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Herbicidal control of *Cirsium arvense* (L.) Scop. roots and shoots in no-till spring wheat (*Triticum aestivum* L.)*

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Summary: Résumé: Zusammenfassung

Three herbicide treatments were applied each year over a period of 4 years to *Cirsium arvense* (L.) Scop. infestations in no-till spring wheat (*Triticum aestivum* L.) in North Dakota, USA. Both chlorsulfuron at 30 g ai ha^{-1}+a non-ionic surfactant and a mixture of clopyralid+2,4-D at 70+280 g ai ha^{-1} gradually reduced *Cirsium arvense* shoot density, root biomass, and adventitious root buds over the 4-year treatment period in two trials. These two treatments did not merely induce adventitious root buds to become dormant. They virtually eliminated roots to a depth of 50 cm by year 4. Tribenuron methyl at 10 g ai ha^{-1}+a non-ionic surfactant was less effective in reducing shoot density and root biomass.

Lutte herbicide contre les racines et les tiges de Cirsium arvense *(L.) Scop. dans du blé de printemps non labouré (*Triticum aestivum *L.)*

Trois traitements herbicides ont été appliqués chaque année pendant 4 ans, contre des infestations de *Cirsium arvense* (L.) Scop. dans du blé de printemps (*Triticum aestivum* L.) non labouré dans le Dakota Nord, USA. Tant le chlorsulfuron à 30 g m.a. ha^{-1}+un surfactant nonionique qu'un mélange de clopyralide+2,4-D à 70+280 g m.a. h^{-1} ont réduit progressivement la densité des pieds de *Cirsium arvense*, la biomasse racinaire, et les bourgeons racinaires adventices pendant les 4 années de traitements dans les 2 essais. Ces traitements ont à peu près éliminé les racines sur une profondeur de 50 cm en 4 ans. Ces deux traitements n'ont pas induit de dormance des bourgeons racinaires adventices. Le tribenuron methyl à 10 g m.a. ha^{-1}+un surfactant non ionique a été moins efficace dans la réduction de la densité de plante et de la biomasse racinaire.

Chemische Bekämpfung von Cirsium arvense *(L.) Scop. in direktgesätem Sommerweizen (*Triticum aestivum *L.)*

In direktgesäter Sommerweizen (*Triticum aestivum* L.) wurdel in North Dakota, USA, Bestände von *Cirsium arvense* (L.) Scop. über 4 Jahre jährlich 3 Herbizidbehandlungen unterzogen. Sowohl Chlorsulfuron mit 30 g AS ha^{-1} + nichtionischem Netzmittel als auch eine Mischung von Clopyralid+2,4D mit 70+280 g AS ha^{-1} verringerten die Sproßdichte der Acker-Kratzdistel, die Wurzelbiomasse und die Adventivknospen an den Wurzeln in 2 Versuchen graduell. Durch diese beiden Behandlungen wurden nicht nur die Adventivknospen dormant, sondern auch die Wurzeln bis zu einer Tiefe von 50 cm bis zum 4. Jahr fast ganz eliminiert. Tribenuron-methyl mit 10 g AS ha^{-1} + nichtionischem Netzmittel war hinsichtlich der Reduktion von Sproßdichte und Wurzelbiomasse weniger wirksam.

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Introduction

Canada thistle, *Cirsium arvense* (L.) Scop., is a perennial weed with an extensive spreading root system (Hayden, 1934; Amor & Harris, 1975). Adventitious root buds arise from roots to form new adventitious shoots which emerge above the soil (Hayden, 1934; Hamdoun, 1970; Hamdoun, 1972).

Because vegetative propagation from adventitious root buds allows *Cirsium* to persist on farmland after seedling establishment, control measures must be directed at killing perennial roots in order to achieve long-term control (Donald, 1990). Seed production and new seedling emergence are not believed to contribute as much to the growth and weediness of *Cirsium* patches as the contributions of the adventitious root bud population formed on the expanding root system (Donald, 1990).

Several alternative non-chemical methods and herbicides can be used to manage *Cirsium* (Donald, 1990). Most past research on the herbicidal control of *Cirsium* has only described shoot damage, which was often only observed for less than 1 year after treatment. The effectiveness of multi-year herbicide treatments for control or eradication of *Cirsium* roots has seldom been studied (Carlson & Donald, 1988).

Persistence of *Cirsium* roots and adventitious root buds in soil has not been reported in the literature (Donald, 1990). Likewise, the time taken to eradicate *Cirsium* roots on infested farms is not known. The time taken for repeated summer fallow tillage to prevent later shoot emergence provides an estimate of root persistence. In the Northern Great Plains, repeated summer fallow tillage for 2 years was found to prevent shoot emergence during the third year (Hodgson, 1970), but this period varied among *Cirsium* ecotypes. Repeated fallow tillage is thought to kill *Cirsium* roots by preventing shoot growth and thus depleting roots of their nutritional reserves over time, leading to their death (Donald, 1990).

Pavlychenko (1943) was the first agronomist to study herbicidal control of *Cirsium* roots in the field, excavating trenches through sodium chlorate-treated *Cirsium* patches to determine the depth at which roots were killed by this non-selective, persistent soil sterilant. Several annual applications of sodium chlorate were needed to eradicate roots. Sodium chlorate residues in soil also prevented new root growth into treated regions from outside the treated area. Such field studies have the potential to increase our understanding of the mechanism of long-term control of perennial weeds with herbicides in the field.

The objectives of these trials were (i) to determine the relative efficacy of broadleaf herbicide treatments for reducing *Cirsium* root growth and adventitious root bud numbers in no-till spring wheat when applied annually to the same plots each year for 4 years, (ii) to determine how quickly annual application of post-emergence herbicides over a 4-year period reduced *Cirsium* root growth, and (iii) to determine whether absolute measurements of root biomass per volume of soil (i.e. fresh weight or adventitious root bud number m^{-3}) differ from one another or offer advantages for distinguishing differences in response to various herbicide treatments over ratios of different root growth measurements (i.e. adventitious root bud number g^{-1} fresh weight of root).

Materials and methods

Treatments

The following broadleaf herbicide treatments were tested for *Cirsium* control: (i) untreated control; (ii) alkanolamine salt formulation of clopyralid+2,4-D (Curtail®, Dow Chemical Co., Agricultural Products Department, P.O. Box 1706, Midland, MI 48640, USA) at 70+280 g ai ha^{-1}; (iii) chlorsulfuron (Glean®, E. I. du Pont de Nemours & Co. (Inc.), Agricultural Products Department, Wilmington, DE 19898, USA) at 30 g ai ha^{-1}+non-ionic surfactant (Ortho X-77, Chevron Chemical Co., 6001 Bollinger Canyon Road, San Ramon, CA 94583, USA) at 0·25% (v/v); and (iv) tribenuron methyl (Express®, E. I. du Pont de Nemours & Co. (Inc.), Agricultural Products Department, Wilmington, DE 19898, USA) at 10 g ai ha^{-1}+non-ionic surfactant at 0·25% (v/v).

Experimental design

The field trials were arranged as a randomized complete block design with three blocks, and were carried out on two nearby sites (trials 1 and 2). Trial 1 was conducted from 1985 to 1988 and trial 2 was conducted from 1986 to 1989.

Blocking was based on the initial shoot density of a natural stand of *Cirsium*. The *Cirsium* subspecies '*arvense*' (Wimm. and Grab.) (Moore & Frankton, 1974) was present in both trials. Individual plots measured 3·3 × 13·2 m in trial 1 and 3·3 × 7 m in trial 2.

Crop management

Each of the two trials was conducted over a 4-year period in no-till spring wheat on adjacent sites that had been chemically fallowed and mowed during the previous growing season. Both trials were located on the North Dakota State University experimental farm in Fargo, on a Fargo silty clay soil with 2% sand, 47% silt, 51% clay, 3·9% organic matter, and a pH of 7·7.

Emerged annual broadleaf and perennial grass weeds present at planting were controlled with glyphosate applied at 1·1 kg ae ha^{-1} in 1985 and 1986, at 0·8 kg ha^{-1} in 1987, and at 0·6 kg ha^{-1} in 1988 in trial 1. In trial 2, glyphosate was applied at 0·4 kg ha^{-1} in 1986 and at 0·8 kg ha^{-1} from 1987 to 1989. Glyphosate was applied on 25 May 1985, 16 May 1986, 23 April 1987, 10 May 1988 and 19 April 1989, shortly before or shortly after spring wheat planting, but before wheat emergence.

'Len' hard red spring wheat was planted in 1985 and 'Wheaton' spring wheat was planted thereafter. These semi-dwarf varieties were planted with a double-disc grain drill at 80 to 100 kg ha^{-1}, 4–5 cm deep in rows spaced 18 cm apart. Wheat was planted and fertilized on 24 May 1985, 15 May 1986, 27 April 1987, 11 May 1988 and 1 June 1989. Nitrogen, as urea, was deep banded at planting approximately 6 cm deep in 35-cm rows half-way between wheat rows at 80–120 kg nitrogen ha^{-1}. Enough nitrogen was applied each year for a 2690 kg ha^{-1} wheat yield goal as recommended by North Dakota State University on the basis of soil analysis.

Wheat stand was determined in mid-June from counts of three to six 1-m^2 quadrats per plot in untreated check plots. In trial 1 wheat stands were 90, 170, 140 and 110 plants m^{-2} from 1984 to 1988 (years 1 to 4, respectively). In trial 2 wheat stands were 120, 110, 110 and 130 plants m^{-2} from 1986 to 1989 (years 1 to 4, respectively).

Herbicides were applied with a single-tyre bicycle sprayer equipped with flat-fan spray nozzles spaced 50 cm apart on a 3·1 m boom and operated at 4·8 km h^{-1} and either 140 or 210 kPa generated by pressurized air. Herbicides were applied on 10 June 1985, 5 June 1986, 29 May 1987, 7 June 1988 and 1 June 1989. Wheat was tillered and *Cirsium* shoots were 1–20 cm tall at herbicide application. No rain fell within 24 h of any herbicide application.

Diclofop methyl at 1·1 kg ha^{-1} was applied each year in June to all plots when spring wheat had tillered and completely controlled sparse, scattered wild oats (*Avena fatua* L.), green foxtail (*Setaria viridis* (L.) Beauv.) and yellow foxtail (*Setaria glauca* L.) plants. Diclofop was applied on 20 June 1985, 16 June 1986, 8 June 1987, 17 June 1988 and 1 June 1989.

Emerged *Cirsium* adventitious root buds were counted in six or eight 0·25- or 0·5-m^2, quadrats per plot at least 0·6 m in from plot borders at spring wheat harvest in mid- to late August. Seedlings were not counted because they were rare. Between 4–11% of the plot surface area was sampled for shoot density in trial 1 and 7–17% of the plot area was sampled in trial 2.

Root measurements

Thickened roots are defined as those not passing through a 14-mesh screen during extraction. Thickened *Cirsium* roots (>1·3 mm in diameter) that are responsible for vegetative propagation of *Cirsium* shoots from adventitious root buds (Prentiss, 1889; Hodgson, 1970; Hamdoun, 1972) were gathered by taking soil cores from each plot shortly after wheat harvest in mid-August. Small lateral roots and elongating, unthickened portions of primary roots do not form adventitious root buds (Prentiss, 1889).

A hydraulically powered, tractor-mounted soil corer was used to take 15 cores, 6·4 cm in diameter, 50 cm deep from each plot. Three cores were taken from the centre of each of five equally spaced subplots 0·6 m in from plot borders, using stratified random sampling. The sampling depth is reported to include most of the root system (Hodgson, 1968; Lauridson *et al.*, 1983; Nadeau & Vanden Born, 1989). Roots were sampled on 26 August 1986, 28–31 August 1987, 29–31 August 1988 and 10–12 August 1989. Soil cores were stored outdoors for 1–3 days in plastic bags until the thickened roots

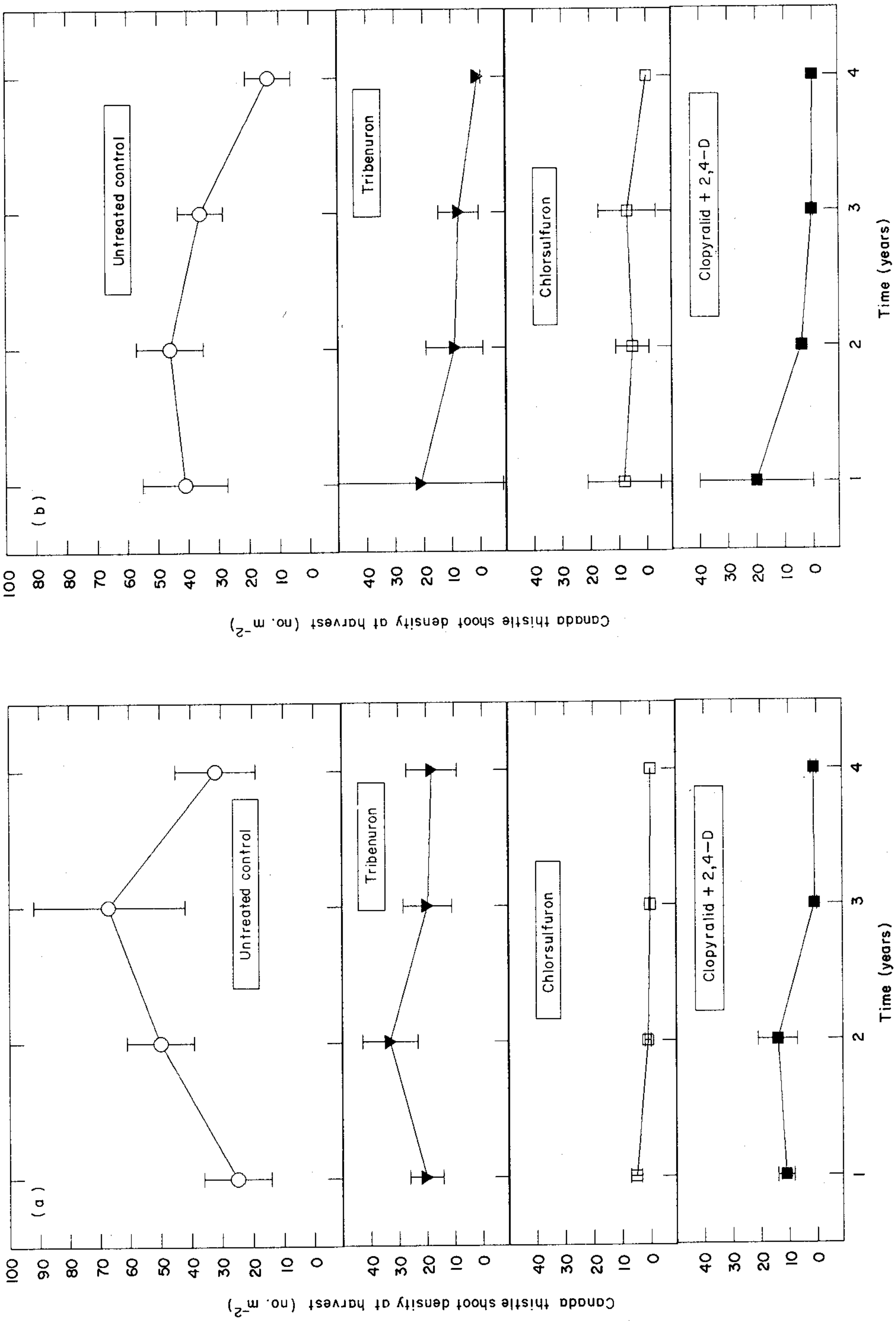

Fig. 1. *Cirsium* shoot density in no-till spring wheat at harvest following repeated annual application of herbicides in spring to the same plots over 4 years in two trials: (a) trial 1; (b) trial 2. Symbols indicate mean values ± standard error (bars).

were separated from the soil using a root washer (Carlson & Donald, 1986, 1988).

Root fresh weight and visible adventitious root bud numbers were determined after pooling all root samples from each plot. One-tenth and 0·2% of the plot surface area were sampled for roots in trials 1 and 2, respectively. Data on root growth and adventitious root bud numbers were expressed per m^3 of soil volume to a depth of 50 cm.

Root growth was measured from the second year of each trial. Past experience suggests that differences in *Cirsium* root growth can be distinguished only after 2 or more years of herbicide treatment because of the high variability of root biomass distribution in the field (Carlson & Donald, 1988).

Detection limits expressed per m^3 were calculated using minimum measurable amounts of root growth found in a total soil sample volume of 0·024 m^{-3} per plot (= 15 soil cores by core volumes of 6·4 × 50 cm each). The total soil sample volume per plot represented 0·1% and 0·2% of the total soil volume per plot to a depth of 50 cm in trials 1 and 2, respectively. If 0·01 g was the smallest amount of root biomass measured for the total sample per plot, the detection limit for root fresh weight would be 0·4 g m^{-3} (the minimum average observed for three plots was 2 g m^{-3}). Similarly, if only one adventitious root bud was detected in the total soil sample volume per plot, the detection limit would be 42 adventitious root buds m^{-3} (the minimum average observed for three plots was 42 buds m^{-3}).

Statistical analysis

Analyses of variance (ANOVA) were performed for each year in each trial using SPSS/PC+ ver. 4 statistical analysis software and, if significant ($P \leq 0{\cdot}01$), means were separated with the least significant difference (L.S.D.) range test ($P \geq 0{\cdot}05$). Orthogonal contrasts were also examined. ANOVA were performed either including or excluding treatments with zero values for all blocks. Root data were transformed as $\log_{10}(x+1)$ before ANOVA to make variance homogeneous. Data were not combined over trials or over years because the ANOVA showed interactions between year and trial.

Results and discussion

Cirsium *shoot density*

Cirsium stands in both trials were denser and more variable in untreated controls (Fig. 1) than in commercial wheat fields in the northern United States (Donald, 1990) shortly before harvest. In commercial wheat fields, average stands ranged from 1 to 7 shoots m^{-2} after herbicide treatment, but could reach a maximum of 42 shoots m^{-2}. As many as 67 ± 25 shoots m^{-2} (mean values ± standard error) were counted in untreated control plots (Fig. 1).

Shoot densities in untreated control plots at harvest (Fig. 1) were lower in the first and third years of the experiment than in the second and third years of trial 1, probably due to drought during the growing season preceding the first and third years (Fig. 2), as observed previously in other years and experiments (Carlson & Donald, 1988; Donald & Prato, 1991). By the fourth year, shoot densities at harvest in untreated controls were only 48% and 38% of those observed in the third year in trials 1 and 2, respectively, following 1 and 2 years of summer drought, respectively. Apparently, water and temperature stress reduced the *Cirsium* stand during the following growing season, independently of herbicide treatment.

Reductions in *Cirsium* stand at harvest caused by herbicide treatments were distinguished in trial 1 one year earlier than in trial 2 (Fig. 1). This may have been due to exposure of *Cirsium* to water stress in the growing season before trial 1 was started, the previous year's rainfall being adequate before trial 2 was started (Fig. 2).

Chlorsulfuron and clopyralid+2,4-D treatments reduced the *Cirsium* stand more quickly, dramatically and consistently over time than tribenuron methyl (Fig. 1). In fact, treatment with either chlorsulfuron or clopyralid+2,4-D virtually eliminated shoots at harvest by the fourth year in both trials.

Root fresh weight

Root fresh weight in untreated plots varied between 262 and 610 g m^{-3} over 3 years (Table 1). These values are similar to those reported previously for dense *Cirsium* stands in fall chisel-ploughed spring wheat (Carlson & Donald, 1988). Root fresh weight in untreated control plots did not change consistently over

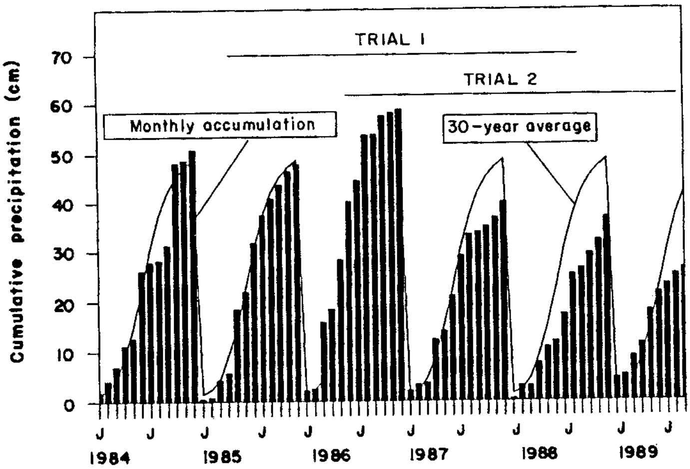

Fig. 2. Cumulative monthly precipitation and 30-year average cumulative monthly precipitation over 6 years for trials 1 and 2. Weather data were gathered at Hector International Airport approximately 1 km north of the experimental site.

time in either trial (Table 1), probably because the climatic conditions fluctuated from year to year (Fig. 2).

Compared to the untreated control, chlorsulfuron applied annually to the same plots reduced *Cirsium* root fresh weight after 2 and 4 years of treatment in trials 1 and 2, respectively (Table 1), as indicated by L.S.D. tests and orthogonal contrasts. Differences in root fresh weight between the untreated control and the clopyralid+2,4-D treatment could first be distinguished in both trials in years 3 and 2 in trials 1 and 2, respectively, by orthogonal contrasts, and in years 3 and 4 by the L.S.D. test. Root fresh weight after four annual treatments with either chlorsulfuron or clopyralid+2,4-D was reduced to 0 or 0·8% of the untreated controls in trial 1, and to 2·1 or 0·9% of the untreated controls in trial 2. Tribenuron methyl did not produce such consistent decreases in root fresh weight. Root length responded to herbicide treatment in much the same way as root fresh weight (data not shown).

Table 1. Herbicide effects on *Cirsium* root fresh weight m^{-3} to a depth of 50 cm over 2–4 years of herbicide treatment

Treatment	Root fresh weight (g m^{-3})		
	Year 2	Year 3	Year 4
Trial 1			
Untreated control	610 ± 143	385 ± 289	262 ± 189
Chlorsulfuron	6 ± 5	8 ± 15	0
Tribenuron	242 ± 54	228 ± 106	334 ± 130
Clopyralid+2,4-D	—	25 ± 21	2 ± 4
Trial 2			
Untreated control	367 ± 47	333 ± 225	465 ± 242
Chlorsulfuron	208 ± 200	160 ± 87	10 ± 18
Tribenuron	254 ± 200	114 ± 103	82 ± 107
Clopyralid+2,4-D	62 ± 35	47 ± 26	4 ± 6

Mean values ± standard error are shown.

Adventitious root buds

Adventitious root bud numbers in untreated control plots ranged from 1273 to 2198 adventitious root buds m^{-3} in the two trials (Table 2). These values are somewhat higher than those previously reported in fall chisel-ploughed spring wheat (Carlson & Donald, 1988). There were no consistent trends in adventitious root bud number and root fresh weight for untreated control plots over time (Tables 1 and 2).

Chlorsulfuron or clopyralid+2,4-D applied annually gradually reduced adventitious root bud numbers from the second to fourth years in both trials (Table 2), as expected from observed decreases in *Cirsium* stand (Fig. 1). By the fourth year adventitious root buds were eliminated from plots treated with either chlorsulfuron or clopyralid+2,4-D in trial 1, and represented 3·6 or 0% of untreated control values in trial 2. Tribenuron methyl did not consistently reduce adventitious root bud number in either trial. Root fresh weight and adventitious root bud numbers provided similar insight regarding the manner in which repeated annual herbicide treatment reduced root growth (Tables 1 and 2).

Table 2. Herbicide effects on *Cirsium* adventitious root bud number m^{-3} to a depth of 50 cm over 2–4 years of herbicide treatment

Treatment	Adventitious root bud numbers m^{-3}		
	Year 2	Year 3	Year 4
Trial 1			
Untreated control	1385 ± 285	1662 ± 957	1273 ± 1003
Chlorsulfuron	40 ± 70	27 ± 46	0
Tribenuron	683 ± 145	925 ± 281	1380 ± 641
Clopyralid+2,4-D	—	54 ± 61	0
Trial 2			
Untreated control	2198 ± 905	1420 ± 897	1849 ± 1582
Chlorsulfuron	965 ± 664	871 ± 644	67 ± 116
Tribenuron	1729 ± 1186	402 ± 368	174 ± 206
Clopyralid+2,4-D	348 ± 284	54 ± 61	0

Mean values ± standard error are shown.

The number of adventitious root buds m^{-1} of root in untreated controls ranged from 12·8 ± 7·8 (mean value ± standard error) to 24·4 ± 3·5 m^{-1} of root and from 2·3 ± 0·3 to 5·9 ± 2·3 g^{-1} of root in both trials (data not shown). No significant differences in adventitious root bud number per unit length or mass of surviving root were found between treatments. These observations demonstrate that roots which survived herbicide treatment formed as many adventitious root buds m^{-1} of root length or g^{-1} of root biomass as did the untreated controls. Surviving roots were healthy, and did not appear to have been damaged or even exposed to herbicide. Because tillage and physical processes, such as frost heaving, disrupt brittle *Cirsium* roots, not all shoots and roots of individual *Cirsium* plants are connected to one another in the field, unlike pot-growth plants used for most herbicide translocation studies (Donald, 1990). Thus translocation of a phytotoxic dose of herbicide from treated shoots to roots may be limited because shoots are not connected to all parts of the *Cirsium* root system. There are few reports documenting patterns or amounts of herbicide translocation from foliage to adventitious root buds on well-established perennial roots of broadleaf weeds, such as *Cirsium*, either in the laboratory or in the field (Donald, 1990).

The best way to measure the impact of herbicides on root growth of *Cirsium* has not yet been resolved (Carlson & Donald, 1988). In the present study, presentation of measurements of absolute root growth (e.g. fresh weight m^{-3}) was found to be preferable to the use of ratios of root-growth measurements for detecting differences in root-growth response to herbicide treatment. Large differences between treatments could be readily distinguished for the former measurements, but not for the latter. Presenting only ratios of root-growth measurements, as some authors have done (McAllister & Haderlie, 1985), to demonstrate the impact of herbicides on root growth has limitations. Ratios between root-growth measurements only estimate the impact of herbicides on surviving roots, not root survival or absolute root biomass. Calculation of ratios also requires multiple measurements, which represent an added research expense.

Sequential measurements of shoot density at spring wheat harvest over time (Fig. 1) are preferable to root growth measurements (Tables 1 and 2) for documenting changes in herbicidal control of *Cirsium*, because shoot density can be measured more quickly and cheaply than root growth. Since a larger proportion of the total treated land can be sampled, statistical precision is generally greater for shoot density than for root measurements.

However, such observational data do not contribute to our understanding of why *Cirsium* shoot emergence or stands decrease over time. To demonstrate that herbicide treatments prevent later reinfestation from adventitious root buds, one must either measure root biomass remaining after the treatment, or monitor changes in shoot density for several years after ending the treatment.

Despite extensive laboratory research on the mechanism of action of herbicides in annual plant species, it remains unclear why field control measures must extend over several years in order successfully to prevent further shoot emergence from adventitious root buds of perennial broadleaf weeds, such as *Cirsium* (Donald, 1990). Annual chlorsulfuron or clopyralid+2,4-D treatment did not merely induce dormancy in adventitious root buds, but greatly reduced root mass (Table 1) and adventitious root bud numbers m^{-3} (Table 2), leading to dramatically reduced *Cirsium* shoot densities over a period of 4 years (Fig. 1).

Conclusions

Lee (1952) stated that 'no single treatment, regardless of practice, can be relied upon to produce complete kill' of *Cirsium arvense*. This viewpoint is still valid today. In 1982, Strand (1982) summarized the extension service's opinion that integrated control programmes for *Cirsium* require 5 to 10 years of effort, and observed that 'Canada thistle control is not a 'one-shot' treatment. A series of well-calculated and timely operations are essential for successful results'. The results of the current study substantiate these assertions for *Cirsium* management using herbicides.

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