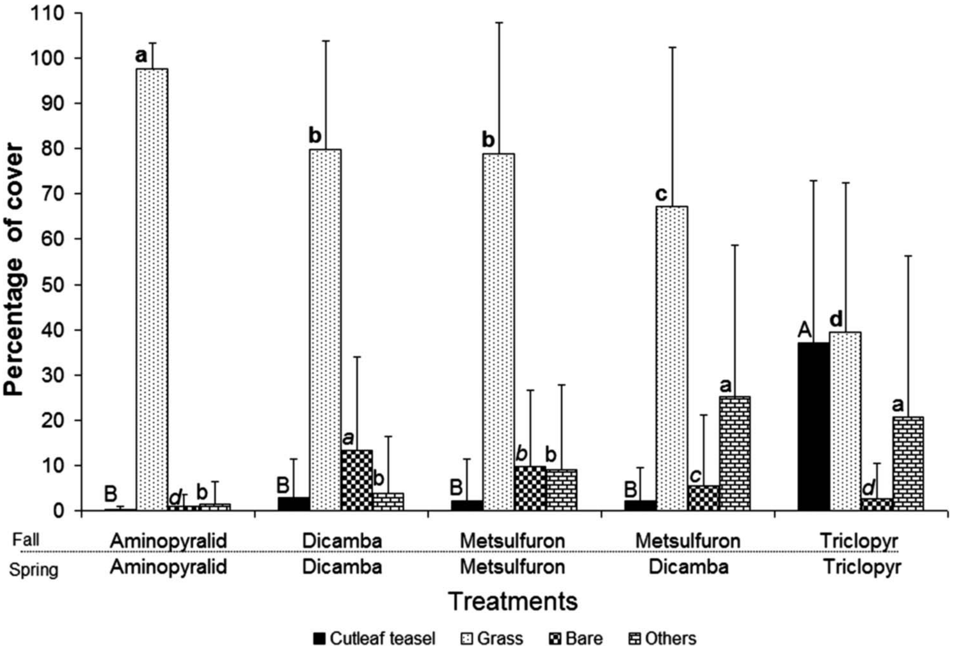

Figure 1. Impact of repeated herbicide applications on cutleaf teasel control and grass establishment along Interstate Highway 70 in Cooper County, MO. Note: Mean distribution of soil coverage for each herbicide programme, 363 d after initial herbicide application. The four classifications of soil coverage include: grass (average of Canada Wildrye and Tall fescue), cutleaf teasel, bare soil and other species. Coverage was determined by processing digital pictures using ENVI. Means within each classification of soil coverage were evaluated across herbicide programs using Fisher's Protected LSD at $p < 0.05$. Vertical lines above each bar indicate standard deviation.

Table 3. Mean grass coverage for the integrated herbicide programme and grass establishment.

Herbicide programme			Grass coverage (%)[b]		
Fall 2006	Spring 2007	Grass type[a]	July 2007	November 2007	August 2008
Aminopyralid	Aminopyralid	CW + B	80 ± 26 a[c]	71 ± 23 a	49 ± 40 a
Dicamba	Dicamba	CW + B	79 ± 6 a	66 ± 19 a	65 ± 19 a
Metsulfuron	Metsulfuron	CW + B	65 ± 23 a	66 ± 12 a	65 ± 13 a
Metsulfuron	Dicamba	CW + B	85 ± 13 a	59 ± 21 a	61 ± 29 a
Triclopyr	Triclopyr	CW + B	68 ± 7 a	48 ± 26 a	31 ± 22 a
Aminopyralid	Aminopyralid	TF + B	81 ± 21 a	74 ± 19 a	68 ± 27 a
Dicamba	Dicamba	TF + B	70 ± 7 a	70 ± 16 a	63 ± 22 a
Metsulfuron	Metsulfuron	TF + B	68 ± 14 a	60 ± 18 a	58 ± 14 a
Metsulfuron	Dicamba	TF + B	85 ± 13 a	59 ± 21 a	58 ± 28 a
Triclopyr	Triclopyr	TF + B	66 ± 15 a	45 ± 29 a	33 ± 19 a

Note: Plots were initiated in Cooper County, Missouri along Interstate Highway 70 from mile marker 89 to 93. The last date of grass seeding was 10 May 2007.

[a] CW, Canada wildrye; TF, tall fescue; B, buffalograss.

[b] The standard deviation for grass establishment follows the estimated mean.

[c] Means followed by the same small letter in each column are not significantly different according to Fisher Protected LSD at $P \leq 0.05$.

3.3. *Seedling cutleaf teasel re-infestation*

The density of cutleaf teasel seedlings was related not only to the initial effectiveness of herbicide treatments, but also to the establishment of desirable grasses (Table 4). There was no two-way interaction between grass type and herbicide programme for seedling cutleaf teasel density (Table 5B). For the 1 November, 2007 evaluation date, variability in cutleaf teasel density was strictly dependent upon the herbicide programme employed. Cutleaf teasel seedling density in November 2007 was 72–92% lower for aminopyralid than triclopyr for each grass type (Table 4). By August 2008 (640 DAIA), seedling density of cutleaf teasel was similar among all herbicide treatments, indicating a lack of residual control for each herbicide programme (Table 5). However, on 5 August, 2008 the establishment of grasses was sufficient to induce a significant effect on seedling cutleaf teasel population (Table 5). Within tall fescue + buffalograss treatments, the density of cut-leaf teasel seedlings was up to 91.4% lower in the plot treated with aminopyralid compared with all other programmes in November 2007. However, cutleaf teasel density was similar for aminopyralid versus other herbicide programmes by 636 DAIA. There was no effect of herbicide 427 days after the last herbicide application; thus, density of cutleaf seedling reflects new teasel emergence. Cutleaf teasel rosette increased in size (not considered to be seedlings, see Materials and Methods), which then covered a greater percentage of the plot area and precluded additional emergence of cutleaf teasel. For Aminopyralid, dicamba + diplufenzopyr, and metsulfuron, Cutleaf Teasel population densities were reduced compared with densities in untreated areas (up to 300 seedlings per square metre).

4. Discussion and conclusions

No studies have integrated the use of herbicides and establishment of desirable vegetation to displace an established population of cutleaf teasel. Control of existing cutleaf teasel was optimal (>99%) for metsulfuron, dicamba, and aminopyralid herbicide programmes up to 242 DAIA (Table 2), but effectiveness declined in a stepwise fashion through 636 DAIA. Bentivegna and Smeda (2008) showed that effective control of cutleaf teasel require more than one amino

Table 4. Mean cutleaf teasel seedling emergence for the integrated herbicide programme and grass establishment.

Herbicide programme			Cutleaf teasel seedlings (no. per m^2)[a]	
Fall 2006	Spring 2007	Grass type	November 2007	August 2008
Aminopyralid	Aminopyralid	CW + B	10 b	20 a
Dicamba	Dicamba	CW + B	17 a	17 ab
Metsulfuron	Metsulfuron	CW + B	15 a	17 ab
Metsulfuron	Dicamba	CW + B	30 a	18 ab
Triclopyr	Triclopyr	CW + B	37 a	12 abc
Aminopyralid	Aminopyralid	TF + B	2 b	10 bc
Dicamba	Dicamba	TF + B	18 a	6 c
Metsulfuron	Metsulfuron	TF + B	27 a	15 abc
Metsulfuron	Dicamba	TF + B	25 a	15 abc
Triclopyr	Triclopyr	TF + B	30 a	8 bc

Note: Plots were initiated in Cooper County, Missouri along Interstate Highway 70 from mile marker 89 to 93. The last date of grass seeding was 10 May 2007.
CW, Canada wildrye; TF, tall fescue; B, buffalograss.
[a]Means followed by the same letter in each column are not significantly different according to Fisher Protected LSD at $P \leq 0.05$.

Table 5. Analysis of variance for grass establishment (A) and cutleaf teasel seedlings emergence (B) influenced by the integrated herbicide programme and grass establishment.

	Evaluation date					
	3 July 2007		1 November 2007		5 August 2008	
A) *Grass establishment*						
	Mean square	*P*-value	Mean square	*P*-value	Mean square	*P*-value
Herbicide	437.25	0.26	854.69	0.11	1344.69	0.09
Grass	48.4	0.68	22.5	0.82	5.63	0.92
Herbicide × Grass	42.5	0.96	39.69	0.98	169.69	0.89
B) *Cutleaf seedling emergence*						
			Mean square	*P*-value	Mean square	*P*-value
Herbicide			1.88	<0.001	0.15	0.46
Grass			0.15	0.48	1.07	0.01
Herbicide × Grass			0.02	0.99	0.22	0.25

acid biosynthesis inhibitor or growth regulator herbicide application. Decreased control of cutleaf teasel was likely the result of new seedling emergence and establishment (Table 4). Out results suggest that applications of effective herbicide are not sufficient to prevent establishment of new cutleaf teasel populations when applications are undertaken further that one year apart. As cutleaf teasel plants became established, factors that led to original success in supplanting established grasses again came into play, leading to reduction in grass coverage (Table 3). It is likely that continued applications of affective herbicide on cutleaf teasel are necessary, but perhaps at a reduced incidence, as the bank of seeds in the soil becomes exhausted.

Triclopyr activity on cutleaf teasel was lowest among all the herbicide programmes (Table 2), resulting in higher cutleaf teasel seedling densities (Table 4). However, 15 months after the last herbicide application, seedling densities were reduced compared with other treatments, and this can be attributed to establishment of larger teasel rosettes. In this study, control of cutleaf teasel alone was ineffective without establishment of desirable grasses. For example, due to the increase in the amount of bare ground in dicamba and metsulfuron programmes (Figure 1), the open areas were suitable for new cutleaf teasel seedlings establishment (Table 4).

Eradication of cutleaf teasel is a long-term process that involves periodic application of selective herbicides and introduction of desirable species such as grasses. Bentivegna and Smeda (2011) found that 6.1% of cutleaf teasel seed remained viable in the soil seedbank 3 years after seed was placed in contact with soil. Robert (1986) also reported that 2.2% of seedlings from *Dipsacus Sylvestris* emerged 4 years after initial sowing. Several herbicides are effective for initial control of teasel rosettes, while others provide suppression of new seedling emergence. Following initial application of herbicides, establishment of desirable grasses can further prevent new infestation of cutleaf teasel (Figure 1). However, despite the high coverage rate of grasses up to five months after herbicide applications, the continued success of grasses appears dependent upon additional herbicide application. Werner (1977) showed that dense stands of grasses reduced teasel emergence.

In comparison, seedling emergence of musk thistle (C*arduus nutans* L.), a biennial plant with a large taproot, was also reduced by the presence of grasses (Wardle et al. 1995). Encouragement of tall fescue as well as other grasses along highway right-of-ways is desirable, enhancing the overall appearance (Bennett 1979).

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