Fall-Applied Glyphosate for Canada Thistle (*Cirsium arvense*) Control in Spring Wheat (*Triticum aestivum*)[1,2]

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Abstract. Effects of repeated late-fall applications of the isopropylamine salt of glyphosate at 1.7 kg ae/ha plus 0.5% (v/v) surfactant[2] on adventitious root buds, thickened propagative roots (> 1.3 mm diam), and shoot density of Canada thistle were studied in continuous hard red spring wheat over a 4-yr period. Glyphosate suppressed Canada thistle shoot density more quickly and to a greater extent than thickened root fresh weight or root bud number. A single fall application of glyphosate drastically decreased Canada thistle shoot density for 1 yr after treatment. However, shoot density was the same as the untreated control by 2 yr after a single fall treatment. Two consecutive late-fall applications of glyphosate in 2 yr decreased Canada thistle shoot density 94% in the fall 1 yr after the last treatment. Glyphosate reduced Canada thistle thickened root fresh weight 70% in the first fall 1 yr after a single fall treatment. However, 2 yr after a single fall application of glyphosate, root fresh weight equalled the controls. Two consecutive fall applications of glyphosate reduced thickened root fresh weight 77% 1 yr after the second treatment. Nomenclature: Glyphosate, *N*-(phosphonomethyl)glycine; Canada thistle, *Cirsium arvense* (L.)Scop. #[4] CIRAR; hard red spring wheat, *Triticum aestivum* L.

Additional index words: Bromoxynil, MCPA, roots, root buds.

INTRODUCTION

Eradication of persistent underground roots should be the primary objective for long-term management of perennial weeds. However, little research has been conducted on the effects of herbicides on the underground propagation systems of perennial weeds because this research is time consuming and laborious. Only two studies of the effect of herbicides on Canada thistle roots excavated from field soil have been published (19, 32).

Canada thistle is a perennial weed which has an extensive, spreading root system and propagates by adventitious root buds (1, 12, 14, 15, 16, 28). Root buds are immature shoots which form on Canada thistle roots larger than 1.3 mm diam (13). The root buds form new (secondary, regrowth, or daughter) shoots after they elongate and emerge from the soil (1, 12, 14, 15, 16, 28). Glyphosate is a foliar-applied herbicide which is translocated to the perennial root system of Canada thistle (11, 21, 30, 31). However, only one other published field study demonstrated that glyphosate reduced Canada thistle root biomass 1 yr after treatment (19). It was conducted at an untilled site with a sparse, artificially established Canada thistle stand which was not cropped.

No published field studies exist on the effects of fall glyphosate treatment for more than 1 yr or the effects of sequential fall applications of glyphosate on the Canada thistle root system. Several preliminary research reports of regional weed control conferences document that glyphosate controls Canada thistle shoots over one growing season. However, none reported on the effectiveness of sequential fall glyphosate treatments in consecutive years on Canada thistle control, shoot density, and root biomass.

The objectives of the present research were to determine the effect of a single fall application and two sequential fall applications of glyphosate on Canada thistle shoot number, thickened root fresh weight, and adventitious root bud number and to describe procedural problems and methods involved in sampling Canada thistle roots in the field as well as the variability in measured shoot and root parameters.

MATERIALS AND METHODS

The six treatments studied are presented in Table 1. Glyphosate was applied at 1.7 kg/ha plus 0.5% (v/v) surfactant in the late fall after wheat harvest when new Canada thistle shoots had emerged (Table 2).

[1] Received for publication Nov. 16, 1987, and in revised form July 11, 1988. Published with the approval of the director, Agric. Exp. Stn., N. D. State Univ. as J. Art. No. 1681.

[2] Surfactant was Ortho X-77® spreader (Principal agent: alkylarylpolyoxyethylene glycols, free fatty acids, and isopropanol; 90%). Mention of a trademark or proprietary product does not constitute a guarantee or warranty 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.

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[4] Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds, Weed Sci. 32, Suppl. 2. Available from WSSA, 309 W. Clark St., Champaign, IL 61820.

Table 1. The six herbicide treatments used for control of Canada thistle in continuous spring wheat.

Treatment abbreviation	Year 1		Year 2	
	Fall[a]	Spring[b]	Fall[a]	Spring[b]
	(Herbicide treatment)			
Control	. . .	. . .	. . .	. . .
B/M	. . .	Bromoxynil + MCPA	. . .	Bromoxynil + MCPA
1 Glyph	Glyphosate	. . .	. . .	. . .
1 Glyph + B/M	Glyphosate	Bromoxynil + MCPA	. . .	Bromoxynil + MCPA
2 Glyph	Glyphosate	. . .	Glyphosate	. . .
2 Glyph + B/M	Glyphosate	Bromoxynil + MCPA	Glyphosate	Bromoxynil + MCPA

[a]Glyphosate was applied at 1.7 kg/ha plus X-77 surfactant at 0.5% (v/v) in the fall after wheat harvest.

[b]Bromoxynil plus MCPA were applied in spring wheat as a tank mix at 0.3 kg/ha each.

Table 2. The dates on which repeated field operations were performed for Trials 1 and 2.

Event	Trial 1					Trial 2			
	1982	1983	1984	1985	1986	1983	1984	1985	1986
	(Date)								
Fertilizer applied		5/3	4/23	4/23	5/15		4/23	4/23	5/15
Field cultivation		5/6	4/25	5/21	5/14		4/25	5/21	5/14
Wheat planted		5/6	4/30	5/21	5/15		4/30	5/22	5/15
Soil cores taken		6/1–6/17	5/24–6/11	. . .	. . .		5/24–6/11	. . .	. . .
Shoot density determined		6/17	6/12	6/13	6/6		6/12	6/13	6/6
Bromoxynil plus MCPA applied		6/17	6/13	6/10	6/5		6/13	6/10	6/5
Diclofop applied		6/25	6/18	6/20	6/16		6/18	6/20	6/16
Wheat harvest		8/9	8/16	8/22	8/21		8/16	8/22	8/21
Soil cores taken		8/29–9/14	8/21–8/23	. . .	. . .	8/21–9/14	8/21–8/23	9/12–9/16	. . .
Shoot density determined and visual rating		10/5	9/29	9/26	8/13	10/5	9/29	9/26	8/15
Glyphosate applied	9/3	10/8	. . .	. . .	. . .	10/8	9/29	. . .	. . .
Chisel plowed	10/31	10/29	10/15	10/17	. . .	10/29	10/15	10/17	. . .

No rain fell within 2 days after any glyphosate application (Table 3). The soil was chisel plowed 13 cm deep with 5 cm-wide chisel points spaced 30 cm apart in the fall at least 16 days after glyphosate application, except for Trial 1 in the fall of 1982 in which half of the treatments were moldboard plowed 20 cm deep (Table 2). Individual plots were chisel plowed and field cultivated lengthwise so that Canada thistle roots were not spread between adjacent plots.

Because large differences in Canada thistle shoot density developed between treatments over time, borders between glyphosate-treated and control plots appeared sharp. Glyphosate-injured plants were not found outisde treated plots in the present study. Chisel plowing disrupted Canada thistle roots and may have limited long-distance herbicide translocation. The octanoic acid ester of bromoxynil (3, 5-dibromo-4-hydroxybenzonitrile) plus the butoxyethyl ester of MCPA [(4-chloro-2-methylphenoxy)acetic acid] premix[5] was applied at 0.3 kg ai/ha plus 0.3 kg ae/ha, respectively, each spring in the wheat crop to control annual broadleaf weeds (Tables 2 and 3). Because bromoxynil plus MCPA suppresses Canada thistle shoot growth, the premix[5] was included as a treatment.

This field experiment was arranged as a randomized complete block design and was repeated on a nearby site. Trial 1 of the experiment was conducted from the fall of 1982 to the fall of 1986, and Trial 2 was conducted from the fall of 1983 to the fall of 1986.

[5]Brominal 3+3® produced by Union Carbide Corp., P. O. Box 12014, Research Triangle Park, NC 27709.

Table 3. Spray parameters and environmental conditions at the time of herbicide application.

Parameters	Glyphosate[a]			Bromoxynil plus MCPA		
	1982	1983	1984	1983	1984	1985
Date applied	9/3	10/8	9/29	6/17	6/13	6/10
Rate (kg/ha)	1.7	1.7	1.7	0.3 + 0.3	0.3 + 0.3	0.3 + 0.3
Carrier volume (L/ha)	93	93	93	131	146	66
Pressure (kPa)	138	138	138	138	138	138
Nozzle size[b]	8002	8002	8002	8002	8003	8001
Ground speed (km/h)	6.4	6.4	6.4	4.8	6.4	4.8
Relative humidity at spraying (%)	60	73	30	60	75	80
Temperature at spraying (C)	21	14	15	21	22	20
Time before first precipitation (days)	8	2	7	1	1	0
Amount of first precipitation (cm)	0.03	0.02	0.15	0.22	0.04	0.10

[a]Additive = Ortho X-77 spreader (Principal agent: alkylarylpolyoxyethylene glycols, free fatty acids, and isopropanol; 90%) at 0.5% (v/v).

[b]Teejet flat fan nozzles were from Spray Systems Company, Wheaton, IL 60187.

Trial 1 had three blocks, and Trial 2 had four blocks. Blocking was based on initial Canada thistle shoot density. Dense natural stands of Canada thistle were used rather than circular patches or artificially established stands. Trials 1 and 2 had 37 ± 13 (mean ± standard deviation) Canada thistle shoots m^{-2} before the experiment was started. Canada thistle subspecies *'arvense'* and *'vestitum'* (Wimm. and Grab.) (23) were present in Trial 1, but only *'arvense'* was present in Trial 2.

Trial 1 was designed to compare two tillage treatments as well as the six herbicide treatments (Table 1). However, the tillage comparison was terminated after the fall of 1982. Because the initial tillage differences did not influence the herbicide treatment means in the statistical analysis, tillage was disregarded, and the six herbicide treatments were placed randomly twice in each block for 12 plots per block in Trial 1.

The experimental sites were on the North Dakota State University experimental farm, Fargo, on a Fargo silty clay (fine, montmorillonitric, frigid Vertic Hapliquolls) with 2.5% sand, 51.7% silt, 45.8% clay, 4.5% organic matter, and a pH of 7.9. The sites were not tilled or cropped for at least 2 yr before the experiment was initiated. Enough urea nitrogen was applied for a 2360-kg/ha wheat yield goal as recommended from soil tests conducted by North Dakota State University. No other mineral nutrients were recommended.

The soil was field cultivated and was harrowed for seedbed preparation each spring before planting semidwarf 'Olaf' hard red spring wheat in 1983 and the genetically related semidwarf variety 'Len' in 1984 with a double disk grain drill[6], at 73 kg/ha in rows spaced 17.5 cm apart (Table 2). Len spring wheat was planted at 84 kg/ha at the same row spacing in 1985 and 1986 with a no-till grain drill[7] at the same row spacing. Diclofop {(±)-2[4-(2,4-dichlorophenoxy) phenoxy] propanoic acid} at 1.1 kg ai/ha was applied each spring to control annual grasses (Table 2). Wheat yield data are not presented because birds and rodents severely damaged the wheat before harvest.

Canada thistle shoot density was obtained from six 0.25-m^2 quadrats/plot except in Trial 1 in the fall of 1985 where six 0.5-m^2 quadrats were used (Table 2). Each plot was divided equally into six subareas. One quadrat was placed randomly in each subarea at least 0.6 m from the plot borders. Control of Canada thistle shoots also was evaluated visually on a scale of 0 (no control) to 100 (complete control).

Thickened Canada thistle roots (⩾ 1.3 mm diam) that are responsible for vegetative propagation of Canada thistle shoots from adventitious root buds (13, 25, 27) were gathered by taking soil cores from each plot (Table 2) (3). Small lateral roots and elongating, unthickened portions of primary roots do not form new shoots from root buds (27).

Soil cores were gathered in the spring and fall (Table 2) except in May, 1985, when it was too wet

[6]Nordsten double disk grain drill, DK-3400 Hilleroed, Denmark.

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

to sample. A manual bucket auger[8] was used to gather soil cores in the spring and fall of 1983. A hydraulically powered, tractor-mounted soil corer[9] was used to gather soil cores thereafter. The bucket auger retrieved an 8.8-cm diam soil core, and the tractor-mounted corer retrieved a 6.4-cm diam core. All cores were taken 50 cm deep. This depth was reported to include most of the root system. Nadeau and Vanden Born (24) found 65% of the Canada thistle root dry weight and 82% of the root buds in the top 40 cm of soil when sampling to a depth of 140 cm. Hodgson (15) found 84% of the root dry weight in the top 38 cm when sampling to a depth of 50 cm. Lauridson et al. (19) found between 69% and 70% of the root dry weight in the top 60 cm when sampling to a depth of 90 cm.

Soil cores were taken using stratified random sampling from the central part of each plot, 0.6 m from the edges. When the manual bucket auger was used, one or two cores were gathered at random after plots were subdivided into six equal subplots. When the tractor-mounted corer was used, three cores were gathered at random from each of four or five equal subplots. Six, 12, and 15 cores/plot were gathered in the spring of 1983, in the fall of 1983 through the fall of 1984, and in the fall of 1985, respectively. Three soil cores from the same plot were placed into plastic bags after sampling and were stored in darkness at 0 to 5 C until they were washed. Thickened roots from each plot were pooled for statistical analysis.

Thickened roots were washed from the soil with a seed washer (8), a root washer (3), or by hand over a 14-mesh screen. The root extraction efficiency (3) was the same regardless of extraction method because a 14-mesh screen was used for all extractions.

Root fresh weight and adventitious bud numbers were determined using the entire pooled root sample of each plot for all sampling dates. Roots were wrapped in paper rolls, were watered with deionized water, and were placed in a dark incubator at 20 C and 100% relative humidity for 3 weeks. The number of visible root buds which grew was recorded. The lactic acid method (22) used to visualize root buds was tried, but it did not clear roots adequately.

All shoot, root, and root bud data are expressed on a "per m^2" basis for normalization. Four to 6% of the area from each plot was sampled to estimate Canada thistle shoot density. Only 0.005 to 0.2% of each plot area could be sampled to estimate the thickened root biomass and root bud number. Because two corer sizes and three numbers of cores/plot were used at different times, results for root parameters could not be compared statistically at different times.

Analyses of variance were conducted, and means were separated with Fisher's protected least significant difference (LSD) (P=0.05). Data were not combined over years because differing environmental conditions and methodology for root parameters produced treatment by year interactions. Coefficients of variation (CVs) provide information regarding data variability not reported in two previous studies of herbicide effects on Canada thistle roots (19, 32).

RESULTS

Control plots. The density of Canada thistle shoots in control plots remained high from the spring of 1983 to the spring of 1984 in Trials 1 and 2 (Table 4). However, shoot density decreased dramatically in both trials by the fall of 1984 compared to the spring. This decrease was large, distinct, and obvious, although it is not statistically valid to make comparisons across years. From mid-June until Sept. 30 of 1984 only 5.2 cm of precipitation fell, which is 74% below the 30-yr average (Figure 1). Evidently, the

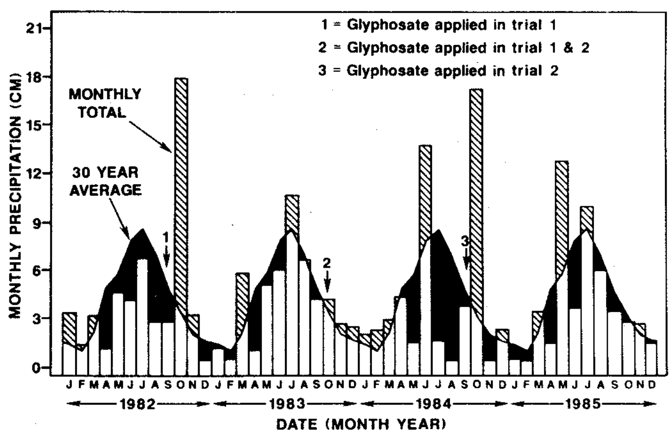

Figure 1. The monthly precipitation totals and the average monthly precipitation for the 4-yr period in which Trials 1 and 2 were conducted.

[8] JMC Professional Auger (PN070) for Clay, Clements Assoc. Inc., R.R. 1, Box 186, Newton, IA 50208.

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

Canada thistle root system was damaged by drought because after the drought very few shoots emerged in 1985 in Trial 2 (Table 4). Moisture stress can limit new shoot regrowth and emergence of Canada thistle (6, 9, 13), especially after prolonged drought (26).

The thickened root fresh weight of controls in both trials remained relatively high compared to the glyphosate treatments from the beginning of the experiment until the fall of 1984 (Table 5). However, in Trial 2, the thickened root fresh weight from control plots in the fall of 1985 was only 25% of that extracted in the fall of 1984, 1 yr earlier. Shoot density of controls decreased in both trials in the fall of 1984 (Table 4), yet thickened root fresh weight did not decrease until 1985 (Table 5, Trial 2). Both thickened root fresh weight and shoot density were reduced in 1985 following the drought in 1984.

A seasonal pattern in adventitious root bud number was observed in the controls (Table 6). More root buds were present in control plots each fall than in the spring. Although comparison of root bud parameters over time is not statistically valid, the seasonal pattern was dramatic and recurred in both trials. In the fall there were 2.9 and 5.1 times as many root buds in the control plots of Trial 1 as in the spring of 1983 and 1984, respectively. In Trial 2, 4.8 times more root buds grew in the fall as in the spring of 1984 in the control plots. Soil cores could not be taken in the spring of 1985 because the heavy clay soil was too moist to sample (Figure 1).

Fall-applied glyphosate. Glyphosate was registered in the U. S. at 1.7 kg/ha for fall treatment of Canada thistle when this research was initiated; however, registered rates have been lowered to 0.75 kg/ha. Following a single fall glyphosate treatment in 1982, Canada thistle shoot density decreased to only 11% and 18% of the density of control plots in the spring and fall of 1983, respectively (Table 4, Trial 1). However, shoot density in Trial 1 was suppressed only 59% in the second spring and did not differ from

Table 4. Canada thistle shoot density in the spring and fall as affected by glyphosate applied either in one fall or two sequential falls and a bromoxynil plus MCPA premix applied annually in spring.

	Canada thistle shoot density						
	1983		1984		1985		1986
Treatment[a]	Spring	Fall	Spring	Fall	Spring	Fall	Fall
	(no./m²)[b]						
Trial 1							
Control	56.5 (100)	65.1 (100)	54.7 (100)	9.9 (100)	18.1 (100)	7.6 (100)	15.0 (100)
B/M	49.2 (87)	54.5 (84)	39.5 (72)	5.7 (58)	13.7 (76)	1.9 (25)	5.0 (33)
1 Glyph	6.0 (11)	11.4 (18)	22.7 (41)	7.4 (75)	14.1 (78)	5.7 (75)	17.1 (114)
1 Glyph + B/M	7.6 (13)	12.0 (18)	28.3 (52)	5.2 (53)	13.6 (75)	2.5 (33)	4.4 (29)
2 Glyph	7.9 (14)	13.5 (21)	2.1 (4)	0.6 (6)	6.6 (36)	4.3 (57)	14.6 (97)
2 Glyph + B/M	12.9 (23)	15.9 (24)	2.7 (5)	0.5 (5)	2.8 (15)	0.8 (11)	2.1 (14)
LSD (0.05)	14.7	15.1	12.0	4.5	6.6	2.5	2.0
P>F	0.0001	0.0001	0.0001	0.0012	0.0024	0.0017	0.0001
CV (%)	53	45	41	80	48	53	55
Trial 2							
Control			55.6 (100)	8.0 (100)	2.4 (100)	4.8 (100)	8.7 (100)
B/M			50.7 (91)	9.8 (123)	5.8 (242)	3.9 (81)	2.7 (31)
1 Glyph			8.2 (15)	1.5 (19)	5.8 (242)	3.8 (79)	7.5 (86)
1 Glyph + B/M			6.9 (12)	0.2 (3)	14.3 (596)	2.3 (48)	1.0 (11)
2 Glyph			9.8 (18)	2.0 (25)	3.8 (158)	4.3 (90)	11.5 (132)
2 Glyph + B/M			7.8 (14)	0.4 (5)	15.7 (654)	1.5 (31)	3.2 (37)
LSD (0.05)			11.8	5.3	NS	NS	2.1
P>F			0.0001	0.0039	0.0622	0.6928	0.1979
CV (%)			34	97	86	96	94

[a]Control = no broadleaf herbicide; B/M = bromoxynil plus MCPA applied at 0.3 kg/ha each; Glyph = glyphosate applied either 1 or 2 falls at 1.7 kg/ha plus 0.5% X-77 surfactant.

[b]Value in parentheses is percent of the control.

control plots in the fall 2 yr after a single fall glyphosate treatment alone. Canada thistle shoot control in the second growing season after a single fall application was rated unacceptable. In Trial 2, Canada thistle shoot density was reduced to 15% of the control density in the first spring and to 19% by fall (1984) following a single fall glyphosate treatment. This reduction was similar to that observed in Trial 1 (Table 4). However, the shoot density in control plots had decreased in 1985 after drought, making it impossible to distinguish statistically between the treatments in Trial 2.

Glyphosate alone applied in each of two consecutive falls (1982 and 1983) continued to suppress Canada thistle shoot density adequately in Trial 1 throughout the third year (1984) (Table 4). However, in the spring and fall of 1985 and fall of 1986 (4 and 5 yr after the experiment began) Canada thistle densities were 36, 57, and 97% of the controls, respectively. Glyphosate applied alone for two consecutive falls controlled Canada thistle shoots for only one growing season after the second glyphosate treatment. Shoot densities gradually recovered after the second summer following the second glyphosate application.

In Trial 2, two consecutive applications of glyphosate alone were made in the fall of 1983 and 1984. However, lack of precipitation in the summer of 1984 (Figure 1) suppressed Canada thistle shoot emergence after wheat harvest, and fewer shoots were present to intercept the second fall glyphosate treatment in Trial 2 in 1984 than in Trial 1 in 1983 (Table 4). The drought reduced control plot densities so that differences between treatments could not be detected at subsequent observation times in Trial 2.

Canada thistle shoot density (Table 4) was suppressed by glyphosate more quickly and to a greater extent than was thickened root fresh weight (Table 5) in Trial 1. Suppression of thickened root fresh weight by glyphosate required one full year to be detected with the sampling procedure used in this experiment

Table 5. Thickened root fresh weight of Canada thistle in the spring and fall as affected by glyphosate applied in either one fall or two sequential falls and a bromoxynil plus MCPA premix applied annually in spring.

	Thickened root fresh weight					
	1983		1984		1985	
Treatment[a]	Spring	Fall	Spring	Fall	Spring	Fall
	(g/m²)[b]					
Trial 1						
Control	164 (100)	126 (100)	138 (100)	239 (100)		
B/M	158 (96)	68 (54)	116 (84)	199 (83)		
1 Glyph	89 (54)	38 (30)	98 (71)	165 (69)		
1 Glyph + B/M	134 (82)	35 (28)	74 (54)	160 (67)		
2 Glyph	98 (60)	50 (40)	43 (31)	54 (23)		
2 Glyph + B/M	116 (71)	32 (25)	30 (22)	65 (27)		
LSD (0.05)	NS	39	71	124		
P>F	0.5871	0.0002	0.0307	0.0294		
CV (%)	69	56	72	72		
Trial 2						
Control			113 (100)	270 (100)	...	67 (100)
B/M			222 (196)	190 (70)	...	120 (179)
1 Glyph			31 (27)	58 (21)	...	67 (100)
1 Glyph + B/M			56 (50)	90 (33)	...	32 (48)
2 Glyph			37 (33)	94 (35)	...	117 (175)
2 Glyph + B/M			61 (54)	19 (7)	...	72 (107)
LSD (0.05)			100	164	...	NS
P>F			0.0081	0.0500	...	0.8969
CV (%)			76	91	...	156

[a]Control = no broadleaf herbicide application; B/M = bromoxynil plus MCPA applied at 0.3 kg/ha each; Glyph = glyphosate applied either 1 or 2 falls at 1.7 kg/ha plus 0.5% X-77 surfactant.

[b]Value in parentheses is percent of the control.

Table 6. Adventitious root bud number of Canada thistle in the spring and fall as affected by glyphosate applied in either one fall or two sequential falls and a bromoxynil plus MCPA premix applied annually in the spring.

	Adventitious root bud number						
	1982	1983		1984		1985	
Treatment[a]	Fall	Spring	Fall	Spring	Fall	Spring	Fall
	(no./m²)[b]						
Trial 1							
Control	...	183 (100)	525 (100)	123 (100)	622 (100)		
B/M	...	55 (30)	297 (57)	37 (30)	337 (54)		
1 Glyph	...	83 (45)	219 (42)	155 (126)	164 (26)		
1 Glyph + B/M	...	110 (60)	183 (35)	64 (52)	181 (29)		
2 Glyph	...	128 (70)	192 (37)	50 (41)	112 (18)		
2 Glyph + B/M	...	110 (60)	133 (25)	5 (4)	121 (19)		
LSD (0.05)	...	NS	NS	NS	218		
P>F	...	0.7268	0.1297	0.1256	0.0003		
CV (%)		127	98	139	72		
Trial 2							
Control			336 (100)	62 (100)	298 (100)	...	83 (100)
B/M			254 (76)	110 (127)	311 (104)	...	176 (212)
1 Glyph			322 (96)	14 (23)	117 (39)	...	104 (125)
1 Glyph + B/M			295 (88)	34 (55)	65 (22)	...	67 (81)
2 Glyph			247 (74)	34 (55)	156 (52)	...	176 (212)
2 Glyph + B/M			308 (92)	48 (77)	220 (74)	...	150 (181)
LSD (0.05)			NS	NS	NS	...	NS
P>F			0.9180	0.3203	0.7493	...	0.9652
CV (%)			47	116	140	...	178

[a]Control = no broadleaf herbicide application; B/M = bromoxynil plus MCPA applied at 0.3 kg/ha each; Glyph = glyphosate applied either 1 or 2 falls at 1.7 kg/ha plus 0.5% X-77 surfactant.

[b]Value in parentheses is percent of the control.

(Table 5). No decrease was detected in the first spring after one glyphosate treatment in either trial, but root fresh weight was 30 and 21% of control fresh weight in the first fall 1 yr after a single fall treatment in Trials 1 and 2, respectively. However, the root system recovered by the second year after a single fall glyphosate application. Using either shoot density or thickened root biomass to measure herbicidal efficacy, a single fall treatment of glyphosate did not control Canada thistle adequately for more than one growing season.

Thickened root fresh weight was 23% of control values in the third fall (1984) in Trial 1 a year after the second fall application of glyphosate (Table 5). In Trial 2, glyphosate applied one or two consecutive falls did not suppress thickened root fresh weight in the third fall (1985) relative to the control plots.

Glyphosate applied in one or two falls reduced both adventitious root bud number (Table 6) and root bud length[10] in the third fall (1984) in Trial 1. Apparently, root bud number decreased after root biomass and shoot density were reduced in response to glyphosate. A decrease in the third fall (1985) in Trial 2 was not observed, probably because of drought. Glyphosate also may not have been translocated to the root system as well as in the previous year in Trial 2 or as in Trial 1 because moisture stress decreases basipetal translocation of glyphosate in Canada thistle (5, 20). Adventitious root bud numbers varied more than either shoot density or thickened root fresh weight per m^2 in either trial (see CVs in Tables 4 to 6).

Spring-applied bromoxynil plus MCPA. A premix of bromoxynil plus MCPA alone reduced Canada thistle shoot density only in the second spring (1984) in Trial 1 (Table 4) when shoot density was determined

[10]Carlson, S. J. 1986. Glyphosate efficacy and induced biological responses in Canada thistle (*Cirsium arvense*) shoots, roots, and adventitious buds. Ph.D. thesis. N. D. State Univ., Fargo.

before the premix was applied. Fall secondary shoots emerging after wheat harvest were suppressed in 1985 and 1986, after 4 and 5 yr of repeated in-crop treatment, respectively. Sequential repeated applications of the bromoxynil plus MCPA premix alone in spring wheat adequately controlled Canada thistle shoots but did not eradicate the roots as expected (Tables 4 and 5).

Canada thistle shoot density was reduced by fall-applied glyphosate to the same relative extent in the spring or fall of 1983 or 1984 and the spring of 1985 whether or not bromoxynil plus MCPA was applied in the crop (Table 4). However, the bromoxynil plus MCPA premix following one or two fall applications of glyphosate improved residual suppression of Canada thistle regrowth in the fall of 1985 and 1986 after 4 and 5 yr of repeated treatment above control achieved with glyphosate alone.

Bromoxynil plus MCPA reduced thickened root fresh weight of Canada thistle much less than did glyphosate when measured in the fall in Trial 1 (Table 5). The increase in root fresh weight in the first spring (1984) after the start of Trial 2 is probably an abberation due to sampling; while it is statistically real, it is probably not biologically important. Some suppression of root fresh weight by bromoxynil plus MCPA was observed in the first fall (1983) in Trial 1. However the suppression achieved by the first fall (1983) was lost by the following spring (1984) in Trial 1. The premix did not suppress additional root fresh weight when applied with either a single or a repeated glyphosate application compared to glyphosate alone.

The bromoxynil plus MCPA premix reduced root bud number but not root bud length[10] in the second fall of Trial 1, but not in Trial 2 (Table 6). Visually evaluated control of Canada thistle shoots at wheat harvest two growing seasons (1.5 yr) after the second glyphosate application was 98 and 91% when the bromoxynil plus MCPA premix was applied annually in the crop following two fall glyphosate treatments in Trials 1 and 2, respectively, in the falls of 1985 and 1986 (Table 7). However, shoot control was only 43 and 59% two growing seasons (1.5 yr) after the second glyphosate application without bromoxynil plus MCPA premix reapplication in Trials 1 and 2, respectively.

Evidently, glyphosate can suppress both Canada thistle shoot density (Table 4) and root biomass (Table 5), but an adequate quality of roots remained after treatment with glyphosate alone for one or two consecutive falls to allow Canada thistle shoots to emerge after two growing seasons (1.5 yr) unless annual in-crop treatments of the bromoxynil plus MCPA premix also were applied. When in-crop treatments of bromoxynil plus MCPA followed an initial fall application of glyphosate, control of Canada thistle shoots was excellent (Table 7).

Table 7. Visual rating of shoot control of Canada thistle in the spring and fall as affected by glyphosate applied in either one fall or two sequential falls and a bromoxynil plus MCPA premix applied annually in spring.

	Canada thistle control		
	1985		1986
Treatment[a]	Spring	Fall	Fall
	(%)[b]		
Trial 1			
Control	0	0	0
B/M	83	95	94
1 Glyph	0	29	8
1 Glyph + B/M	83	98	93
2 Glyph	13	43	18
2 Glyph + B/M	88	98	88
LSD (0.05)	17.9	30.7	19.6
P>F	0.0001	0.0002	0.0001
CV (%)	33	42	32
Trial 2			
Control	0	0	0
B/M	71	71	95
1 Glyph	35	43	25
1 Glyph + B/M	61	94	99
2 Glyph	20	70	59
2 Glyph + B/M	39	96	91
LSD (0.05)	61.7	52.1	43.5
P>F	NS	0.0294	0.0031
CV (%)	109	56	47

[a]Control = no broadleaf herbicide application; B/M = bromoxynil plus MCPA applied at 0.3 kg/ha each; Glyph = Glyphosate applied either 1 or 2 falls at 1.7 kg/ha plus 0.5% X-77 surfactant.

[b]Value in parentheses is percent of the control.

DISCUSSION

The decrease in Canada thistle shoot density (Table 4), root biomass (Table 5), and adventitious root buds (Table 6) in control plots following a drought in 1984 (Figure 1) showed that drought controlled shoots and roots significantly. However, shoot density was reduced by the fall following a drought in Trials 1 and 2, whereas root biomass and adventitious root buds decreased only 1 yr later in Trial 2.

There are several potential reasons why the 1984 drought reduced the number of plants on control plots by fall. Low humidity and soil moisture may have suppressed adventitious root bud elongation even after parent shoots were cut at harvest (13, 17). The clay soil became hard due to lack of moisture and may have physically rduced successful secondary shoot emergence after wheat harvest in the fall of 1984. Why drought did not reduce root biomass at the same time as shoot density in Trial 2 is unknown. Perhaps drought predisposed Canada thistle roots to die and to decay over winter. The winter of 1984 to 1985 following the 1984 drought was severe; the average air temperature was −13.1 C from December, 1984, through February, 1985. The depth of soil freezing is likely to have been greater than average since air temperature was quite low (18). Average depths of freezing at Fargo are 137 cm on moldbord plowed land in winter.

Rogers (29) found that Canada thistle root buds, which elongated in the fall, died over winter and in the following spring. Root buds were more susceptible to cold conditions than were roots (29). Root bud death in winter may explain why fewer buds were found in the spring of 1985 than in the fall of 1984 in Trial 2 in the control plots (Table 6). McAllister and Haderlie (20) found no seasonal fluctuations in root bud number per cm root length when roots were excavated from an undisturbed, uncropped field over the course of a year. Their research (20) was conducted in a nontilled, noncropped area whereas the present research site was both fall chisel plowed and was planted to spring wheat. In this study, a seasonal pattern was not observed for thickened root fresh weight (Table 5) or thickened root length[10].

Canada thistle shoot density in North Dakota grain fields surveyed after herbicide application (7) was less than the density observed at the start of ths study, 37 ± 13 (mean ± standard deviation) plants m^{-2}. The mean Canada thistle shoot density in infested wheat in North Dakota was 2.9 plants m^{-2}, ranging from 0.2 to 23 plants m^{-2} (7). The density observed in this experiment is typical of that found in the center of well-established Canada thistle patches. Canada thistle is highly competitive with wheat. While only 2.4 plants m^{-2} reduced wheat yield about 15% (10, 15, 16), densities of 30 plants m^{-2} reduced yields 60% (10) or 70% (15, 16). Consequently, control strategies must succeed in reducing Canada thistle densities to at least 1 plant m^{-2} or less to minimize or to prevent spring wheat yield losses.

In both trials, a single fall treatment with glyphosate alone failed to control Canada thistle shoots in the second or subsequent growing seasions after treatment (Table 4). Glyphosate applied alone for two consecutive falls did not control shoots adequately two growing seasons (1.5 years) after the last treatment. When such a treatment was followed by bromoxynil plus MCPA applied in spring wheat, visually rated control was good (≥85%) (Table 7). Even when fall application conditions were good in Trial 1, glyphosate applied in two consecutive falls did not eradicate Canada thistle roots (Tables 5 and 6).

Any strategy for control of Canada thistle which requires repeated treatments of relatively expensive herbicides, such as glyphosate, over several years for lasting control of roots likely will fail because climatic conditions can fluctuate drastically from year to year as they did in this research (Figure 1). The effects of drought on Canada thistle control in Trial 2 highlights this limitation of such a control strategy. Drought-induced reductions of shoot density in control plots apparently masked any further shoot suppression following the two sequential fall applications of glyphosate in Trial 2 (Table 4).

Fall-applied glyphosate reduced shoot density (Table 4) more quickly and to a greater degree than thickened root biomass or root bud numbers (Tables 5 and 6). Perhaps the sharp decrease observed in the number of emerged shoots resulted from both a decrease in root biomass and some internal inhibitory mechanism which prevented existing root buds from elongating to form emerged regrowth or secondary shoots (13). Also, low concentrations of glyphosate in roots may have inhibited root bud outgrowth either directly or indirectly.

The thickened root fragments recovered from glyphosate-treated plots appeared healthy in this field research. However, in greenhouse studies, cortical tissue of well-developed, thickened roots decomposed within 45 days after foliar treatment with 1.1 kg/ha glyphosate (4). Only a thin vascular strand was left intact. The Canada thistle root system in the field may have been fragmented before glyphosate application due to soil cracking or to the innate tendency of Canada thistle to fragment (2). Root fragments without emerged shoots whould not be exposed to glyphosate in the fall after harvest and would have survived to send up new shoots.

In the past, visual estimates of control of shoot density or biomass were used to estimate control or suppression of Canada thistle even though this perennial weed propagates vegetatively by root growth and root buds. Herbicide-induced decreases of shoot density overestimated control of the Canada thistle root system. Fall-applied glyphosate reduced the shoot density of heavy stands of Canada thistle more quickly than the root system. Adequate root biomass remained to reinfest the site in subsequent years even after two consecutive fall applications of glyphosate alone. However, fall-applied glyphosate might be more effective and might control younger or sparser stands of Canada thistle longer.

It might be more economical to suppress dense stands or patches of Canada thistle by applying glyphosate in a single fall followed by repeated in-crop herbicide treatments over several years in spring wheat or other crops until Canada thistle shoots no longer emerge. A single fall-applied glyphosate treatment will not provide long-term control but should suppress Canada thistle shoot regrowth for most of the growing season following treatment even for dense stands, but only if plants are not drought stressed at the time of fall glyphosate treatment.

More studies are needed to determine if Canada thistle shoot suppression would continue with repeated yearly in-crop herbicide applications after initial fall glyphosate treatment and whether such treatments would reduce or would eradicate roots over a period of years. Comparison of the bromoxynil plus MCPA premix with other in-crop herbicides, such as 2,4-D [(2,4-dichlorophenoxy)acetic acid], dicamba (3,6-dichloro-2-methoxybenzoic acid), metsulfuron {2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)aminocarbonyl]amino]sulfonyl]benzoic acid}, chlorsulfuron {2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzenesulfonamide}, and clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) are needed to determine which treatment most quickly reduces Canada thistle roots while suppressing shoots in the year of treatment.

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