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Efficacy and Economics of Herbicides for Canada Thistle (*Cirsium arvense*) Control in No-till Spring Wheat (*Triticum aestivum*)[1]

WILLIAM W. DONALD and TONY PRATO[2]

Abstract. The objective of this field research was to compare relative effectiveness and profitability of alternative herbicides applied to the same plots for four consecutive years for controlling and reducing dense Canada thistle infestations in no-till spring wheat. Chlorsulfuron at 30 g ai ha^{-1} plus nonionic surfactant or clopyralid plus 2,4-D at 70 plus 280 g ae ha^{-1}, respectively, applied annually for 4 yr controlled Canada thistle and was more effective for gradually reducing Canada thistle stands than 2,4-D at 560 g ae ha^{-1}, MCPA plus bromoxynil at 280 plus 280 g ae ha^{-1}, or tribenuron at 20 g ai ha^{-1}. Chlorsulfuron and clopyralid plus 2,4-D also controlled Canada thistle ≥ 90% earlier (by 2 yr) than other treatments. Stochastic dominance analysis, a form of economic analysis, predicted that either chlorsulfuron or clopyralid plus 2,4-D would be preferred by farmers to the untreated check, MCPA plus bromoxynil, or 2,4-D treatments. Chlorsulfuron also would be preferred to clopyralid plus 2,4-D by risk-neutral farmers, whereas clopyralid plus 2,4-D would be preferred to chlorsulfuron by highly risk-averse farmers, those who are most likely to pick only consistently effective herbicides. Nomenclature: Bromoxynil, 3,5-dibromo-4-hydroxybenzonitrile; chlorsulfuron, 2-chloro-*N*-[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]benzenesulfonamide; clopyralid, 3,6-dichloro-2-pyridinecarboxylic acid; tribenuron, methyl 2-[[[[*N*-(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methyl-amino]carbonyl]-amino]sulfonyl]benzoate; MCPA, (4-chloro-2-methylphenoxy)acetic acid; 2,4-D, (2,4-dichlorophenoxy)acetic acid; Canada thistle, *Cirsium arvense* (L.) Scop. #[3] CIRAR; wheat, *Triticum aestivum* L.
Additional index words. Adventitious root bud, perennial weed, root, zero tillage, CIRAR.

INTRODUCTION

Canada thistle is a perennial weed with an extensive spreading root system (2, 12, 14, 29). Seed production and seedling emergence are important for establishment of new Canada thistle patches, but adventitious root bud formation on the expanding root system contributes more to patch growth and weediness. The life history and biology of Canada thistle have been summarized (6, 13, 14, 15, 16).

Integrated control programs for Canada thistle have been proposed which likely would require 5 to 10 yr of effort if implemented by farmers (10, 20, 31). Control measures need to be repeated in a timely fashion to be effective. Recently, Canada thistle control using nonchemical crop management and herbicides has been reviewed (8). There are few published studies of the effects of repeated annual herbicide treatment on Canada thistle control over time (8).

Farmers' preferences for herbicides can be evaluated three major ways. First, preferences can be based on average financial return; the herbicide having the highest average return is preferred. Unfortunately, this approach can be misleading because variation in return is ignored. For example, if herbicide A has a higher average return but a greater variance of return than herbicide B, then a risk-averse farmer may prefer B to A.

The second approach for evaluating farmer preferences for herbicides is the expected value or mean-variance approach. This approach overcomes the weakness of the first approach by considering both the mean and variance of return. A farmer is assumed to maximize the expected utility of profit. If $U(p_i)$ is the utility or satisfaction associated with profit level i and r^i is the probability of earning a profit of p_i for a particular herbicide, then the expected utility of profit for that herbicide is: $E(p_i) = \sum_i r_i * U(p_i)$ where $\sum_i r_i = 1$. If the utility of profit exhibits constant absolute risk aversion, maximizing expected utility of profit is equivalent to maximizing the expression: $(E(p) - h\ \mathrm{var}(p)$, where $E(p)$ is expected profit or expected net return, var(p) is the variance of the profit, and h is the absolute risk aversion coefficient (11, 22, 24) which differs according to farmers' risk preferences (25). With the mean-variance approach, farmers' preferences for herbicides are evaluated by substituting the respective profit means, profit variances, and risk aversion coefficients into the above expression. Then, preferences for different herbicides can be ranked according to the expected utility of profit. A major weakness of the mean-variance approach is that it imposes somewhat arbitrary restrictions on the shape of the utility of profit (26).

The third approach is stochastic dominance with respect to a function (SDWF)[4] (17, 18, 35). This approach involves

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[2]Res. Agron., Cropping Syst. Water Quality Res. Unit, Agric. Res. Serv., U. S. Dep. Agric., formerly of Agric. Res. Serv. Biosciences Res. Lab., and Dep. Crop and Weed Sci., North Dakota State Univ., Fargo, ND 58105; and Prof., Dep. Agric. Econ., Univ. Missouri, Columbia, MO 65211. Senior author's current address: 244 Agric. Engr., Univ. Missouri, Columbia, MO 65211.

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

[4]Abbreviations: ANOVA = analysis of variance; LSD = least significant difference; NS = nonsignificant; SDWF = stochastic dominance with respect to a function.

pairwise comparisons of the cumulative net return probability distributions for a particular set of alternative treatments. SDWF is an especially attractive form of stochastic dominance because it provides more discrimination between efficient and inefficient choices than first-degree and second-degree stochastic dominance (35). SDWF ranks risky alternatives for decision makers having risk preferences that fall within an interval defined by upper and lower risk aversion coefficients (35).

The objectives of this experiment were to: 1) determine the relative efficacy of five POST broadleaf herbicides for Canada thistle control in no-till spring wheat when applied annually to the same plots each year for 4 yr; 2) determine how quickly repeated annual treatment with these five herbicides over 4 yr reduced Canada thistle shoot density; and 3) determine whether repeated herbicide treatment was a profitable strategy for decreasing Canada thistle infestations in no-till spring wheat.

MATERIALS AND METHODS

Treatments. The six herbicide treatments for Canada thistle control were: an untreated check; the octanoic ester of bromoxynil plus the butoxyethyl ester of MCPA premix at 280 g ai ha^{-1} plus 280 g ha^{-1}, respectively; the alkanolamine salt formulation of 2,4-D at 560 g ha^{-1}; the alkanolamine salt formulation (of the ethanol and isopropanol series) of clopyralid plus 2,4-D premix at 70 g ha^{-1} plus 280 g ha^{-1}, respectively; chlorsulfuron at 30 g ai ha^{-1} plus nonionic surfactant[5] at 0.25% by volume; and tribenuron at 20 g ai ha^{-1} plus nonionic surfactant[5] at 0.25% by volume. These treatments were applied to the same plots for 4 yr.

This field experiment was arranged as a randomized complete block design with three blocks and was repeated on a nearby site (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 initial Canada thistle shoot density in natural stands of Canada thistle. The Canada thistle subspecies '*arvense*' (Wimm. and Grab.) (21) was present in both trials. Individual plots measured 3.3 by 13.2 m in trial 1 and 3.3 by 7 m in trial 2.

Each trial was conducted for 4 yr 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 at Fargo, on a Fargo silty clay (fine, montmorillonitic, frigid Vertic Haplaquolls) with 2% sand, 47% silt, 51% clay, 3.9% organic matter, and a pH of 7.7. Dates of significant field events are presented in Table 1.

Emerged annual broadleaf and perennial grass weeds present at planting were controlled with glyphosate [*N*-(phosphonomethyl)glycine] applied at 1.1 kg 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 (Table 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 plus nonionic surfactant[5] at 0.5% by vol in 1985 and 1986 and 0.25% by vol thereafter were sprayed shortly before or shortly after spring wheat planting, but before wheat emergence. A tractor-drawn garden sprayer, equipped with flat-fan nozzles[6] spaced 50 cm apart on a 3.1-m boom, was drawn at 5.5 km h^{-1} and delivered 140 to 190 L ha^{-1} water carrier when operated at 140 to 170 kPa.

'Len' hard red spring wheat was planted in 1985 and 'Wheaton' thereafter. These semidwarf varieties were planted with a double-disc grain drill[7] at 80 to 100 kg ha^{-1} 4 to 5 cm deep in rows spaced 18-cm apart.

Nitrogen, as urea, was deep banded at planting approximately 6 cm deep in 35-cm rows halfway between wheat rows at 120, 120, 80, 120, and 100 kg nitrogen ha^{-1} from 1985 to 1989, respectively (Table 1). Enough nitrogen was applied each year for a 2690 kg ha^{-1} wheat yield goal as recommended by North Dakota State University based on fertility analysis of soil samples collected in late fall. No other mineral nutrients were recommended for the desired yield goal.

Wheat stand was determined from counts of three to six 1-m^2 quadrats per plot in untreated check plots because environmental conditions influenced emergence from year to year. In trial 1 wheat stands were 90, 170, 140, and 110 plants m^{-2} from 1985 to 1988 (years 1 to 4), respectively. In trial 2 wheat stands were 120, 150, 110, and 130 plants m^{-2} from 1986 to 1989 (years 1 to 4), respectively.

Herbicides were applied POST to the same plots each year with a single-tire bicycle sprayer equipped with flat-fan spray nozzles[8] 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. Wheat was tillered and Canada thistle shoots were from 1 to 20 cm tall at herbicide application. No rain fell within 24 h of any herbicide application.

The methyl ester of diclofop {(±)-2-[4-(2,4-dichlorophenoxy)phenoxy]propanoic acid} at 1.1 kg ha^{-1} was applied to all plots when spring wheat had tillered and completely controlled sparse, scattered wild oats (*Avena fatua* L. # AVEFA), green foxtail [*Setaria viridis* (L.) Beauv. # SETVI], and yellow foxtail (*Setaria glauca* L. # SETLU) plants.

Canada thistle shoots arising from adventitious root buds on established root systems 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 shortly after broadleaf herbicide spraying in spring, at midseason (data not shown), and at harvest (dates of measurement are presented in Table 1). Seedlings were not counted because they were rare. Four to 11% of the plot surface area was sampled for shoot density in trial 1, whereas 7 to 17% of the plot area was sampled in trial 2. Canada

[5]Ortho X-77 (alkylaryl polyoxyethylene glycols, free fatty acids, and isopropanol 90%). Chevron Chem. Co., Agric. Chem. Div., 6001 Bollinger Canyon Rd., San Ramon, CA 94583.

[6]TeeJet 8003 flat-fan nozzles. Spraying System Co., North Ave., Wheaton, IL 60188.

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

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

Table 1. Dates when field operations were performed.

Field operation	Trial 1				Trial 2			
	1985	1986	1987	1988	1986	1987	1988	1989
	date							
Glyphosate applied	5/25	5/16	4/23	5/10	5/16	4/23	5/10	4/19
Wheat planted and fertilized	5/24	5/15	4/27	5/11	5/15	4/27	5/11	5/1
Wheat emergence began	5/29	5/23	5/11	5/23	5/23	5/11	5/23	5/12
Wheat stand determined	6/10	6/4	6/9	6/16	6/4	6/8	6/16	6/6
Canada thistle herbicides applied	6/10	6/5	5/29	6/7	6/5	5/29	6/7	6/1
Diclofop applied	6/20	6/16	6/8	6/17	6/16	6/9	6/17	6/1
Canada thistle emergence first observed	4/30	4/24	5/7	5/23	5/15	5/7	5/23	5/12
Canada thistle density measured	6/13	5/20	5/24	6/8	5/21	5/24	6/8	6/6
	8/14	6/6	6/1	7/11	6/6	6/1	6/22	7/11
	–	8/13	7/27	7/26	8/13–15	7/30	7/26	8/7
Canada thistle control evaluated	7/2	6/12	5/29	6/8	6/12	5/29	6/8	7/11
	8/5	6/30	7/6	6/22	6/30	7/6	6/22	8/9
	–	8/7	7/30	7/26	8/7	7/30	7/26	–
Wheat harvested	8/27	8/19	8/13	–	8/25	8/3	–	–

thistle control was evaluated visually on a scale of 0 (no control) to 100 (complete control) at these sampling times.

A 1.3-m-wide swath of wheat was harvested from each plot with a small-plot combine[9]. Wheat yields were based on grain weight adjusted to 12% moisture after drying and cleaning. Wheat was not harvested in 1988 or 1989 because of drought and damage by insects, birds, and rodents.

Analyses of variance were conducted for each year by trial using SPSS/PC+ version 4.0 statistical analysis software (28, 29), and means were separated by the LSD range test ($P \leq 0.05$). Data were not combined over trials or years because of interactions between year and trial. Also, environment was not constant (see remarks on drought years below), and observations could not be assumed to be independent because environmental history (e.g., several consecutive years of drought before starting the experiment) likely influenced perennial weed growth both before and during the two trials.

Economic analysis. Net return ha^{-1} was estimated by subtracting herbicide cost ha^{-1} from gross return ha^{-1}. Herbicide cost ha^{-1} equals kg ha^{-1} multiplied by \$ kg^{-1} active ingredient plus herbicide application cost ha^{-1}. Gross return equals the product of wheat yield (kg ha^{-1}) and wheat price (\$ ha^{-1}). Wheat yield, wheat price, gross return, herbicide cost, and net return were determined for the untreated check, MCPA plus bromoxynil, chlorsulfuron, 2,4-D alone, and clopyralid plus 2,4-D treatments. Tribenuron was excluded from the economic analysis because it was not sold commercially during the experiment. Only the first 3 yr of trial 1 (1985 to 1987) were analyzed because wheat was not harvested in 1988 and 1989. Furthermore, economic analysis was not performed for trial 2 because wheat yields were not available for 2 of the 4 yr of this trial.

SDWF was chosen for economic analysis in preference to the other two methods of economic analysis on the basis of the reasons discussed in the introduction. SDWF was conducted using yield data from three blocks for the 3 yr of trial 1 that could be harvested, for a total of nine observations per treatment. Treatment means were not used for SDWF because it would have masked data variability, which was the object of study. SDWF was used to determine farmers' preferences for herbicide treatments for three risk aversion intervals: [−0.005, 0.005] for risk neutrality, [0.005, 0.025] for moderate risk aversion, and [0.025, 0.049] for strong risk aversion. These risk aversion coefficients are larger than ones commonly used in SDWF applications because the return units for this analysis are in \$ ha^{-1} rather than \$ per farm (25, 26).

RESULTS AND DISCUSSION

Canada thistle control. Canada thistle control following annual treatment with chlorsulfuron, clopyralid plus 2,4-D, and tribenuron generally was fair (≥ 75%) to excellent (≥ 95%) at harvest all years in both trials (Figure 1). Control at harvest with chlorsulfuron varied from 95 to 99% from years 1 to 4 of trial 1 and increased from 80 to 99% in trial 2. Canada thistle control with clopyralid plus 2,4-D improved dramatically after four annual treatments; Canada thistle control increased from 80 to 99% in trial 1 and from 78 to 97% in trial 2 from years 1 to 4, respectively. Canada thistle control at harvest following repeated annual application of tribenuron over 4 yr was inconsistent. With repeated tribenuron treatment, Canada thistle control decreased from 92 to 75% in years 1 to 4, respectively, in trial 1, but it increased from 77 to 95% in trial 2, respectively.

Canada thistle control with either 2,4-D or bromoxynil plus MCPA tended to be lower and was less consistent over time than either chlorsulfuron or clopyralid plus 2,4-D treatment, especially during the first and second year of

[9]Hege Equipment, Inc., Colwich, KS 67030.

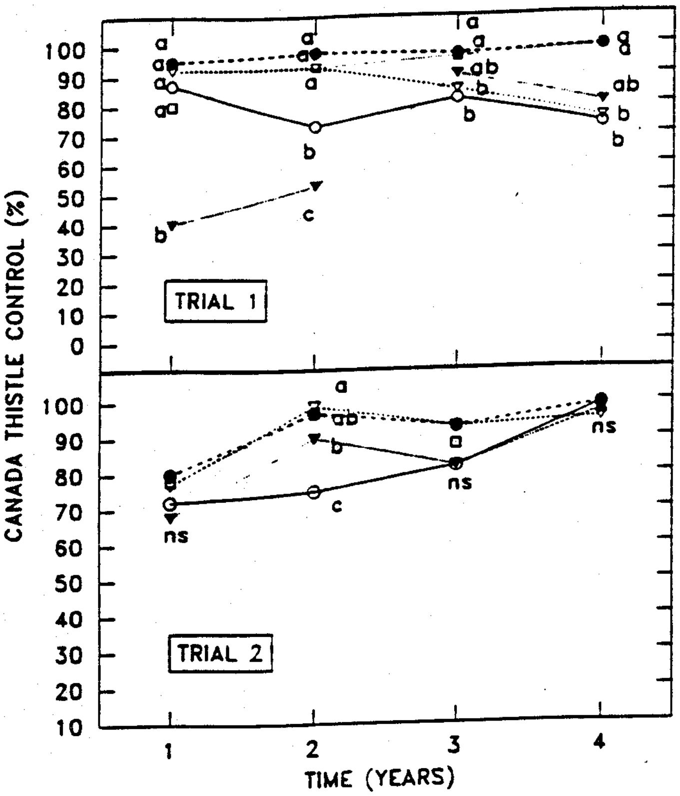

Figure 1. Visually evaluated percent control of Canada thistle shoots infesting no-till spring wheat over 4 yr following repeated annual reapplication of various herbicides to the same plots in spring. Means within a year followed by the same letter were not significantly different at P = 0.05 by the LSD range test (NS = not significantly different). The herbicide treatments were bromoxynil plus MCPA (open circle, solid line), chlorsulfuron (solid circle, dashed line), clopyralid plus 2,4-D (open square, dotted line), 2,4-D (solid triangle, dotted line), and tribenuron (open triangle, dotted line).

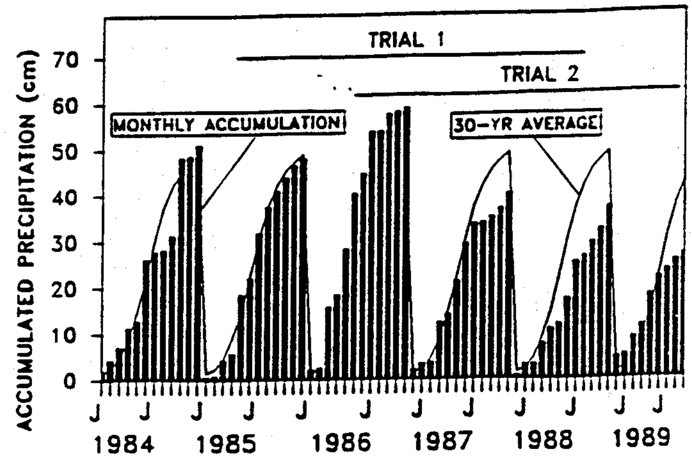

Figure 2. Accumulative monthly precipitation (= bars) and 30-yr average accumulative monthly precipitation (= cubic splined line) over 6 yr for trials 1 and 2. Weather data were gathered at Hector International Airport approximately 1 km north of the experimental site.

treatment (Figure 1). However, in trial 1, Canada thistle control at harvest improved following 2 to 4 yr of annual treatment with 2,4-D compared with only one treatment. When 2,4-D was applied annually, control at harvest increased from 40 to 80% between years 1 and 4, respectively, in trial 1 and from 68 to 97% between years 1 and 4, respectively, in trial 2. Because Canada thistle control with 2,4-D at 560 g ha^{-1} was inferior to 2,4-D plus clopyralid at 280 plus 70 g ha^{-1} during the first 2 yr and thereafter in trial 1, clopyralid likely is largely responsible for the better Canada thistle control achieved with this mixture compared with 2,4-D alone. Clopyralid alone generally provides better long-term Canada thistle control than does 2,4-D (8), although side-by-side comparisons at equivalent rates have not been reported.

Canada thistle control at harvest with bromoxynil plus MCPA gradually improved from 73 to 87% in trial 1 and 72 to 99% in trial 2 from years 1 to 4, respectively (Figure 1). Control also gradually improved over 4 yr in earlier research with annual application of bromoxynil plus MCPA at the same rate in continuous, chisel-plowed spring wheat (5).

Growing season drought (Figure 2) probably contributed to observed differences in Canada thistle response to herbicides between trials 1 and 2 (Figure 1). Rainfall often was limited in June, July, and/or August. Midsummer drought in 1984, 1 yr before starting trial 1, may have suppressed Canada thistle regrowth in the following growing season (year 1 of trial 1), making some herbicides appear more effective in year 1 of trial 1 than in year 1 of trial 2 (Figure 1). In contrast, rainfall was adequate one growing season before starting trial 2, except in fall (Figure 2). Above-normal rainfall during the first year of trial 2 also may have encouraged new shoot emergence from adventitious root buds during the first year of trial 2 more than in the first year of trial 1, making herbicides appear less effective in year 1 of trial 2 than in year 1 of trial 1. The third and fourth years of trial 1 and the second through fourth years of trial 2 experienced midseason drought (Figure 2). This drought probably contributed to the excellent control observed with all herbicides tested by the fourth year of trial 2.

The impact of water stress on Canada thistle control is controversial. Canada thistle control was reportedly better in some studies with tillage (3, 30) or rotation (3) following drought years than following wet years. Few Canada thistle shoots emerged and root biomass was reduced 1 yr after a drought in other research (1, 5). In contrast, glyphosate, dicamba (3,6-dichloro-2-methoxybenzoic acid), or picloram (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid) treatment with moisture stress did not control transplanted Canada thistle 1 yr later in Nebraska (19).

Canada thistle shoot density. Reductions in Canada thistle stand at harvest caused by sequences of herbicide treatments were distinguished 1 yr earlier in trial 1 than in trial 2 (Figures 3 and 4), probably because Canada thistle was water stressed in the growing season before trial 1 was started, but not before trial 2 (Figure 2). Chlorsulfuron and clopyralid plus 2,4-D applied annually for several years reduced Canada thistle stand more rapidly and consistently over time than did the other three herbicide treatments in both trials (Figures 3 and 4), as one might expect based on visually evaluated control (Figure 1). Both herbicide sequences nearly eliminated shoots at harvest by the fourth year in both trials.

Even after 4 yr of treatment with bromoxynil plus MCPA, tribenuron, or 2,4-D, Canada thistle stands at harvest were greater in trial 1 than in trial 2 (Figures 3 and 4). For these three herbicide treatments, shoot densities at harvest in year 4 were 34, 56, and 19% of the untreated check density, respectively, in trial 1, and 1, 6, and 4% of the untreated check density, respectively, in trial 2. In trial 1 bromoxynil plus MCPA and tribenuron treatment did not greatly change Canada thistle density at harvest over time, in contrast to the gradually decreasing densities over time observed in trial 2. Repeated annual bromoxynil plus MCPA treatment reduced Canada thistle stands in trial 2 much as treatment did in a previous field experiment (5) following 4 yr of annual treatment with bromoxynil plus MCPA at 280 plus 280 kg ha^{-1}.

Residual effects of repeated herbicide treatment over several growing seasons on Canada thistle shoot emergence from adventitious root buds were measured in spring, before herbicide application (Table 2). Shoot emergence in spring was reduced after only one annual treatment of certain herbicides in trial 1 and after two annual treatments in trial 2. Chlorsulfuron and clopyralid plus 2,4-D reduced early-season Canada thistle stands to a greater extent than other herbicide treatments. O'Sullivan (23) observed that chlorsulfuron at 50 g ha^{-1} applied POST in spring wheat or barley (*Hordeum vulgare* L.) controlled shoot emergence from adventitious root buds 1 yr after treatment, although he did not examine effects of repeated herbicide application over a longer period. Our results with chlorsulfuron also verify Fay's observation that chlorsulfuron applied to the same plots for three consecutive years drastically decreased Canada thistle stands (9, 10). By year 4 of both trials, early-season Canada thistle stands were sufficiently dense (2 to 60 shoots m^{-2}) for the other three herbicide treatments to warrant application even after three consecutive annual herbicide applications (Table 2).

Canada thistle densities in untreated check plots increased from spring (Table 2) to midseason (data not presented) before decreasing by wheat harvest (Figures 3 and 4). Shoot densities in untreated check plots at harvest (Figure 3) were lower in years 1 and 4 than in years 2 and 3 of trial 1, probably due to drought during the preceding growing season (Figure 2). Untreated check shoot densities at harvest in year 4 were only 48 and 38% of those observed in year 3 in trials 1 and 2, respectively, following 1 and 2 yr of summer drought, respectively (Figures 3 and 4). Apparently, water and temperature stress experienced by Canada thistle in one growing season reduced Canada thistle stand in the following growing season, independent of herbicide treatment.

Canada thistle stands in both trials were denser and more variable in untreated checks (Figures 3 and 4) than in commercial wheat fields in either the northern United States (4, 7, 8, 14) or Canada (32, 33, 34) shortly before spring

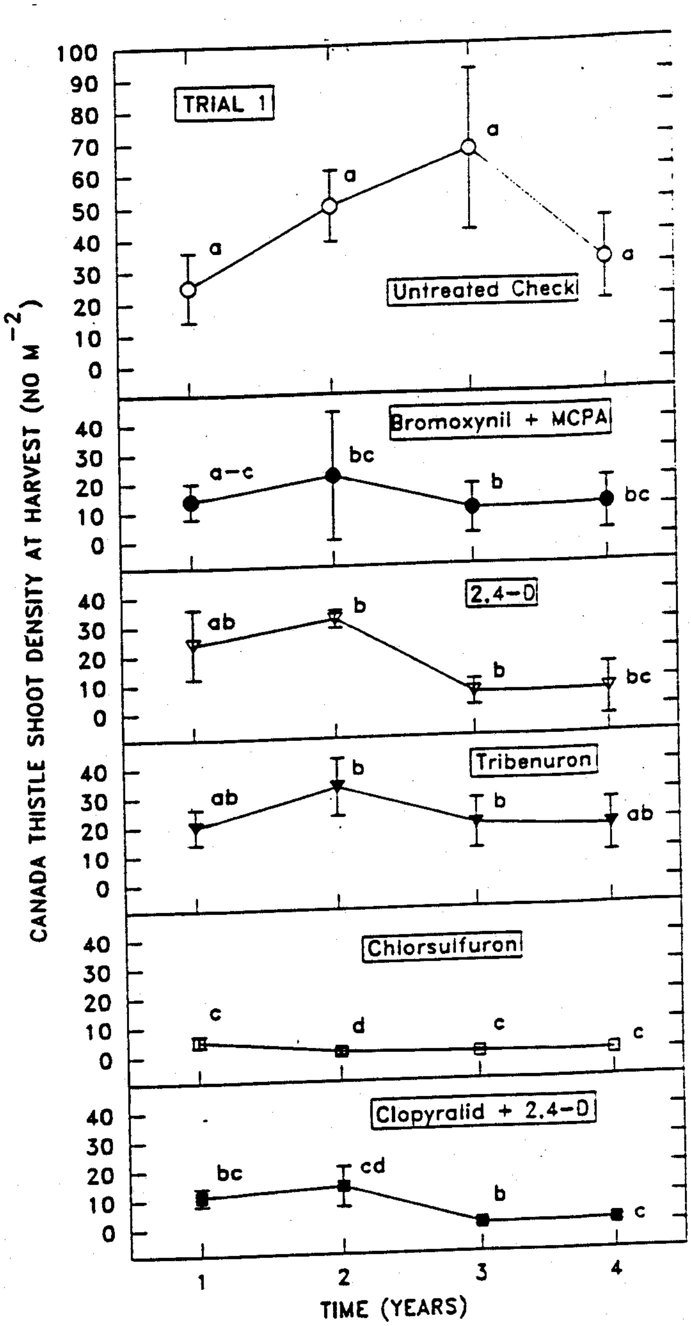

Figure 3. Canada thistle shoot density at spring wheat harvest following repeated annual reapplication of various herbicides in spring to the same plots over 4 yr for trial 1. Means ± standard errors (bars) are presented. Means within a year followed by the same letter were not significantly different at P = 0.05 by Fisher's Protected LSD Test.

wheat 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} (means ± standard error) were counted in untreated check plots (Figure 3). Because results likely pertain to "worst-case" conditions which are characteristic of

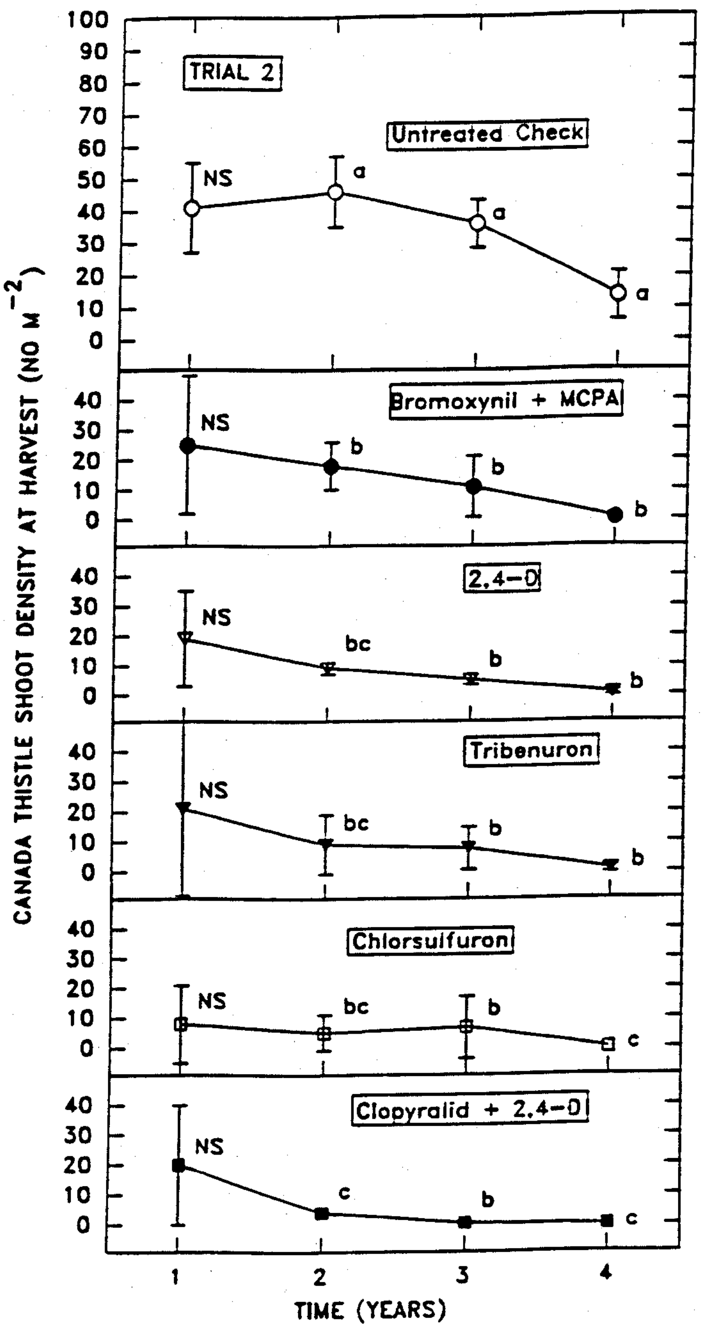

Figure 4. Canada thistle shoot density at spring wheat harvest following repeated annual reapplication of various herbicides in spring to the same plots over 4 yr for trial 2. Means ± standard errors (bars) are presented. Means within a year followed by the same letter were not significantly different at P = 0.05 by Fisher's Protected LSD Test.

Table 2. Residual effects of herbicides on Canada thistle shoot density at spraying time in spring after 2 to 4 yr of annual herbicide application to the same plots[a].

Treatment		Canada thistle density at spraying by year		
Herbicide	Rate[b]	2	3	4
Trial 1:	g ha^{-1}		no. m^{-2}	
Untreated check	–	27 a	20 ab	63 a
Bromoxynil + MCPA	280 + 280	25 a	8 c	29 b
Chlorsulfuron[c]	30	2 c	0 c	5 c
Tribenuron[c]	20	11 bc	10 bc	60 a
2,4-D	560	22 ab	24 a	19 bc
Clopyralid + 2,4-D	70 + 280	16 a–c	6 c	9 bc
P > F		0.0155	0.0051	0.0002
Trial 2:				
Untreated check	–	4[d]	50 a	39 a
Bromoxynil + MCPA	280 + 280	1	22 bc	12 b
Chlorsulfuron[c]	30	8	38 ab	15 b
Tribenuron[c]	20	1	26 a–c	14 b
2,4-D	560	2	16 bc	9 b
Clopyralid + 2,4-D	70 + 280	0	7 c	2 b
P > F		NS	0.0429	0.0215

[a]Means in a column for each trial followed by the same letter were not different at P ≤ 0.05 by the LSD procedure.

[b]Rate are ae, except chlorsulfuron and tribenuron which are ai.

[c]X-77 surfactant at 0.25%, by vol, was added.

[d]"Protected LSD" letters are not presented because the ANOVA was nonsignificant.

Canada thistle patches that have not been controlled for several years, farmers with sparser infestations likely will achieve greater, earlier control with herbicide treatments.

Net wheat yield. No-till spring wheat yields (Table 3) never achieved their full potential for which they were fertilized because drought (Figure 2) likely limited yield even when herbicide control of Canada thistle was good (Figures 1, 3, and 4). Bromoxynil plus MCPA and chlorsulfuron treatments increased spring wheat yield relative to the untreated check in both trials in all years in which yield could be determined. Clopyralid plus 2,4-D increased yield in 2 of 3 yr in trials 1 and 2. Tribenuron increased yield all 3 yr in trial 1 and equaled the untreated check in trial 2.

Economic analysis. Net returns ha^{-1} averaged over 3 yr were ranked: chlorsulfuron = clopyralid plus 2,4-D ≥ MCPA plus bromoxynil ≥ 2,4-D > untreated check (Table 4). While the net return averaged over 3 yr for the chlorsulfuron treatment was statistically equivalent to the clopyralid plus 2,4-D treatment, variance was greater (data not shown). Hence, preference between these two herbicides cannot be determined without considering farmers' risk preferences.

The results of SDWF summarize expected farmer preferences (Table 5). Likely herbicide preferences are reported for three farmer risk aversion preferences: risk neutral, moderately risk averse, and highly risk averse. For risk-averse farmers, herbicide treatments that increase returns but also increase variability of returns are less attractive than those that increase returns somewhat less but also have lower variability of returns. Risk-averse farmers are most likely to choose herbicides for Canada thistle control on the basis of consistent, high efficacy. The order of herbicides listed in the preferred column (Table 5) does not indicate the order of preference within a risk category.

Table 3. Effects of herbicides for Canada thistle control on mean net yield of spring wheat after 1 to 3 yr of herbicide treatment to the same plots[a].

Treatment		Mean net wheat yield[a]				
		Trial 1				Trial 2
Herbicide	Rate[b]	Year 1	Year 2	Year 3	3-yr average	Year 1
	g ha^{-1}	kg ha^{-1}				
Untreated check	–	930 b	630 b	460 c	680 c	600 b
Bromoxynil + MCPA	280 + 280	1830 a	2190 a	1760 ab	1930 ab	1180 a
Chlorsulfuron[c]	30	2220 a	2350 a	2300 a	2290 a	1090 a
Tribenuron[c]	20	1800 a	1820 a	1450 b	1690 b	850 b
2,4-D	560	1710 b	1660 a	1420 b	1590 b	1320 a
Clopyralid + 2,4-D	70 + 280	1740 b	2170 a	1990 ab	1970 ab	1200 a
P > F		0.0500	0.0002	0.0001	0.0052	0.0657

[a]Means in a column for each trial followed by the same letter are not different at P = 0.05 by the LSD procedure.

[b]Rates are ae, except chlorsulfuron and tribenuron, which are ai.

[c]X-77 surfactant at 0.25%, by vol, was added.

Table 4. Net return for herbicide treatments for Canada thistle control in trial 1[a].

Treatment		Net return[b]			
Herbicide	Rate[c]	Year 1	Year 2	Year 3	3-yr average
	g ha^{-1}	\$ ha^{-1}			
Untreated check	–	30 b	–22 b	–6 c	1 c
Bromoxynil + MCPA	280 + 280	133 a	120 a	123 b	125 ab
Chlorsulfuron[d]	30	179 a	135 a	179 a	164 a
2,4-D	560	117 a	70 a	89 b	92 b
Clopyralid + 2,4-D[c]	70 + 280	121 a	135 a	152 ab	136 a
P > F		0.0500	0.0030	0.0050	0.0001

[a]Means in a column for each trial followed by the same letters were not different at P = 0.05 by the LSD procedure.

[b]Negative values represent a net \$ ha^{-1} loss.

[c]Rates are ae, except chlorsulfuron and tribenuron, which are ai.

[d]X-77 surfactant at 0.25%, by vol, was added.

The four herbicide treatments are preferred to the untreated checks for all three farmer risk preference cases (Table 5). MCPA plus bromoxynil is preferred to 2,4-D, and chlorsulfuron is preferred to both MCPA plus bromoxynil and 2,4-D for all farmer risk preference cases. Chlorsulfuron is preferred to clopyralid plus 2,4-D by risk-neutral farmers. Clopyralid plus 2,4-D is preferred to both MCPA plus bromoxynil and 2,4-D for all risk preference cases and to chlorsulfuron in the highly risk-averse case.

SDWF suggests that either chlorsulfuron or clopyralid plus 2,4-D was the most preferred herbicide treatments for Canada thistle control in spring wheat (Table 5). Chlorsulfuron would be preferred to clopyralid plus 2,4-D by risk-neutral farmers, whereas clopyralid plus 2,4-D would be preferred to chlorsulfuron by highly risk-averse farmers. No clear preference ordering was indicated when farmers are moderately risk averse. Conclusions drawn from the SDWF analysis are conditional on the herbicide application rates, wheat yields, and herbicide and wheat prices used for the analysis. Changes in these variables could alter predicted farmer preferences for herbicides.

Although results of this research likely apply to relatively dense stands of Canada thistle, the best herbicide treatments tested (i.e., chlorsulfuron and clopyralid plus 2,4-D) should perform consistently well even for worst-case Canada thistle infestations. However, the chlorsulfuron rates applied were greater than the 1990 registered rates (30 versus 10 g ha^{-1}) in spring wheat, whereas those for clopyralid plus 2,4-D were half of the 1990 registered rates. Clopyralid plus 2,4-D applied at half of the 1990 registered rates provided consistently good-to-excellent Canada thistle control over several years[10].

This research provides farmers with an effective, predictable multiyear program of Canada thistle control, which reduces the severity of this perennial weed over time and which may have application in rotational crops. It also is

[10]These herbicide rates were suggested by representatives of E. I. du Pont de Nemours Co. and Dow Chemical Co. before starting this study and before herbicide registration.

Table 5. Results of stochastic dominance analysis for three risk preferences.

Farmer risk preference category	Herbicide preference[a]	
	Preferred	Not preferred
Risk neutral	Bromoxynil + MCPA	Untreated check 2,4-D
	Chlorsulfuron	Untreated check Bromoxynil + MCPA 2,4-D Clopyralid + 2,4-D
	2,4-D	Untreated check
	Clopyralid + 2,4-D	Untreated check Bromoxynil + MCPA 2,4-D
Moderately risk averse	Bromoxynil + MCPA	Untreated check 2,4-D
	Chlorsulfuron	Untreated check Bromoxynil + MCPA 2,4-D
	2,4-D	Untreated check
	Clopyralid + 2,4-D	Untreated check Bromoxynil + MCPA 2,4-D
Strongly risk averse	Bromoxynil + MCPA	Untreated check 2,4-D
	Chlorsulfuron	Untreated check Bromoxynil + MCPA 2,4-D
	2,4-D	Untreated check
	Clopyralid + 2,4-D	Untreated check Bromoxynil + MCPA 2,4-D Chlorsulfuron

[a]The order of herbicides listed in the preferred column does not indicate the order of preference within a risk category.

consistent with current no-till spring wheat production systems in the northern Great Plains. The data also support the contention that drought can suppress Canada thistle growth and enhance the efficacy of repeated annual herbicide treatments for Canada thistle control.

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