Fall-applied Herbicides for Canada Thistle (*Cirsium arvense*) Root and Root Bud Control in Reduced-till Spring Wheat[1,2]

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Abstract. Several sequences of POST herbicides applied each year in fall alone, in spring alone, or both in fall and again in spring controlled Canada thistle stands in spring wheat by severely decreasing root biomass and the numbers of adventitious root buds to a depth of 50 cm over four years. These treatments included dicamba applied at 1.7 or 2.2 kg ae ha^{-1} for the first two successive falls followed in wheat by either chlorsulfuron at 30 g ai ha^{-1} plus nonionic surfactant, MCPA plus bromoxynil at 280 plus 280 g ha^{-1}, or 2,4-D amine at 560 g ha^{-1} applied annually for each of four consecutive years from the start. Chlorsulfuron at 30 g ha^{-1} applied alone in spring for each of four years also reduced and prevented Canada thistle root growth as effectively as a sequence of fall-applied dicamba followed by spring-applied chlorsulfuron in spring wheat. **Nomenclature.** Bromoxynil, 3,5-dibromo-4-hydroxybenzonitrile; chlorsulfuron, 2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzenesulfonamide; dicamba, 3,6-dichloro-2-methoxybenzoic acid; MCPA, (4-chloro-2-methylphenoxy)acetic acid; 2,4-D, (2,4-dichlorophenoxy)acetic acid; Canada thistle, *Cirsium arvense* (L.) Scop. #[4] CIRAR; wheat, *Triticum aestivum* L.

Additional index words: Adventitious root bud, perennial weed.

INTRODUCTION

Canada thistle is a perennial broadleaf weed with an extensive spreading root system (1, 12). Adventitious root buds form on its long-lived roots and give rise to new adventitious shoots above ground (8, 9, 10). The term "shoot" will be used in this article for adventitious shoots that arise from adventitious root buds and emerge through the soil surface, although other terms have been used (4). Vegetative propagation from roots allows Canada thistle to persist on farmland after seedling establishment. Seed production and new seedling emergence are not believed to contribute greatly to patch growth and weediness of Canada thistle after establishment (4). Patch growth results from root bud formation on the expanding root system and subsequent adventitious shoot emergence (4). Consequently, control measures should be directed at killing the perennial root system.

Knowledge of how herbicides damage Canada thistle roots in the field is rudimentary (4). Pavlychenko (18) was the first to study herbicidal damage to Canada thistle roots in the field. He excavated trenches through sodium chlorate-treated Canada thistle patches to determine how deeply roots were killed and noted that several annual applications of sodium chlorate were needed to eradicate roots. Persistent sodium chlorate residues in soil prevented new root encroachment into treated regions from outside treated areas. Pavlychenko's early observations provide valuable insight regarding how persistent soil sterilant chemicals kills Canada thistle roots and prevent subsequent reinfestation.

Although there are several nonchemical methods and herbicides for managing Canada thistle (4, 13), there are few documented studies concerning the direct effects of annual herbicide treatment on Canada thistle root systems over several years (3, 5). Such research is laborious, time consuming, and expensive. Field studies of the impact of herbicides on perennial weed roots promise to increase our understanding of the mechanism of long-term control of perennial weeds with herbicides. The objectives of this research were: 1) to compare the efficacy of several sequences of herbicides for reducing Canada thistle root growth in reduced-till spring wheat, including fall-applied broadleaf herbi-

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[2] Mention of a trademark or proprietary product does not constitute a guarantee of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that also may be suitable.

[3] Res. Agron., Cropping Syst. Water Qual. Res. Unit, Agric. Res. Serv., U.S. Dep. Agric., 244 Agric. Engineering Bldg., UMC, Columbia, MO 65211, formerly of Agric. Res. Serv., Biosci. Res. Lab., Fargo, ND 58105.

[4] Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds, Revised 1989. Available from WSSA, 309 W. Clark St., Champaign, IL 61820.

Table 1. Herbicide treatments and times of application.

				Treatment						
Fall herbicide	Rate	In-crop herbicide	Rate	Year 0 Fall	Year 1 In-crop	Year 1 Fall	Year 2 In-crop	Year 3 In-crop	Year 4 In-crop	Year 5 Fallow
	kg ha^{-1}		g ha^{-1}							
Trial 1										
Untreated check	–	Untreated check	–	No	No	No	No	No	No	No
Dicamba	1.7	–	–	Yes	No	Yes	No	No	No	No
Dicamba	2.2	–	–	Yes	No	Yes	No	No	No	No
–	–	Chlorsulfuron	30	No	Yes	No	Yes	Yes	Yes	No
Dicamba	2.2	Chlorsulfuron	30	Yes	Yes	Yes	Yes	Yes	Yes	No
2,4-D	1.7	–	–	Yes	No	Yes	No	No	No	No
2,4-D	1.7	2,4-D	560	Yes	Yes	Yes	Yes	Yes	Yes	No
–	–	2,4-D	560	No	Yes	No	Yes	Yes	Yes	No
Dicamba	1.7	2,4-D	560	Yes	Yes	Yes	Yes	Yes	Yes	No
Dicamba	2.2	2,4-D	560	Yes	Yes	Yes	Yes	Yes	Yes	No
Trial 2										
Untreated check	–	Untreated check	–	No	No	No	No	No	No	No
Dicamba	1.7	–	–	Yes	No	Yes	No	No	No	No
Dicamba	2.2	–	–	Yes	No	Yes	No	No	No	No
–	–	Chlorsulfuron	30	No	Yes	No	Yes	Yes	Yes	No
Dicamba	2.2	Chlorsulfuron	30	Yes	Yes	Yes	Yes	Yes	Yes	No
Glyphosate	1.7	–	–	Yes	No	Yes	No	No	No	No
Glyphosate	1.7	MCPA + bromoxynil	280 + 280	Yes	Yes	Yes	Yes	Yes	Yes	No
–	–	MCPA + bromoxynil	280 + 280	No	Yes	No	Yes	Yes	Yes	No
Dicamba	1.7	MCPA + bromoxynil	280 + 280	Yes	Yes	Yes	Yes	Yes	Yes	No
–	–	2,4-D + clopyralid	280 + 70	No	Yes	No	Yes	Yes	Yes	No

cides applied for two consecutive falls to the same plots either alone or followed by selective broadleaf herbicides applied in wheat for each of four years from the start, and 2) to determine how quickly these sequences of POST herbicides reduced adventitious root bud number per m^3 and thickened root fresh weight per m^3 of Canada thistle over four years.

MATERIALS AND METHODS

The experimental design, agronomic practices (Tables 1 and 2), herbicide applications, harvesting, and statistical analysis of the data were described previously (7).

Treatment sequences. Five herbicide treatment sequences were common to two trials (Table 1): a) an untreated check; b) dicamba[5] alone at 1.7 kg ae ha^{-1} applied for the first two consecutive falls; c) dicamba alone at 2.2 kg ae ha^{-1} applied for the first two consecutive falls; d) chlorsulfuron[6] at 30 g ai ha^{-1} plus nonionic surfactant[7] at 0.25% (v/v) applied alone in wheat for each of four years; and e) dicamba applied at 1.7 kg ae ha^{-1} for the first two consecutive falls followed by chlorsulfuron at 30 g ai ha^{-1} plus nonionic surfactant at 0.25% (v/v) applied in wheat for each of four years.

In Trial 1, five additional treatments were included (Table 1): f) the alkanolamine salt formulation of 2,4-D[8] at 1.7 kg ae ha^{-1} applied alone for the first two consecutive falls; g) 2,4-D at 560 g ha^{-1} applied alone in wheat for each of four years; h) 2,4-D at 1.7 kg ha^{-1} applied in fall for the first two consecutive falls followed by 2,4-D at 560 g ha^{-1} applied in wheat for each of four years; i) dicamba at 1.7 kg ha^{-1} applied in the first two consecutive falls followed by 2,4-D at 560 g ha^{-1} applied in wheat for each of four years; and j) dicamba at 2.2 kg ha^{-1} applied for the first two consecutive falls followed by 2,4-D at 560 g ha^{-1} applied in wheat for each of four years.

In Trial 2, the following five treatments were added to the five basic treatments (Table 1): f) glyphosate[9] [*N*-

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[5] Banvel, Sandoz Crop Protection Corp., 1300 East Touhy, Des Plaines, IL 60018.

[6] Glean, E. I. du Pont de Nemours & Co. (Inc.), Agricultural Products Department, Wilmington, DE 19898.

[7] Surfactant was Ortho X-77 (alkylaryl polyoxyethylene glycols, free fatty acids, and isopropanol 90%) produced by Chevron Chemical Co., Agricultural Division, P.O. Box 18300, Greensboro, NC 27419.

[8] Formula 40, Dow Chemical U.S.A., Agricultural Products Dept., P.O. Box 1706, Midland, MI 48640.

Table 2. Dates of important field operations.

	Dates					
Field operation	Year 0 1983	Year 1 1984	Year 2 1985	Year 3 1986	Year 4 1987	Year 5 1988
Trial 1						
Fall herbicides applied	09/29	10/01	09/25	–	–	–
Seedbed prepared	–	04/25	05/21	05/14	04/16	–
Wheat planted and fertilized	–	05/04	05/24	05/15	04/27	–
Wheat stand determined	–	05/29	–	06/04	06/02	–
Broadleaf herbicides applied	–	06/22	06/10	06/05	05/29	–
Diclofop applied	–	–	06/20	06/16	06/08	–
Wheat harvested	–	–	08/27	08/19	–	–
Canada thistle roots sampled	–	09/26-27	09/18-19	08/20-26	09/1-2	8/14-22
Canada thistle roots processed	–	10/8-26	09/23-10/18	08/21-28	09/3-9	8/18-25
Fall chisel plowed	10/25	11/08	10/17-18	10/14-15	10/07	
Trial 2	1984	1985	1986	1987	1988	1989
Fall herbicides applied	10/01	09/25	10/01	–	–	–
Seedbed prepared	–	–	05/22	05/14	04/16	04/14
Wheat planted and fertilized	–	05/22	05/15	04/27	05/11	–
Wheat stand determined	–	06/10	06/04	06/08	06/16	–
Broadleaf herbicides applied	–	06/10	06/05	05/29	06/07	–
Diclofop applied	–	06/20	06/16	06/09	06/17	–
Wheat harvested	–	08/27	08/21	08/03	–	–
Canada thistle roots sampled	10/9-11/1	09/27	09/5-9	08/19-21	09/8-12	08/10-14
Canada thistle roots processed	10/9-11/1	10/16-18	09/8-25	08/20-24	09/9-13	08/11-15
Fall chisel plowed	11/08	10/17-18	10/15	10/17	09/27	–

(phosphonomethyl)glycine] at 1.7 kg ae ha^{-1} plus nonionic surfactant applied for the first two consecutive falls; g) glyphosate at 1.7 kg ae ha^{-1} plus nonionic surfactant applied for the first two consecutive falls followed by the octanoic ester of bromoxynil plus the butoxyethyl ester of MCPA applied in wheat as a premix[10] at 280 g ai ha^{-1} plus 280 g ae ha^{-1}, respectively, for each of four years; h) the same premix at 280 g ha^{-1} plus 280 g ha^{-1}, respectively, applied alone in wheat for each of four years; i) dicamba at 1.7 kg ha^{-1} applied in the first two consecutive falls followed by the same bromoxynil plus MCPA premix at 280 g ha^{-1} plus 280 g ha^{-1}, respectively, applied in wheat for each of four years; and j) the alkanolamine salt formulation (of the ethanol and isopropanol series) of clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) plus 2,4-D at 70 plus 280 g ae ha^{-1} applied in wheat as a premix[11] for each of four years.

Experimental design. A randomized complete block design with three blocks was used on two adjacent sites (Trials 1 and 2, respectively). Trial 1 lasted from the fall of 1983 to 1988, and Trial 2 ran from the fall of 1984 to 1989 (Table 2 and Figure 1). Blocking was based on initial Canada thistle shoot density. Dense natural stands of Canada thistle were present in all blocks except block one of Trial 2, which was artificially established from Canada thistle root cuttings two growing seasons before initial treatment. Canada thistle stands were 47 ± 26 shoots per m^2 (mean ± standard deviation) and 10 ± 4 shoots per m^2 in the first fall of Trials 1 and 2, respectively. Because results in Trial 1 were obtained with dense stands of Canada thistle, the herbicide treatments should perform consistently even for "worse-case" infestations. The Canada thistle subspecies in both trials was '*arvense*' (Wimm. and Grab.) (16). Individual plots measured 3.0 by 12.2 m in both trials.

The trials were treated for four years and observed for five years from the start (Table 1). Spring wheat was planted for the first four years of each trial followed by mechanical fallow with a field cultivator-harrow for weed control in year five. Land for Trial 1 had been pastured for four years, and Trial 2 had been in spring wheat for three years before initial treatment. Both trials were on the North Dakota State University experimental farm, Fargo, on a Fargo silty clay (fine,

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[9] Roundup, Monsanto Co., 800 No. Lindbergh Blvd., St. Louis, MO 63167.

[10] Brominal 3 + 3, Union Carbide Corp., P.O. Box 12014, Research Triangle Park, NC 27709.

[11] Curtail, Dow Chemical Co., Agricultural Products Dept., P.O. Box 1706, Midland, MI 48640.

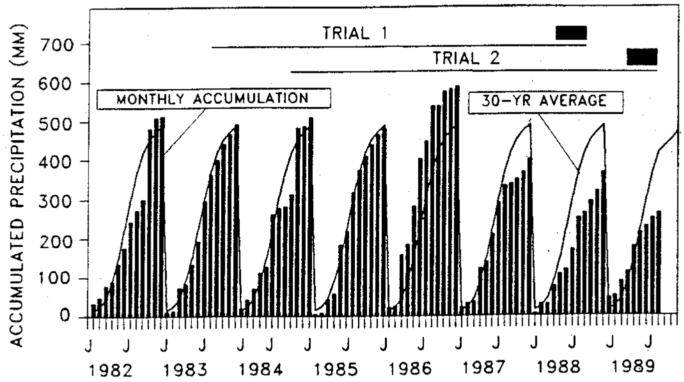

Figure 1. Monthly precipitation (= bars) and 30-yr average precipitation (= line) over six years for Trials 1 and 2. Weather data were gathered at Hector International Airport approximately 1 km north of the experimental sites. The period of mechanical fallow is indicated by horizontal bars.

montmorillonitic, frigid Vertic Haplaquolls) with 2% sand, 47% silt, 51% clay, 3.9% organic matter, and a pH of 7.7.

Agronomic practices. Dates of important field events are presented in Table 2. 'Len' hard red spring wheat was planted in 1984 and 1985 and 'Wheaton' spring wheat was planted thereafter. These semi-dwarf cultivars were planted with a double-disc grain drill[12] at 84 to 100 kg ha^{-1} 3.8 to 5 cm deep in rows spaced 17.5 cm apart.

At planting, nitrogen as urea was banded approximately 6 cm deep in 35-cm rows half-way between wheat rows at 0, 100, 120, and 70 kg N ha^{-1} in Trial 1 from 1984 to 1987, respectively, and at 100, 120, 80, and 120 kg ha^{-1} N in Trial 2 from 1985 to 1988, respectively (Table 2). Enough N was applied each year for a 2400 kg ha^{-1} wheat yield goal as recommended by North Dakota State University from soil tests on samples collected in late fall. No other mineral nutrients were either recommended or applied.

Selective POST broadleaf herbicides were applied in 70 L ha^{-1} with a single-tire bicycle sprayer equipped with flat fan spray nozzles[13] spaced 50 cm apart on a 3.1-m boom and operated at 4.8 km ha^{-1} and 140 kPa generated by pressurized air (Table 2). Rain fell no sooner than 1 d after any treatment. Wheat was tillered, and Canada thistle shoots were 1 to 20 cm tall at herbicide application.

Diclofop[14] {(+/–)-2-[4-(2,4-dichlorophenoxy)phenoxy]propanoic acid} at 1.1 kg ae ha^{-1} was applied as the methyl ester formulation to the entire experiment to control sparse wild oat (*Avena fatua* L. # AVEFA), green foxtail [*Setaria viridis* (L.) Beauv. # SETVI], and yellow foxtail (*Setaria glauca* L. # SETLU) after wheat tillered (Table 2). A tractor-drawn garden sprayer equipped with flat fan nozzles[15] spaced 50 cm apart on a 3.1-m boom, was used to apply diclofop at 5.5 km h^{-1}, and delivered 140 to 190 L ha^{-1} water carrier when operated at 138 to 172 kPa.

Root growth. Thickened roots are defined as those not passing out of a 14-mesh screen during extraction. Thickened Canada thistle roots (≥ 1.3 mm diam) that are responsible for vegetative propagation of Canada thistle shoots from adventitious root buds (9, 12, 19) were gathered by taking soil cores from each plot in late summer (Table 1). Small lateral roots and elongating, unthickened portions of primary roots do not form new shoots from root buds (19). A hydraulically powered, tractor-mounted soil corer[16] was used to take 15 cores (6.4 cm diam by 50 cm deep) from each plot. Three cores were taken from the center of each of five equally spaced subplots 0.6 m from plot borders. This depth reportedly includes most roots (11, 14, 17). Thickened roots were separated from the soil with a root washer (2, 3). Root fresh weight and visible adventitious root bud numbers per m^3 of soil to a depth of 50 cm were determined after pooling all root samples from each plot.

Detection limits for root buds per m^3 were calculated with 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 cm diam by 50 cm each). The total soil sample volume per plot represented 0.1% of the total soil volume per plot to a depth of 50 cm in both trials. 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 per m^3. Root growth was measured two to five years after starting each trial. Past research (3, 5) indicated that differences among treatments in Canada thistle root growth could be distinguished only after two or more years of herbicide treatment because root

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[12] Haybuster 107 double-disc grain drill with deep-banding fertilizer attachment, Haybuster Manufacturing, Box 1950, Jamestown, ND 58401.

[13] TeeJet 8001 flat fan sprayer nozzles, Spraying Systems Co., North Ave., Wheaton, IL 60188.

[14] Hoelon, Hoechst-Roussel Agri-Vet Co., Route 202-206 North, Somerville, NJ 08876.

[15] Teejet 8003 flat fan spray nozzle, Spraying System Co., North Ave., Wheaton, IL 60188.

[16] Giddings Machine Co., P.O. Drawer 2024, Ft. Collins, CO 80522.

biomass and distribution are highly variable in the field.

Statistical analysis. Analyses of variance (ANOVA)[17] were conducted using SPSS/PC+ statistical analysis software[18]. Means or log-transformed means (not presented) were separated by Fisher's protected least significant difference (LSD) test ($P = 0.05$) if overall F values were significant. Data were not combined over trials or over years because rainfall varied dramatically both within and between growing seasons. Thus, each trial had a unique environmental history (Figure 1). The ANOVA assumption of independence of observations ignores the likelihood that several consecutive years of drought influenced root growth of this perennial weed and its response to herbicides, as shown in previous research (3, 5, 6, 7, 17).

RESULTS AND DISCUSSION

Untreated check plots. In untreated check plots in yr 2, there were 1200 ± 330 (mean ± standard error) and 710 ± 420 adventitious root buds per m^3 in Trials 1 and 2, respectively, measured to a depth of 50 cm (Figures 2 and 3). These estimates are of the same magnitude as a previous estimate (3) in reduced-till spring wheat, but somewhat less than those of another study (5) in no-till spring wheat. Numbers of adventitious root buds in untreated check plots (Figures 2 and 3) changed differently over time than did shoot density (7). Shoot density changes were related to the difference between growing season rainfall during the previous year and the 30-yr average precipitation for the same period (30-yr average = 32.7 cm between April and September) (7). Changes in numbers of adventitious root buds in untreated checks also were related to the difference between accumulative rainfall for the current growing season and the 30-yr average accumulated precipitation for the same period. In Trial 1, adventitious root buds peaked in year 4 before decreasing in year 5 (Figure 2). The latter half of year 4 and of all year 5 experienced drought (Figure 1). In Trial 2, adventitious root buds peaked in year 3 before decreasing in years 4 and 5 (Figure 3).

Treatment sequences common to both trials. In both trials, chlorsulfuron applied alone in wheat decreased root bud numbers below the untreated check in most years after year 2 (Figures 2 and 3). Fall-applied dicamba at 2.2 kg ha^{-1} followed by chlorsulfuron applied in wheat did not reduce numbers of adventitious root buds any more than chlorsulfuron alone. These results for chlorsulfuron alone in reduced tillage spring wheat verify results in no-till spring wheat (5). Although numbers of adventitious root buds in Trial 1 fell below the untreated check by the second season following treatment with fall-applied dicamba alone at 2.2 kg ha^{-1} for two years, adventitious root buds increased in subsequent years without herbicide retreatment. In contrast, dicamba applied alone at either rate for two consecutive falls in Trial 2 largely prevented Canada thistle adventitious root buds from increasing over five years without herbicide retreatment. Herbicide sequences reduced numbers of adventitious root buds over time in Trial 1 (Figure 2) and appeared to prevent adventitious root buds from forming over time in Trial 2 (Figure 3). Similar conclusions were drawn after studying data on root length (data not presented) and fresh weight per m^3 (Figures 4 and 5).

There are several reasons why herbicide treatments reduced numbers of adventitious root buds more in Trial 2 than in Trial 1 over five years (Figures 2 and 3). Root biomass was greater and adventitious root buds were more numerous in Trial 1 than in Trial 2 from the start. If better established roots are less susceptible to herbicides, this may explain how Canada thistle adventitious root buds increased in Trial 1 following some treatment sequences, but not in Trial 2 following the same treatment sequences. Summer drought the year before starting Trial 2 also may have reduced the ability of Canada thistle roots to form new adventitious root buds, as others have observed (17). Trial 2 also experienced more years of drought than Trial 1, especially toward year 5.

Treatment sequences unique to each trial. In Trial 1, 2,4-D applied alone in wheat at 560 g ha^{-1} for each of four years gradually reduced numbers of adventitious root buds to values achieved by chlorsulfuron applied alone (Figure 2). Dicamba at 1.7 or 2.2 kg ha^{-1} applied for the first two consecutive falls followed by 2,4-D at 560 g ha^{-1} applied in wheat for four years also gradually reduced adventitious root buds to densities comparable to those achieved with either chlorsulfuron or 2,4-D alone in wheat.

In Trial 2, numbers of adventitious root buds for all herbicide sequences were less than those of the untreated check in years 3 and 4 (Figure 3). The extent to

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[17] Abbreviations: ANOVA, analysis of variance.

[18] SPSS/PC+ ver. 4.0 software, SPSS Inc., 444 N. Michigan Ave., Chicago, IL 60611.

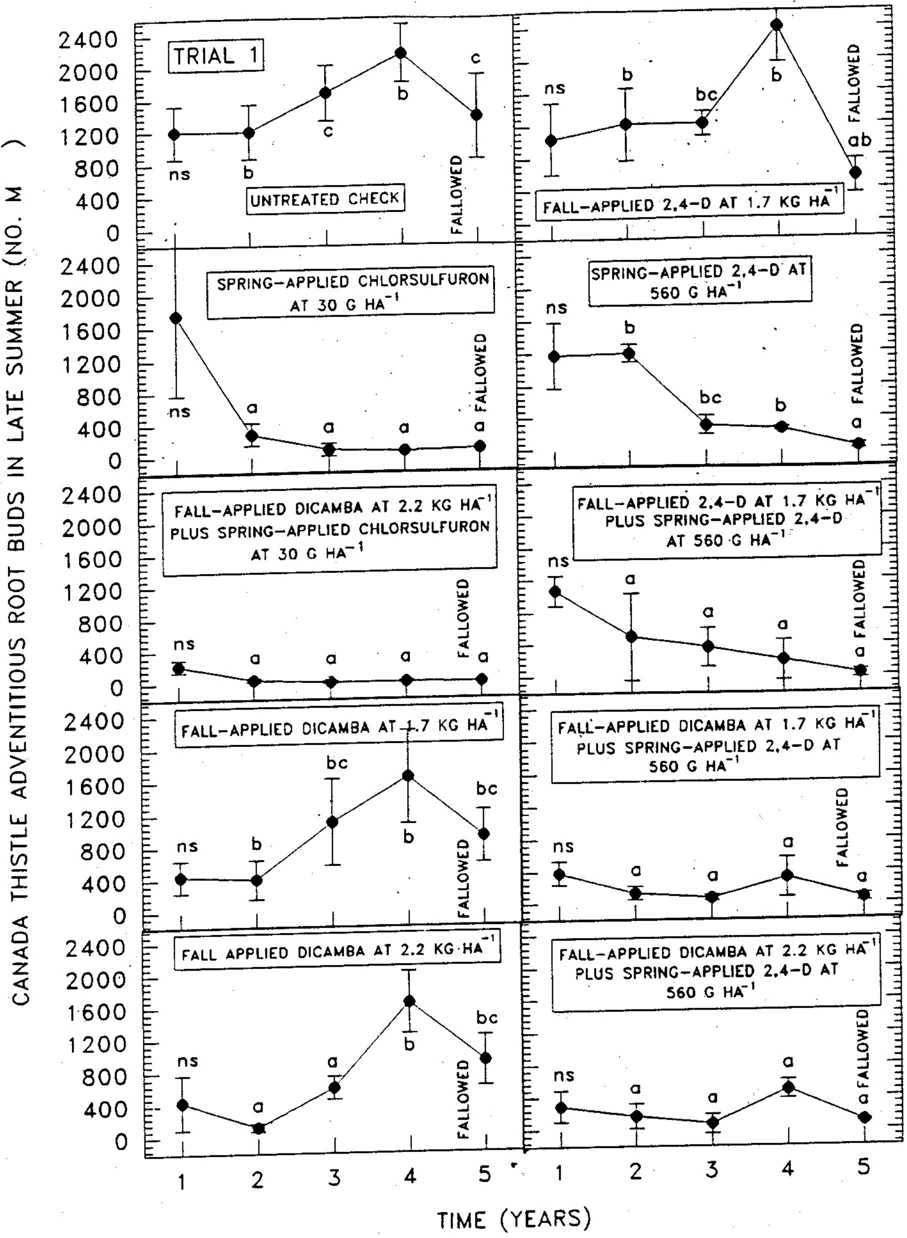

Figure 2. Numbers of adventitious root buds of Canada thistle in late summer after one to four years of repeated sequences of herbicide treatment in Trial 1. Wheat was grown in years 1 to 4 and the site was mechanically fallowed in year 5. Means ± standard errors are presented. Means within a year followed by the same letter were not different at P = 0.05 by the LSD test.

which several successive years of drought reduced root growth independently of herbicide treatment was difficult to estimate because adventitious root buds of untreated check plots also decreased during the latter half of Trial 2. By year 5, numbers of adventitious root buds from herbicide-treated plots in Trial 2 were no different than those of the untreated check plots following three years of drought.

Numbers of adventitious root buds per m^3 (Figures 2 and 3) generally responded in the same way to herbicide sequences from years 2 to 5 than both thickened root length (data not presented) and fresh weight per m^3 (Figures 4 and 5). These data verify that these three parameters respond similarly to herbicide treatment (3, 5). Sequences of either fall-applied dicamba or 2,4-D the first two falls followed by either chlorsul-

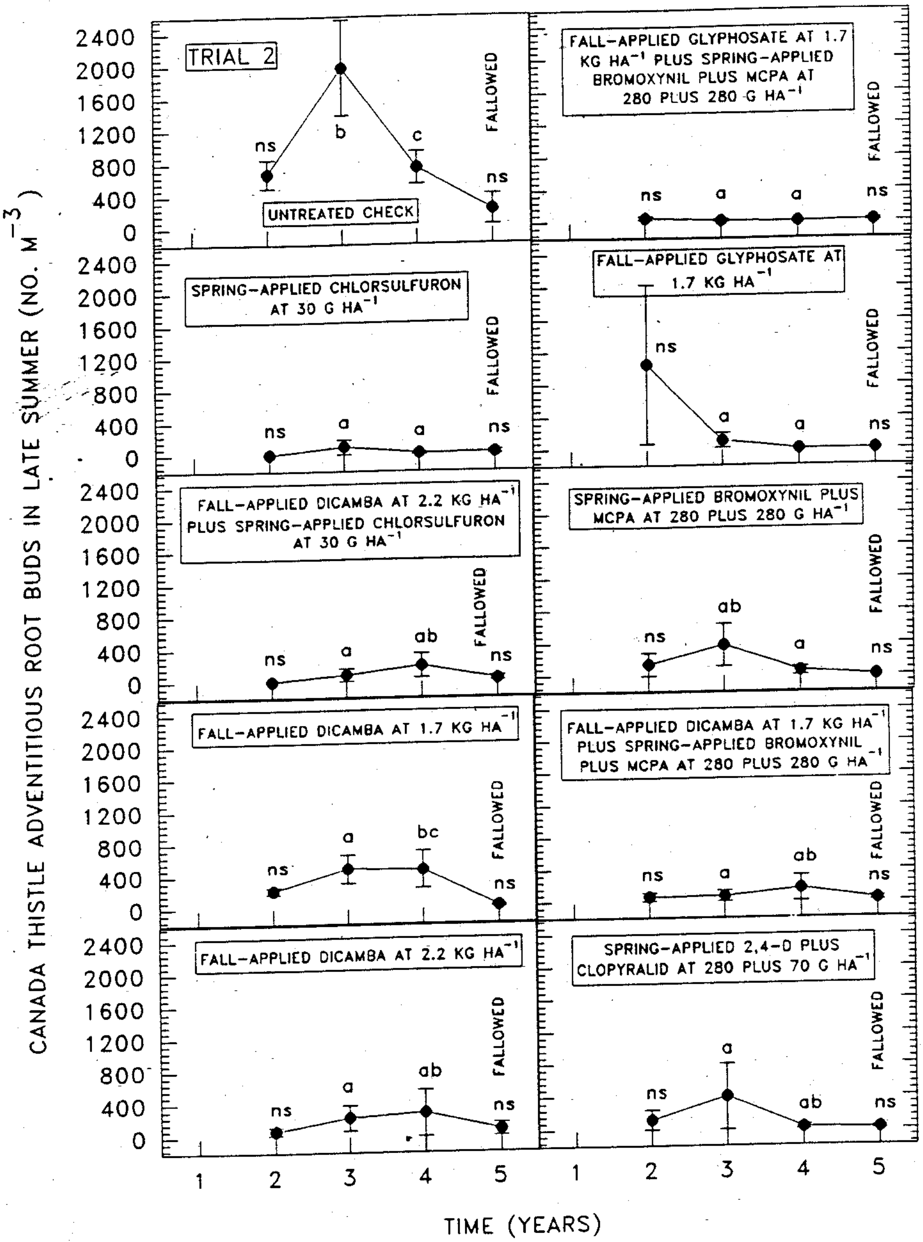

Figure 3. Numbers of adventitious root buds of Canada thistle in late summer after one to four years of repeated sequences of herbicide treatment in Trial 2. Wheat was grown in years 1 to 4 and the site was mechanically fallowed in year 5. Means ± standard errors are presented. Means within a year followed by the same letter were not different at P = 0.05 by the LSD test.

furon or 2,4-D applied in wheat for four years suppressed root growth in the long-term better than fall applied herbicides alone. In Trial 1, neither fall-applied dicamba nor 2,4-D at high rates alone for only the first two consecutive falls reduced long-term root growth (over five years) unless additional herbicide treatments were subsequently applied in spring wheat.

Despite extensive research on herbicide mode of action in annual plants, the reasons that herbicide treatment must extend over two to three years or more to successfully prevent further shoot emergence of Canada thistle, or other perennial weeds, remain obscure (4). This study and related research (3, 5) show that various herbicide treatments do not merely induce dormancy of

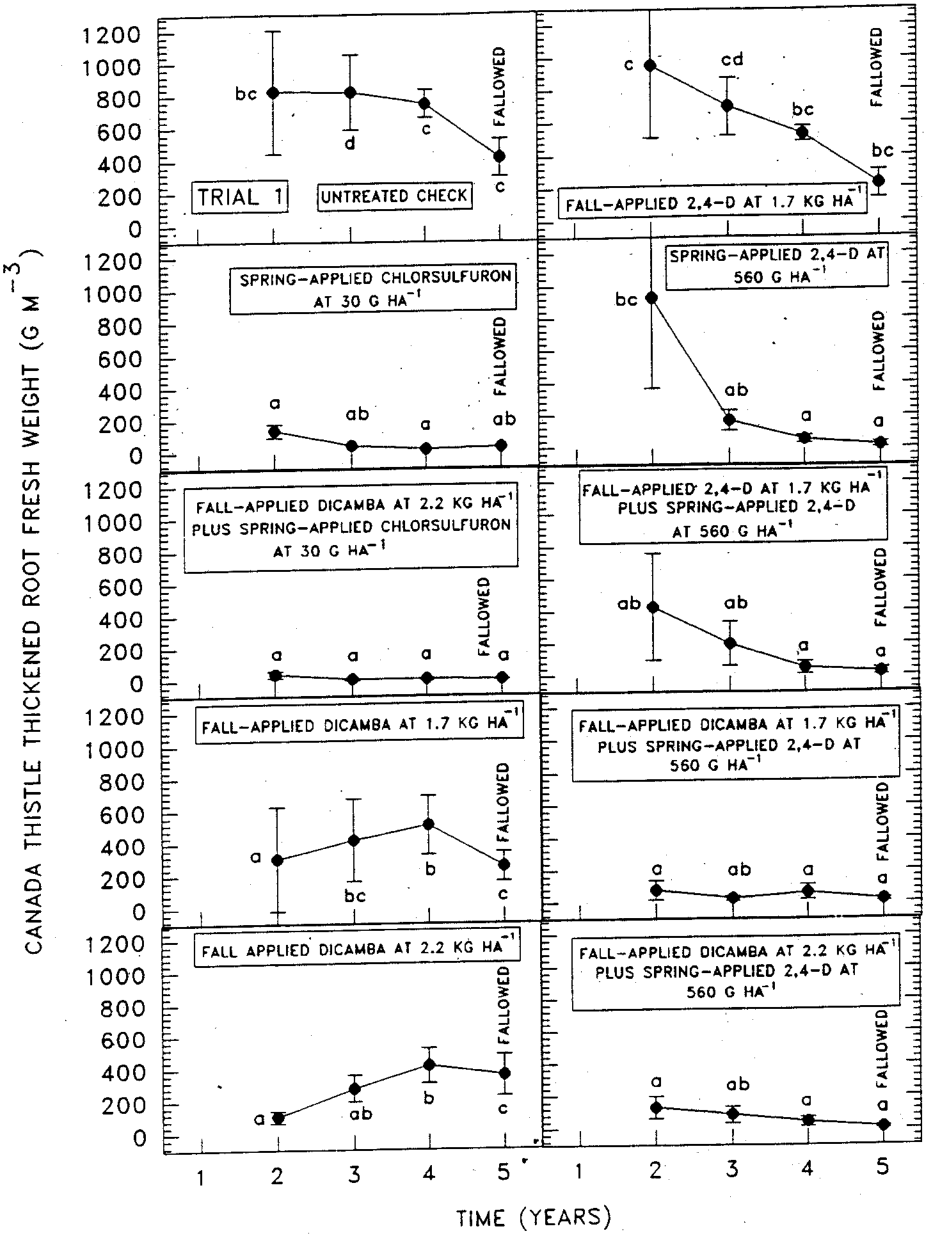

Figure 4. Thickened root fresh weight of Canada thistle in late summer after one to four years of repeated sequences of herbicide treatment in Trial 1. Wheat was grown in years 1 to 4 and the site was mechanically fallowed in year 5. Means ± standard errors are presented. Means within a year followed by the same letter were not different at P = 0.05 by the LSD test.

adventitious root buds for extended periods. Annual fall applications of nonselective herbicides and/or selective in-crop-applied herbicides severely reduced adventitious root bud numbers per m^3 (Figures 2 and 3), as well as both thickened root biomass per m^3 (Figures 4 and 5) and length per m^3 (data not presented) to a depth of 50 cm. Gradual decreases in root biomass over several years probably were caused by both root death and prevention of new root formation.

In 1952 Lee (15) stated, "no single treatment, regardless of practice, can be relied upon to produce complete kill [of Canada thistle]." Thirty years later in 1982, Strand (20) reaffirmed this opinion when he speculated that control programs for this weed required at least

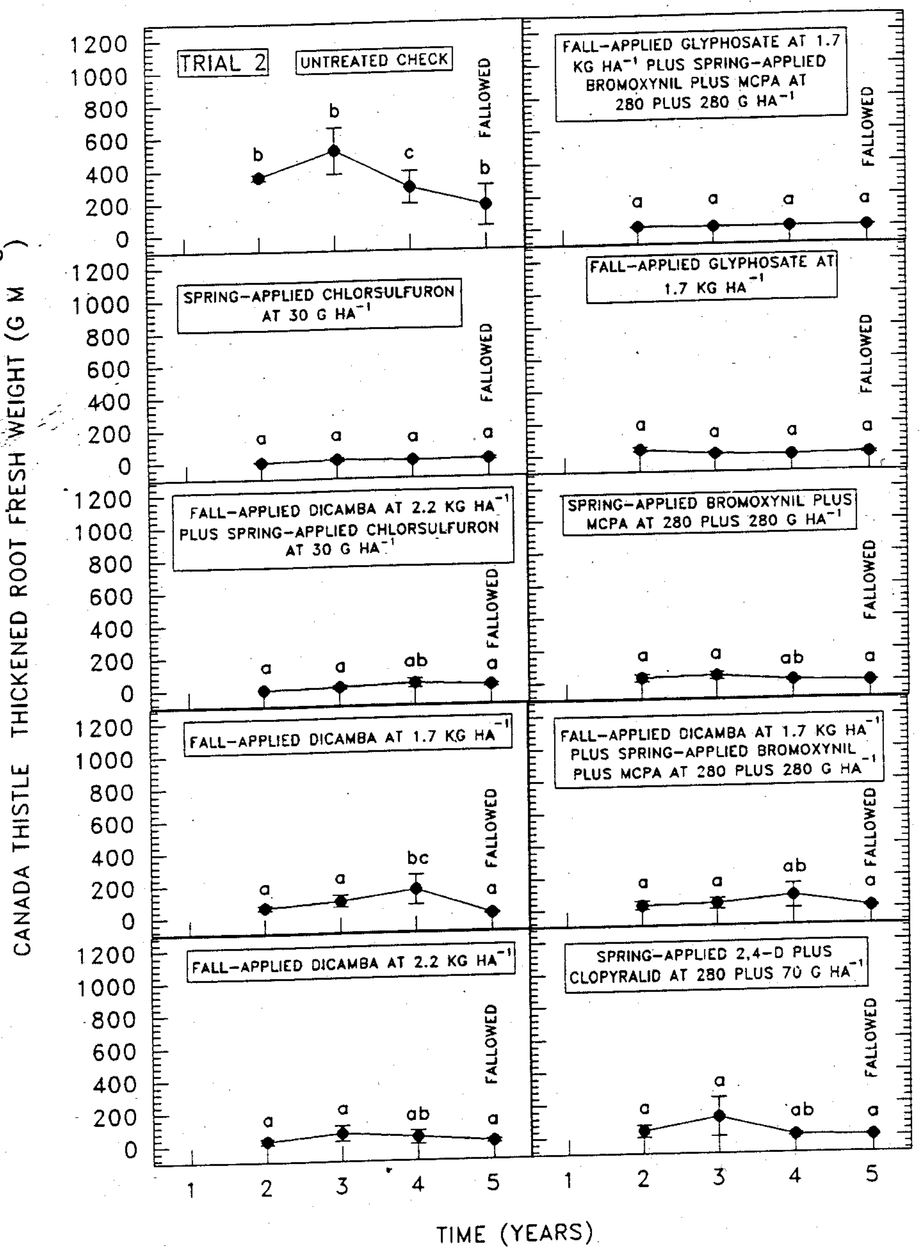

Figure 5. Thickened root fresh weight of Canada thistle in later summer after one to four years of repeated sequences of herbicide treatment in Trial 2. Wheat was grown in years 1 to 4 and the site was mechanically fallowed in year 5. Means ± standard errors are presented. Means within a year followed by the same letter were not different at $P = 0.05$ by the LSD test.

five to ten years of effort. This study (Figures 2 and 3 and Table 3) and previous research (3, 4, 5, 6, 7) supports the contention that several well calculated and timely operations are essential for successful results (20).

This research helps weed scientists better evaluate multi-year strategies for reducing Canada thistle infestations in spring wheat. It provides weed scientists with information on the limitations of multi-year strategies that incorporate fall-applied herbicides for reducing Canada thistle adventitious root buds and root systems. Several sequences of herbicides can be used to manage Canada thistle in reduced-till spring wheat, although dicamba or chlorsulfuron may limit rotational crop options. Certain herbicides, such as chlorsulfuron, applied in wheat for four years greatly decreased root biomass

(Figures 4 and 5), numbers of adventitious root buds (Tables 2 and 3), and shoot density (5, 6, 7) in 2 to 3 yr. However, rotation of sulfonylurea herbicides with other effective herbicide combinations, such as clopyralid plus 2,4-D, would be preferable to prevent the buildup of sulfonylurea herbicide-resistant annual weed populations.

Sequential measurements of shoot density over time is preferable to measuring root growth for documenting changes in herbicidal control of Canada thistle infestations over time. Shoot density can be measured more quickly and cheaply than root growth, and a larger proportion of the total treated area can be nondestructively sampled for shoot growth, leading to more accurate and precise statistics. However, information on the impact of herbicides on root biomass and adventitious root buds may have application in modelling Canada thistle population dynamics. The time-course data are consistent with the suggestion (3, 5) that drought can enhance the efficacy of repeated annual herbicide treatment for Canada thistle control, although this point was not proven in this research.

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