Effectiveness and economics of repeated sequences of herbicides for Canada thistle (*Cirsium arvense*) control in reduced-till spring wheat (*Triticum aestivum*)[1]

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Donald, W. W. and Prato, T. 1992. **Effectiveness and economics of repeated sequences of herbicides for Canada thistle (*Cirsium arvense*) control in spring wheat (*Triticum aestivum*).** Can. J. Plant Sci. **72**: 599–618. Several postemergence herbicides applied in fall for 2 yr either alone or followed by other spring-applied herbicides for 4 yr reduced densities of Canada thistle (*Cirsium arvense* (L.) Scop.) infesting reduced-till spring wheat (*Triticum aestivum* L.). However, fall-applied herbicides for 2 yr had little value for maintaining long-term Canada thistle control, unless supplemented by in-crop herbicide treatment. Neither fall-applied dicamba at 1.7 or 2.2 kg ha^{-1}, glyphosate at 1.7 kg ha^{-1} plus nonionic surfactant, nor 2,4-D at 1.7 kg ha^{-1} applied each of 2 yr kept Canada thistle densities below that of the untreated check through year five. Spring-applied chlorsulfuron at 30 g ha^{-1} plus nonionic surfactant for each of four consecutive years reduced Canada thistle density in wheat to the same extent as fall-applied dicamba followed by chlorsulfuron applied in wheat. Fall herbicide treatments, with or without in-crop herbicide treatments, were economically risky and were seldom profitable. The relative ranking of farmer preference for five treatments common to two trials was similar: untreated check ≥ spring-applied chlorsulfuron at 30 g ha^{-1} ≥ fall-applied dicamba at either 1.7 or 2.2 kg ha^{-1} (rank reverses between trials 1 and 2) ≥ fall-applied dicamba at 2.2 kg ha^{-1} followed by spring-applied chlorsulfuron at 30 g ha^{-1}. The only treatments that were preferred to the untreated check were both spring-applied 2,4-D at 560 g ha^{-1} and fall-applied 2,4-D at 1.7 kg ha^{-1} in trial 1 and both spring-applied (4-chloro-2-methylphenoxy) acetic acid (MCPA) plus bromoxynil 280 plus 280 g ha^{-1}, respectively, and spring-applied 2,4-D plus clopyralid at 280 plus 70 g ha^{-1}, respectively, in trial 2.

Key words: Bromoxynil + MCPA, chlorsulfuron, dicamba, glyphosate, 2,4-D

Donald, W. W. et Prato, T. 1992. **Efficacité et économie de séquences répétées de traitements herbicides pour la lutte contre le chardon des champs dans le blé de printemps cultivé en régime de travail réduit.** Can. J. Plant Sci. **72**: 599–618. Plusieurs herbicides de post-levée appliqués en automne pendant deux ans, seuls ou suivis de quatre années d'applications de printemps, ont réduit les infestations de chardon des champs (*Cirsium arvense* (L.) Scop.) dans des cultures de blé de printemps (*Triticum aestivum* L.) en régime de travail du sol réduit. Toutefois, deux ans de traitements d'automne se sont révélés peu efficaces pour assurer une maîtrise durable du chardon, à moins d'être complétés par un traitement en culture. Ni le dicamba, aux doses de 1,7 ou de 2,2 kg m.a. ha^{-1}, ni le glyphosate à 1,7 kg ha^{-1} avec surfactant non ionique, ni le 2,4-D à 1,4 kg ha^{-1}, utilisés en application d'automne pendant 2 ans n'ont pu maintenir jusqu'à la cinquième année les densités d'infestation en deçà de celles des parcelles témoins. L'épandage de chlorsulfuron au printemps à la dose de 30 g ha^{-1} avec surfactant non ionique, quatre années de suite, a amené les mêmes réductions d'infestation que le traitement

[1]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.
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d'automne au dicamba suivi d'un traitement au chlorsulfuron en culture. Les traitements d'automne, complétés ou non de désherbage en culture, présentaient des risques économiques, en plus d'être rarement rentables. Le classement relatif des préférences des agriculteurs à l'égard des cinq traitements communs à deux essais était le même, soit témoin (sans désherbage) ≥ traitement de printemps au chlorsulfuron ≥ traitement d'automne au dicamba aux doses de 1,7 ou 2,2 kg ha^{-1} (classement inversé dans les deux essais) ≥ désherbage d'automne au dicamba 2,2 kg ha^{-1} suivi de traitement de printemps au chlorsulfuron. Les seules options préférées au témoin étaient, dans l'essai 1, le traitement au 2,4-D au printemps à 560 g ha^{-1} puis en automne à 1,7 kg ha^{-1} et, dans l'essai 2, le traitement de printemps au MCPA avec bromoxynil (aux doses de 280 g ha^{-1} chacun) et le traitement de printemps au 2,4-D avec clopyralide (aux doses respectives de 280 et 70 g ha^{-1}).

Mots clés: Bromoxynil, MCPA, chlorsulfuron, dicamba, glyphosate, 2,4-D

Canada thistle persists from year to year because new adventitious shoots arise from adventitious root buds on Canada thistle's extensive, perennial, spreading root system (Moore 1975; Donald 1990). Control of Canada thistle by nonchemical crop management and herbicides and crop yield loss assessment have been reviewed (Donald 1990). Management of Canada thistle on cropland must be a sustained effort over several years regardless of the crop management used, such as tillage or herbicides (Donald 1990). Several multiple year strategies for reducing the severity of Canada thistle employ (i) selective postemergence herbicides applied in-crop for several years; (ii) nonselective nonpersistent herbicides applied at high rates for several falls; (iii) nonselective persistent herbicides applied at high rates for several falls preceding crops that tolerate persistent, potentially phytotoxic herbicide residues; or (iv) sequences of either (ii) or (iii) followed by (i) to further suppress Canada thistle shoot and root growth. Such herbicide sequences are designed to kill existing shoots and roots and suppress subsequent root and adventitious root bud formation by forcing surviving roots and adventitious root buds to deplete nutritional storage reserves (Donald 1990).

The objectives of this experiment were to (i) compare the efficacy of fall-applied herbicides for Canada thistle control in reduced-till spring wheat when applied to the same plots for each of two consecutive years either by themselves or followed by additional spring-applied broadleaf herbicides in-crop for four consecutive years starting in the spring after the first fall herbicide application; (ii) determine the rate of Canada thistle shoot density reduction over 4 yr; and (iii) determine whether fall-applied herbicide treatments were a profitable strategy for decreasing Canada thistle infestations in reduced-till spring wheat. Profitability was examined in terms of net return and farmer risk assessment.

MATERIALS AND METHODS

Treatments

Herbicide sequences are summarized in Table 1. Five herbicide treatments were common to two trials: (a) an untreated check; (b) fall-applied dicamba (3,6-dichloro-2-methoxybenzoic acid) at 1.7 kg a.e. ha^{-1} in each of 2 yr; (c) fall-applied dicamba at 2.2 kg a.e. ha^{-1} in each of 2 yr; (d) spring-applied chlorsulfuron {2-chloro-*N*-[[(4-methoxy-6-ethyl-1,3,5-triazin-2-yl)amino] carbonyl]benzenesulfonamide} at 30 g a.i. ha^{-1} plus nonionic surfactant [Ortho X-77 (alkylaryl polyoxyethylene glycols, free fatty acids, and isopropanol 90%)] at 0.25% (vol vol^{-1}) in-crop in each of 4 yr; and (e) fall-applied dicamba at 2.2 kg a.e. ha^{-1} in each of 2 yr followed by spring-applied chlorsulfuron at 30 g a.i. ha^{-1} plus nonionic surfactant at 0.25% (vol vol^{-1}) in-crop in each of 4 yr.

In trial 1, five additional treatments were included (Table 1): (f) the alkanolamine salt formulation of 2,4-D ((2,4-dichlorophenoxy)acetic acid) at 1.7 kg a.e. ha^{-1} applied alone in each of two falls; (g) the alkanolamine salt formulation of 2,4-D at 560 g ha^{-1} applied in-crop in each of 4 yr; (h) fall-applied 2,4-D at 1.7 kg a.e. ha^{-1}

Table 1. Herbicide treatments and times of application

Treatment				Application timing						
				Year 0	Year 1		Year 2	Year 3	Year 4	Year 5
Fall herbicide	Rate (kg ha^{-1})	In-crop herbicide	Rate (g ha^{-1})	Fall	In-crop	Fall	In-crop	In-crop	In-crop	Fallow
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

applied in each of 2 yr followed by spring-applied 2,4-D at 560 g ha^{-1} in-crop in each of 4 yr; (i) fall-applied dicamba at 1.7 kg a.e. ha^{-1} in each of 2 yr followed by spring-applied 2,4-D at 560 g ha^{-1} in-crop in each of 4 yr; and (j) fall-applied dicamba at 2.2 kg a.e. ha^{-1} in each of 2 yr followed by spring-applied 2,4-D at 560 g ha^{-1} in-crop in each of 4 yr.

In trial 2, five additional treatments were included (Table 1): (f) fall-applied glyphosate [*N*-(phosphonomethyl)glycine] at 1.7 kg a.e. ha^{-1} plus nonionic surfactant in each of 2 yr; (g) fall-applied glyphosate at 1.7 kg a.e. ha^{-1} plus nonionic surfactant applied in each of 2 yr followed by the octanoic ester of bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) plus the butoxyethyl ester of MCPA ((4-chloro-2-methylphenoxy)acetic acid) applied in-crop as a premix at 280 g a.i. ha^{-1} plus 280 g a.e. ha^{-1}, respectively, in each of 4 yr; (h) the same premix at 280 g ha^{-1} plus 280 g ha^{-1}, respectively, applied alone in-crop in each of 4 yr; (i) fall-applied dicamba at 1.7 kg a.e. ha^{-1} in the first 2 yr followed by the same bromoxynil plus MCPA premix at 280 g ha^{-1} plus 280 g ha^{-1}, respectively, applied in-crop in each of 4 yr; 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 a.e. ha^{-1} applied in-crop as a premix in each of 4 yr. The chlorsulfuron rate tested was greater than 1990 United States Environmental Protection Agency registration label rates (30 versus 10 g ha^{-1}) in spring wheat, whereas those for clopyralid plus 2,4-D were half of the registration rate. These rates were suggested by the manufacturers before starting this experiment, prior to herbicide registration.

Experimental Design

A randomized complete block design with three blocks was used on two adjacent sites (trials 1

Table 2. The dates when significant field operations were performed

	Date					
	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Field operation	1983	1984	1985	1986	1987	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	—
Canada thistle density determined						
At spraying	—	06/13	06/13	06/06	06/01	06/07
In late summer	—	08/02	08/14	08/13	07/27	08/12
Canada thistle control evaluated						
in late summer	—	08/05	08/07	08/09	08/12	08/12
Wheat harvested	—	—	08/27	08/19	—	—
Fall chisel plowed	10/25	11/08	10/17–10/18	10/14–10/15	10/07	—
	1984	1985	1986	1987	1988	1989
Trial 2						
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	—
Canada thistle density determined						
At spraying		06/13	06/06	06/01	06/08	05/09
In late summer	—	08/14	08/15	07/30	07/26	07/19
Canada thistle control evaluated						
in late summer	—	08/15	08/07	07/30	07/26	08/09
Wheat harvested	—	08/27	08/21	08/03	—	—
Fall chisel plowed	11/08	10/17–10/18	10/15	10/17	09/27	—

and 2, respectively). Trial 1 lasted from the fall of 1983 to 1988, and trial 2 ran from the fall of 1984 to 1989. Blocking was based on initial Canada thistle shoot density. High natural densities of Canada thistle were present in trial 1 and blocks 2 and 3 of trial 2. Block 1 of trial 2 was artificially established from Canada thistle root cuttings that were planted two growing seasons before starting this trial. Canada thistle density and shoot dry weight were 47 $\pm$ 26 shoots m^{-2} (mean $\pm$ standard deviation) and 28 $\pm$ 14 g m^{-2}, respectively, in the first fall of trial 1 and were 10 $\pm$ 4 shoots m^{-2} and 5 $\pm$ 3 g m^{-2}, respectively, in the first fall of trial 2. These Canada thistle densities were selected to represent a "worst-case" situation. The Canada thistle subspecies *arvense* (Wimm. and Grab.) (Moore and Frankton 1974) was present in both trials. Individual plots measured 3.0 by 12.2 m in both trials.

Trials were treated for 4 yr and observed for 5 yr from the start (Table 1). Spring wheat was planted in each of 4 yr, followed by mechanical fallow using a field cultivator - harrow for weed control in year 5. Land for trial 1 had been pastured for 4 yr before starting this trial, whereas trial 2 had been in continuous spring wheat for 3 yr. Both trials were on the North Dakota State University experimental farm, 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.

Agronomic Practices

Dates of significant 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 semidwarf varieties were planted 3.8–5 cm deep with a Haybuster 107 double-disc grain drill at 84–100 kg ha^{-1} in rows spaced 17.5 cm apart.

Wheat density was counted 3–4 wk after planting in one or two 1-m^2 square quadrats per plot placed at random in the untreated check plots. In trial 1 wheat densities were 94, 169, 175, and 110 plants m^{-2} from 1984 to 1987 (years 1–4), respectively. In trial 2 wheat densities were 88, 152, 110, and 100 plants m^{-2} from 1985 to 1988 (years 1–4), respectively.

At planting, nitrogen as urea was banded approximately 6 cm deep in 35-cm rows halfway between wheat rows at 0, 100, 120, and 70 kg nitrogen ha^{-1} from years 1 to 4, respectively, in trial 1 and at 100, 120, 80, and 120 kg nitrogen ha^{-1} from years 1 to 4, respectively, in trial 2 (Table 1). Enough nitrogen 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 the previous fall. No other mineral nutrients were recommended.

Selective postemergence broadleaf herbicides were applied in 70 L ha^{-1} with a single-tire bicycle sprayer equipped with TeeJet 8001 flat fan sprayer nozzles spaced 50 cm apart on a 3.1-m boom and operated at 4.8 km h^{-1} and 140 kPa generated by pressurized air (Table 2). Rainfall occurred at least one or more days after treatment. Wheat was tillered, and Canada thistle shoots were 1–20 cm tall at herbicide application.

Diclofop {(+/−)-2-[4-(2,4-dichlorophenoxy) phenoxy]propanoic acid} at 1.1 kg a.e. ha^{-1} was applied as the methyl ester formulation to the entire experiment after wheat tillered to control sparse wild oat (*Avena fatua* L.), green foxtail (*Setaria viridis* (L.) Beauv.), and yellow foxtail (*Setaria glauca* L.) (Table 2). Diclofop was applied with a tractor-drawn garden sprayer equipped with Teejet 8003 flat fan nozzles spaced 50 cm apart on a 3.1-m boom at 5.5 km h^{-1} and delivered 141–189 L ha^{-1} water carrier when operated at 138–172 kPa (Table 2).

Measured Parameters

Canada thistle shoot densities were determined in six or eight randomly placed 0.25- or 0.5-m^2 square quadrats per plot in spring at the time of broadleaf herbicide application (data not presented) and again in late summer (Table 1). Canada thistle seedlings were not counted. Two to 11% of the plot surface area at least 0.5 m in from plot borders was randomly sampled for shoot density. Weed control was evaluated visually on a scale of 0 (no control) to 100 (complete control) in mid-August (Table 1). Wheat was harvested in a 1.3-m wide swath down the length of each plot with a Hege small-plot combine. Net wheat yields were based on grain weight adjusted to 12% moisture after air drying and cleaning. Wheat was not harvested every year because of drought and damage by insects, birds, and rodents (Table 2).

Statistical Analysis

Analyses of variance (ANOVA) (Sokal and Rohlf 1969) were conducted using SPSS/PC$^+$ version 4.0 statistical analysis software. The untreated check was excluded from the ANOVA's for visually evaluated control data. Means or transformed means were separated using Fisher's protected least significant different (LSD) test (P = 0.05) if overall ANOVA's were significant. Data were not combined over trials or over years because rainfall varied dramatically both within and between growing seasons, giving each trial unique environmental histories (Fig. 1). The ANOVA assumption of independence of observations ignores the possibility that several years of drought may influence perennial weed growth and response to herbicides, as previously established (Carlson and Donald 1988). Also, growing season environment during the year preceding the start of either trial may have influenced the results.

Risk Assessment and Herbicide Preference

STOCHASTIC DOMINANCE ANALYSIS. Farmers' preferences for herbicides were predicted using stochastic dominance (Kramer and Pope 1981; Klemme 1985; Williams 1988). This approach employs pairwise comparisons of the cumulative net return probability distributions for sets of alternatives. Stochastic dominance with respect to a function (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 (Robison and Barry 1987). SDWF ranks risky alternatives for decision makers having risk preferences that fall within an interval defined by upper and lower risk-aversion coefficients (Williams 1988). SDWF was used in this analysis with the following 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 income units for this analysis are in dollars per hectare rather than dollars per farm (Raskin and Cochran 1986; Prato 1990). Conclusions drawn from SDWF analysis are conditional and depend on herbicide application rate, wheat yield, and both wheat and herbicide prices used in the analysis. Changing these variables alters farmer risk preference rankings for treatments.

NET RETURNS. Net returns were estimated by subtracting herbicide cost from total returns. Herbicide cost equals kilograms per hectare times price per kilogram plus herbicide application cost. Total returns equal wheat yield times wheat price. Since the benefit of using a herbicide can extend beyond the year in which it was applied, the present value of net returns for each block within a treatment was used to evaluate likely farmer preferences for different herbicide treatments. Present value of net returns for block i in treatment j is

$$PV_{ij} = \sum_t n_{ijt}/(1 + r)^t$$

where n_{ijt} is the net return per hectare for block i in treatment j for year t, and r is the discount rate. Since there are three blocks in each treatment, three present values of net returns were calculated for each treatment. These three values were compared using SDWF for trials 1 and 2 separately. Three observations per treatment is a minimum for SDWF analysis, although more points would be desirable.

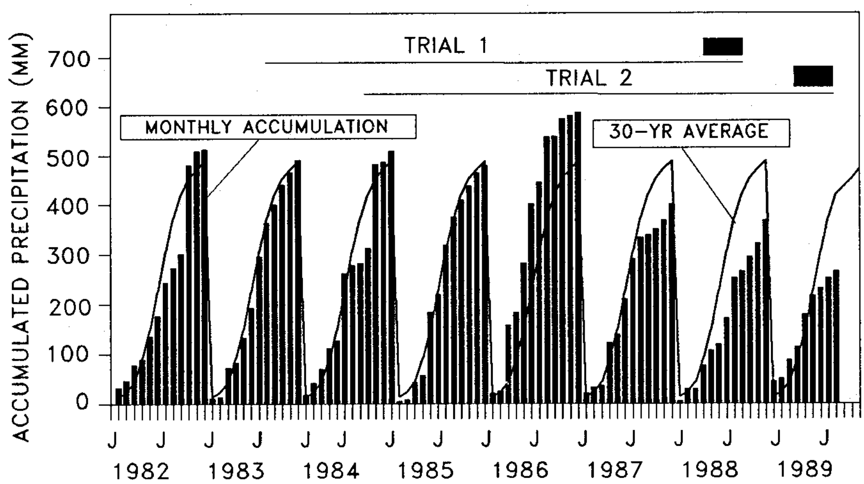

Fig. 1. Monthly accumulated precipitation (solid vertical bars) over 8 yr for trials 1 and 2 and the 30-yr average accumulated precipitation (cubic splined line). Weather data were gathered at Hector International Airport, Fargo, approximately 1 km north of the experimental sites. Trials 1 and 2 were mechanically fallowed in year 5 (solid horizontal bars).

RESULTS AND DISCUSSION

Canada Thistle Shoot Density

RAINFALL EFFECTS ON UNTREATED CHECKS. Canada thistle densities in the untreated check in trial 1 were denser than wheat fields in both the United States and Canada surveyed before harvest (Donald 1990) (Fig. 2). In the untreated check in the fall, 47 ± 26 shoots m^{-2} (mean ± SE) were counted, whereas infestations averaged 1–7 shoots m^{-2} in surveyed fields, but reached a maximum of 42 shoots m^{-2}. Consequently, results of trial 1 likely pertain to worst-case conditions, where Canada thistle has grown uncontrolled for several years. In trial 2, fall Canada thistle density (10 ± 4 shoots m^{-2}) (Fig. 3) was similar to surveyed fields (Donald 1990). Differences between trials in response to herbicide sequences may be due to differences in initial Canada thistle density.

Canada thistle shoot density responded to rainfall in the previous growing season (Figs. 1–3). Canada thistle shoot densities in untreated plots decreased 1 yr after growing season drought and increased 1 yr after above-normal growing season rainfall. Thus, lagged year-to-year changes in Canada thistle shoot density were related to the difference between accumulated January–August rainfall compared with the 30-yr average for the same period (Fig. 3). Accumulated growing season rainfall was below normal (75% of 30.75 cm, the 30-yr average rainfall accumulated between January and August), normal (103%), above normal (144%), and below normal (95%) in years 1–4, respectively, for trial 1 (Fig. 1). In turn, there was a decrease, no change, an increase, and a decrease in Canada thistle shoot densities in late summer between years 1 and 2, 2 and 3, 3 and 4, and 4 and 5, respectively in trial 1 (Fig. 2). Accumulated growing season rainfall was normal (103%), above normal (144%), below normal (95%), and below normal (56%) in years 1–4, respectively, in trial 2 (Fig. 1). In turn, there was an increase, an increase, a decrease, and a decrease in Canada thistle shoot densities between years 1 and 2, 2 and 3, 3 and 4, and 4 and 5, respectively, in trial 2 (Fig. 3).

Thus, growing season rainfall had a major impact on year-to-year fluctuations of Canada thistle density in the untreated check. Pearson correlation coefficients were calculated between normalized Canada thistle density for the untreated check and the difference between the accumulated monthly rainfall over various combinations of months and the 30-yr average rainfall 1 yr earlier for the same period. Correlation coefficients (r) were 0.92 and 0.95 ($P = 0.09$ and 0.05, respectively) between the change in normalized Canada thistle density and the difference in accumulated April plus May rainfall of the previous year from the 30-yr accumulated average for the same period. Correlation coefficients (r) were 0.94 and 0.95 ($P = 0.055$ and 0.054, respectively) in trials 1 and 2, respectively, between the change in normalized Canada thistle density and the difference in accumulated June–September rainfall from the 30-yr accumulated average rainfall for the same period. Correlation coefficients for other relationships either were smaller than these relationships or were inconsistent between trials.

HERBICIDE EFFECTS. Chlorsulfuron was largely responsible for decreasing Canada thistle density for treatment sequences of fall-applied dicamba followed by spring-applied chlorsulfuron in wheat in both trials (Figs. 2 and 3). Spring-applied chlorsulfuron alone decreased or kept Canada thistle densities below those of the untreated check in trials 1 or 2, respectively, from years 2 to 5. These results in chisel-plowed spring wheat verify previous research in no-till spring wheat (Donald and Prato 1992) and conventionally tilled wheat (Fay and Davis 1986). Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr followed by spring-applied chlorsulfuron in wheat did not reduce Canada thistle density any more than chlorsulfuron alone. Herbicide sequences including chlorsulfuron nearly eliminated Canada thistle densities over time.

In trial 1 Canada thistle densities were reduced below the untreated check following fall-applied dicamba alone at either 1.7 or 2.2 kg ha^{-1} for each of 2 yr (Fig. 2). However, Canada thistle densities increased

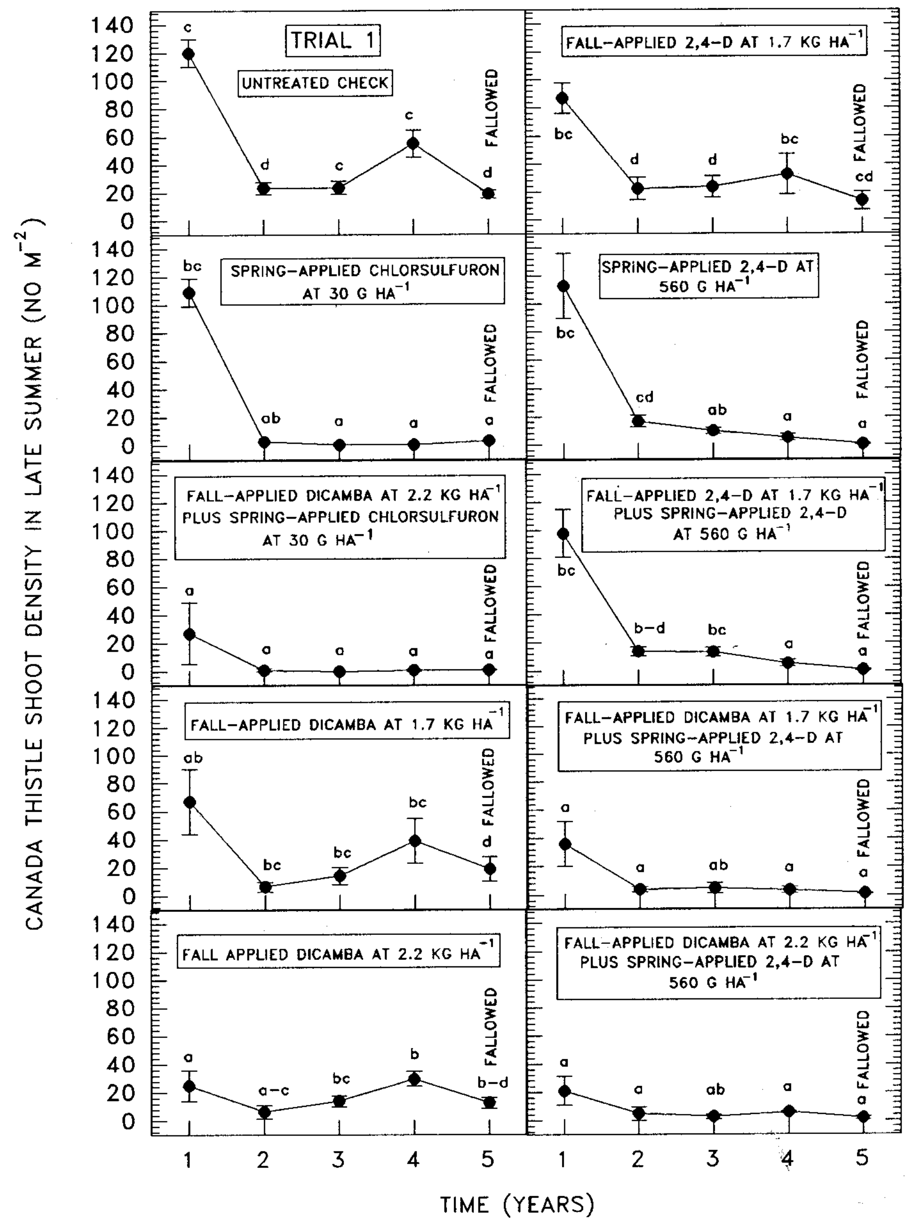

Fig. 2. Canada thistle shoot density in late summer after 1–4 yr of repeated herbicide treatment in trial 1. Wheat was grown in years 1–4, and the site was fallowed in year 5. Means ± standard errors are presented. Means within a year followed by the same letter were not significantly different at $P = 0.05$ according to the LSD test.

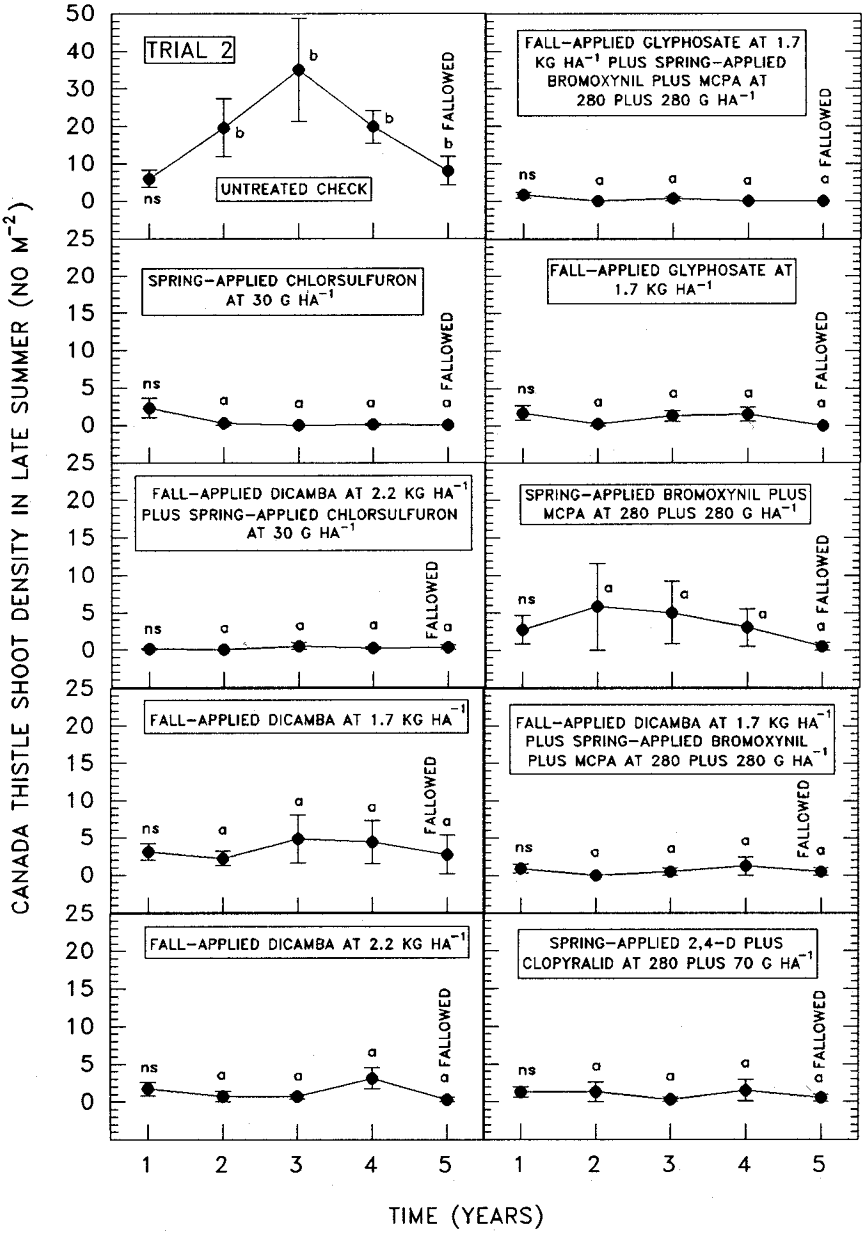

Fig. 3. Canada thistle shoot density in late summer after 1–4 yr of repeated herbicide treatment in trial 2. Wheat was grown in years 1–4, and the site was fallowed in year 5. Means ± standard errors are presented. Means within a year followed by the same letter were not significantly different at $P = 0.05$ according to the LSD range test.

in subsequent years without herbicide retreatment in trial 1. In contrast, dicamba prevented Canada thistle densities from increasing over 5 yr without any additional herbicide treatment in trial 2 (Fig. 3).

There are several possible reasons why these four treatments had a greater impact on Canada thistle in trial 2 than in trial 1 (Figs. 2 and 3). Canada thistle shoots were fivefold denser in trial 1 than in trial 2 before starting the experiment. Perhaps denser infestations have better established, deeper roots that are less likely to be killed by translocated herbicides. Summer drought 1 yr before starting trial 2 also may have reduced Canada thistle emergence in spring after initial fall herbicide treatments, making fall treatments appear to reduce Canada thistle density more in trial 2 than in trial 1. Water stress enhanced residual Canada thistle control of a naturally established infestation with herbicides in the following growing season in earlier research (Donald 1990; Donald and Prato 1992), but artificially established Canada thistle infestations responded differently to herbicides and water stress (Lauridson et al. 1983).

In trial 1, most herbicide treatments decreased Canada thistle density below the untreated check by year 2, except for fall-applied 2,4-D alone at 1.7 kg ha^{-1} or spring-applied 2,4-D at 560 g ha^{-1} alone in wheat (Fig. 2). Treated Canada thistle densities also remained below the untreated check through year 5 in trial 1, except fall-applied dicamba alone at 1.7 or 2.2 kg ha^{-1} or fall-applied 2,4-D alone at 1.7 kg ha^{-1}. The Canada thistle densities of these three treatments responded to year-to-year fluctuations in growing season rainfall in the previous year like the untreated check. A lagged response to previous rainfall for other herbicides was not observed, probably because low Canada thistle densities experience small year-to-year fluctuations.

In trial 2, all herbicide sequences reduced Canada thistle densities below the untreated check by 2 yr and through year 5 (Fig. 3). Fall-applied glyphosate at 1.7 kg ha^{-1} followed by bromoxynil plus MCPA in wheat (Table 1) reduced Canada thistle density (Fig. 3) more effectively than in previously published research (Carlson and Donald 1988). Bromoxynil plus MCPA alone progressively reduced Canada thistle density over time, as observed previously (Carlson and Donald 1988).

Canada thistle shoot density in spring before broadleaf herbicide application estimates residual Canada thistle control from herbicides applied in previous years (unpublished data). Nevertheless, herbicide sequences that reduced Canada thistle density most by late summer also decreased Canada thistle shoot emergence in subsequent successive springs. In fact, most conclusions regarding the response of Canada thistle density in late summer to herbicide sequences also apply to shoot density in the subsequent spring. No treatment sequence totally prevented shoot emergence in spring in year 5 (Figs. 2 and 3), indicating that sufficient root biomass remained to reinfest plots, despite 4 yr of herbicide treatment. Apparently, application of the same fall-applied herbicides at high rates for 2 yr was insufficient alone to maintain subsequent control of Canada thistle shoots, unless supplemented with in-crop herbicide treatment.

Canada Thistle Control

Visual observations of Canada thistle control support conclusions for Canada thistle shoot density data (Table 3). Although Canada thistle control in late summer was fair (≥75%) to excellent (≥90%) in both trials for the 2 yr immediately following treatment with fall-applied dicamba alone, subsequent control became unacceptable (≤75%) in years 3–5 in trial 1. In trial 1, fall-applied dicamba required additional treatment with 2,4-D in wheat for 4 yr to maintain good to excellent Canada thistle control. When fall-applied dicamba at 2.2 kg ha^{-1} was followed by chlorsulfuron in wheat for 4 yr, Canada thistle control was excellent through year 5 (Table 3, Fig. 2). Chlorsulfuron applied in-crop for 4 yr also provided good to excellent Canada thistle control in both trials. In trial 2, good (≥80%) to excellent

Table 3. Visually evaluated Canada thistle control in spring wheat in late summer after 1–4 years of repeated sequences of herbicide treatments

	Visually evaluated Canada thistle control (%)[y]				
	Year				
Treatment[z]	1	2	3	4	5
Trial 1					
Fall-applied dicamba at 1.7 kg ha^{-1} for 2 yr	82*b*	77*cd*	40*ab*	25*a*	28*a*
Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr	92*bc*	95*cd*	57*bc*	0*a*	25*a*
Spring-applied chlorsulfuron at 30 g ha^{-1} for 4 yr[x]	90*bc*	93*cd*	99*d*	99*b*	81*bc*
Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr plus spring-applied chlorsulfuron[x] at 30 g ha^{-1} for 4 yr	90*bc*	99*d*	98*d*	99*b*	94*c*
Fall-applied 2,4-D at 1.7 kg ha^{-1} for 2 yr	0*a*	17*a*	10*a*	0*a*	45
Fall-applied 2,4-D at 1.7 kg ha^{-1} for 2 yr plus spring-applied 2,4-D at 560 g ha^{-1} for 4 yr	50*b*	65*bc*	80*cd*	95*b*	91*bc*
Spring-applied 2,4-D at 560 g ha^{-1} for 4 yr	0*a*	33*ab*	72*bcd*	95*b*	93*c*
Fall-applied dicamba at 1.7 kg ha^{-1} for 2 yr plus spring-applied 2,4-D at 560 g ha^{-1} for 4 yr	93*bc*	88*cd*	92*d*	98*b*	86*bc*
Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr plus spring-applied 2,4-D at 560 g ha^{-1} for 4 yr	97*c*	92*cd*	95*d*	98*b*	77*bc*
$P \geq F$	0.0001	0.0003	0.0002	0.0001	0.0234
Trial 2					
Fall-applied dicamba at 1.7 kg ha^{-1} for 2 yr	82	97	86	60*a*	62
Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr	88	98	97	80*abc*	95
Spring-applied chlorsulfuron at 30 g ha^{-1} for 4 yr[x]	93	99	99	98*c*	95
Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr plus spring-applied chlorsulfuron at 30 g ha^{-1} for 4 yr[x]	97	99	98	98*c*	99
Fall-applied glyphosate at 1.7 kg ha^{-1} [x] for 2 yr	87	99	95	77*ab*	98
Fall-applied glyphosate[x] at 1.7 kg ha^{-1} for 2 yr plus spring-applied bromoxynil plus MCPA at 280 plus 280 g ha^{-1} for 4 yr	98	99	99	99*c*	99
Spring-applied bromoxynil plus MCPA at 280 plus 280 g ha^{-1} for 4 yr	83	95	92	83*bc*	95
Fall-applied dicamba at 1.7 kg ha^{-1} for 2 yr plus spring-applied bromoxynil plus MCPA at 280 plus 280 g ha^{-1} for 4 yr	99	99	99	97*bc*	90
Spring-applied clopyralid plus 2,4-D at 280 plus 70 g ha^{-1} for 4 yr	93	99	99	95*bc*	93
$P \geq F$	NS	NS	NS	0.0063	NS

[z]Treatments are more fully described in Tables 1 and 2.
[y]Means errors are presented. % = percentage of untreated check plots (=0). Means in a column for each trial followed by the same letter were not significantly different at $P = 0.05$ according to the LSD procedure.
[x]X-77 surfactant at 0.25% (v/v) was added.

Table 4. Herbicide effects on spring wheat yield after 1-3 years of controlling Canada thistle with repeated sequences of herbicide treatments in spring wheat

	Wheat yield (t ha^{-1})[y]			Present value of net return	
	Year			Discount rate	
Treatment[z]	1	2	3	6%	8%
Trial 1					
Untreated check	—	0.76+0.16*a*	0.77±0.22*a*	−4.84± 0.37	−4.01± 0.37
Fall-applied dicamba at 1.7 kg ha^{-1} for 2 yr	—	1.38±0.48*abc*	1.62±0.64*bcd*	−12.00± 0.36	−9.53± 0.36
Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr	—	1.51±0.11*abc*	1.20±0.27*abc*	−12.83± 0.99	−10.38± 0.99
Spring-applied chlorsulfuron[x] at 30 g ha^{-1} for 4 yr	—	2.13±0.24*c*	2.21±0.19*d*	−7.22± 0.31	−6.12± 0.31
Fall-applied dicamba at 1.7 kg ha^{-1} for 2 yr plus spring-applied chlorsulfuron at 30 g ha^{-1} for 4 yr	—	1.89±0.47*bc*	2.34±0.20*d*	−15.33± 0.68	−12.44± 0.68
Fall-applied 2,4-D at 1.7 kg ha^{-1} for 2 yr	—	1.00±0.15*ab*	0.90±0.17*ab*	−2.51± 1.22	−2.98± 1.22
Fall-applied 2,4-D at 1.7 kg ha^{-1} for 2 yr plus spring-applied 2,4-D at 560 g ha^{-1} for 4 yr	—	1.81±0.29*bc*	1.83±0.23*cd*	−4.75± 0.78	−4.38± 0.78
Spring-applied 2,4-D at 560 g ha^{-1} for 4 yr	—	1.99±0.08*c*	1.56±0.18*abcd*	−2.56± 0.19	−2.85± 0.19
Fall-applied dicamba at 1.7 kg ha^{-1} for 2 yr plus spring-applied 2,4-D at 560 g ha^{-1} for 4 yr	—	2.25±0.54*c*	2.09±0.19*d*	−9.59± 1.09	−8.20± 1.09
Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr plus spring-applied 2,4-D at 560 g ha^{-1} for 4 yr	—	1.61±0.32*abc*	1.76±0.32*cd*	−11.09± 0.59	−9.41± 0.59
$P \geq F$	—	0.0641	0.0094		

Trial 2					
Untreated check	2.48±0.09	1.22±0.20	0.21±0.07*a*	42.06± 2.61	32.37± 2.00
Fall-applied dicamba at 1.7 kg ha^{-1} for 2 yr	2.62±0.28	1.88±0.19	1.70±0.24*bcd*	37.82± 3.49	28.82± 2.61
Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr	2.37±0.28	1.79±0.14	1.49±0.34*bc*	39.43± 0.97	30.15± 0.92
Spring-applied chlorsulfuron[x] at 30 g ha^{-1} for 4 yr	2.58±0.11	1.86±0.19	2.15±0.23*cd*	41.88± 7.86	31.95± 6.02
Fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr plus spring-applied chlorsulfuron[x] at 30 g ha^{-1} for 4 yr	2.63±0.13	2.04±0.16	2.20±0.18*cd*	27.55± 7.72	21.07± 5.95
Fall-applied glyphosate[x] at 1.7 kg ha^{-1} for 2 yr	2.40±0.28	1.83±0.31	1.83±0.20*bcd*	31.50± 3.92	24.01± 2.94
Fall-applied glyphosate[x] at 1.7 kg ha^{-1} for 2 yr plus spring-applied bromoxynil plus MCPA at 280 plus 280 g ha^{-1} for 4 yr	2.79±0.48	2.41±0.11	2.43±0.18*d*	27.70± 4.23	21.10± 3.39
Spring-applied bromoxynil plus MCPA at 280 plus 280 g ha^{-1} for 4 yr	278±0.07	1.90±0.27	1.54±0.44*bc*	49.18± 1.74	37.72± 1.49
Fall-applied dicamba at 1.7 kg ha^{-1} for 2 yr plus spring-applied bromoxynil plus MCPA at 280 plus 280 g ha^{-1} for 4 yr	2.54±0.19	2.08±0.30	2.31±0.15*cd*	32.11± 7.85	24.48± 5.98
Spring-applied clopyralid plus 2,4-D at 280 plus 70 g ha^{-1} for 4 yr	2.96±0.09	1.64±0.13	1.25±0.54*b*	49.35±12.98	37.40±10.04
$P \geq F$	NS	NS	0.0011		

[z]Treatments are described in more detail in Tables 1 and 2.
[y]Means ± standard errors are presented. Means in a column for each trial followed by the same letter were not significantly different at P = 0.05 according to the LSD procedure.
[x]X-77 surfactant at 0.25% (v/v) was added.

Table 5. The effect of farmer risk aversion on preferences of one herbicide treatment over alternative treatments for trial 1 at a discount rate of 6%, estimated by stochastic dominance analysis[z]

	Preferred to:		
Herbicide	Risk neutral	Moderately risk averse	Strongly risk averse
Untreated check	Dicamba 1.7	Dicamba 1.7	Dicamba 1.7
	Dicamba 2.2	Dicamba 2.2	Dicamba 2.2
	Chlorsulfuron 30	Chlorsulfuron 30	Chlorsulfuron 30
	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
	Dicamba 1.7 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560
	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560
Dicamba 1.7	Dicamba 2.2	Dicamba 2.2	Dicamba 2.2
	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
Dicamba 2.2	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
Chlorsulfuron 30	Dicamba 1.7	Dicamba 1.7	Dicamba 1.7
	Dicamba 2.2	Dicamba 2.2	Dicamba 2.2
	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
	Dicamba 1.7 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560
	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560
Dicamba 2.2 + chlorsulfuron 30	—	—	—
2,4-D 1.7	Untreated check	Untreated check	Untreated check
	Dicamba 1.7	Dicamba 1.7	Dicamba 1.7
	Dicamba 2.2	Dicamba 2.2	Dicamba 2.2
	Chlorsulfuron 30	Chlorsulfuron 30	Chlorsulfuron 30
	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
	2,4-D 1.7 + 2,4-D 560	2,4-D 1.7 + 2,4-D 560	2,4-D 1.7 + 2,4-D 560
	2,4-D 560	?2,4-D 560?[y]	
	Dicamba 1.7 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560
	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560
2,4-D 1.7 + 2,4-D 560	Untreated check	Untreated check	Untreated check
	Dicamba 1.7	Dicamba 1.7	Dicamba 1.7
	Dicamba 2.2	Dicamba 2.2	Dicamba 2.2
	Chlorsulfuron 30	Chlorsulfuron 30	Chlorsulfuron 30
	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
	Dicamba 1.7 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560
	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560

2,4-D 560	Untreated check	Untreated check	Untreated check
	Dicamba 1.7	Dicamba 1.7	Dicamba 1.7
	Dicamba 2.2	Dicamba 2.2	Dicamba 2.2
	Chlorsulfuron 30	Chlorsulfuron 30	Chlorsulfuron 30
	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
	2,4-D 1.7 + 2,4-D 560	?2,4-D 1.7?[y]	2,4-D 1.7
	Dicamba 1.7 + 2,4-D 560	2,4-D 1.7 + 2,4-D 560	2,4-D 1.7 + 2,4-D 560
	Dicamba 2.2 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560	Dicamba 1.7 + 2,4-D 560
		Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560
Dicamba 1.7 + 2,4-D 560	Dicamba 1.7	Dicamba 1.7	Dicamba 1.7
	Dicamba 2.2	Dicamba 2.2	Dicamba 2.2
	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560	Dicamba 2.2 + 2,4-D 560
Dicamba 2.2 + 2,4-D 560	Dicamba 1.7	Dicamba 1.7	Dicamba 1.7
	Dicamba 2.2	Dicamba 2.2	Dicamba 2.2
	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30

[z] Numbers with a decimal following treatment refer to kilograms active ingredient or acid equivalent ha^{-1}, and those without to g a.i. or a.e. ha^{-1}.
[y] Question marks preceeding and following a treatment indicate indeterminancy in the preference ordering.

control was maintained through year 5 following fall-applied dicamba at 2.2 kg ha^{-1} for 2 yr, but not with fall-applied dicamba at 1.7 g ha^{-1} for 2 yr, in contrast with results on shoot density (Table 3, Fig. 3).

In trial 1, fall-applied 2,4-D for 2 yr did not control Canada thistle well in subsequent years (Fig. 2). When fall-applied 2,4-D was followed in spring by 2,4-D at 560 g ha^{-1}, however, Canada thistle control gradually increased and was excellent (≥90%) in years 4 and 5. When 2,4-D at 560 g ha^{-1} was applied in-crop, Canada thistle control increased more slowly but was excellent by years 4 and 5.

In trial 2, glyphosate at 1.7 kg ha^{-1} provided good to excellent Canada thistle control most years over 5 yr (Table 3, Fig. 3), in sharp contrast with shorter-lived control observed previously (Carlson and Donald 1988). In this earlier experiment (Carlson and Donald 1988), a herbicide had to be applied in-crop for several additional years to maintain the high initial control achieved by glyphosate. In trial 2 spring-applied tank-mix combinations of bromoxynil plus MCPA at 280 plus 280 g ha^{-1}, respectively, or 2,4-D plus clopyralid at 70 plus 280 g ha^{-1}, respectively, also provided good to excellent Canada thistle control for 5 yr. These observations for bromoxynil plus MCPA substantiate previous research (Carlson and Donald 1988).

Wheat Yield

Herbicide treatment increased wheat yield above the untreated check in 1985, 1986, and 1987, probably because Canada thistle densities limited yield in those years (Table 4). Canada thistle is highly competitive with wheat and reduces wheat yield because (i) it emerges slightly before or with spring wheat in most years, (ii) it can be very dense in patches, and (iii) its roots can reach subsoil moisture better than can shallower wheat roots (Donald 1990).

In trial 1, fall-applied herbicides for 2 yr followed by either spring-applied chlorsulfuron or 2,4-D increased wheat yield above that of the untreated check (Table 4). Spring-applied chlorsulfuron increased yield in all

Table 6. The effect of farmer risk aversion on preferences of one herbicide treatment over alternative treatments for trial 2 at a discount rate of 6%, estimated by stochastic dominance analysis[z]

	Preferred to:		
Herbicide	Risk neutral	Moderately risk averse	Strongly risk averse
Untreated check	Dicamba 1.7 Dicamba 2.2 Chlorsulfuron 30 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil	Dicamba 1.7 Dicamba 2.2 Chlorsulfuron 30 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil	Dicamba 1.7 Dicamba 2.2 Chlorsulfuron 30 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil
Dicamba 1.7	Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil	Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil	Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil
Dicamba 2.2	Dicamba 1.7 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil	Dicamba 1.7 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil	Dicamba 1.7 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil
Chlorsulfuron 30	Dicamba 1.7 Dicamba 2.2 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil	Dicamba 1.7 Dicamba 2.2 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil	Dicamba 1.7 Dicamba 2.2 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil
Dicamba 2.2 + chlorsulfuron 30	—	—	—
Glyphosate 1.7	Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 + MCPA + bromoxynil	Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 + MCPA + bromoxynil	Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 + MCPA + bromoxynil ?Dicamba 1.7 + MCPA + bromoxynil?[y]
Glyphosate 1.7 + MCPA + bromoxynil	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
MCPA 280 + bromoxynil	Untreated check Dicamba 1.7 Dicamba 2.2 Chlorsulfuron 30 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil 2,4-D 280 + clopyralid 70	Untreated check Dicamba 1.7 Dicamba 2.2 Chlorsulfuron 30 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil 2,4-D 280 + clopyralid 70	Untreated check Dicamba 1.7 Dicamba 2.2 Chlorsulfuron 30 Dicamba 2.2 + chlorsulfuron 30 Glyphosate 1.7 Glyphosate 1.7 + MCPA + bromoxynil Dicamba 1.7 + MCPA + bromoxynil 2,4-D 280 + clopyralid 70

Dicamba 1.7 + MCPA + bromoxynil	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
	Glyphosate 1.7	Glyphosate 1.7	?Glyphosate 1.7?[y]
	Glyphosate 1.7 + MCPA + bromoxynil	Glyphosate 1.7 + MCPA + bromoxynil	Glyphosate 1.7 + MCPA + bromoxynil
2,4-D 280 + clopyralid 70	Untreated check	Untreated check	Untreated check
	Dicamba 1.7	Dicamba 1.7	Dicamba 1.7
	Dicamba 2.2	Dicamba 2.2	Dicamba 2.2
	Chlorsulfuron 30	Chlorsulfuron 30	Chlorsulfuron 30
	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30	Dicamba 2.2 + chlorsulfuron 30
	Glyphosate 1.7	Glyphosate 1.7	Glyphosate 1.7
	Glyphosate 1.7 + MCPA + bromoxynil	Glyphosate 1.7 + MCPA + bromoxynil	Glyphosate 1.7 + MCPA + bromoxynil
	MCPA 280 + bromoxynil 280	Dicamba 1.7 + MCPA + bromoxynil	Dicamba 1.7 + MCPA + bromoxynil
	Dicamba 1.7 + MCPA + bromoxynil		

[z]Numbers with a decimal following treatment refer to kilograms active ingredient or acid equivalent ha^{-1}, and those without to g a.i. or a.e. ha^{-1}.
[y]Question marks preceding and following a treatment indicate indeterminancy in the preference ordering.

years, whereas 2,4-D alone increased yield in 1 of 2 yr in trial 1. Fall-applied dicamba alone at 1.7 kg ha^{-1} increased yield in 1 of 2 yr, whereas dicamba at 2.2 kg ha^{-1} did not increase yield in either year, even though these dicamba treatments adequately controlled Canada thistle (Table 3) and decreased shoot densities (Figs. 2 and 3). Dicamba did not appear to carry over because wheat was neither damaged nor stunted in the growing season following fall application.

In trial 2, fall-applied herbicide treatments for 1 to 2 yr followed by either spring-applied chlorsulfuron or bromoxynil plus MCPA in-crop increased yield relative to the untreated check in 1 of 3 yr (Table 4). In-crop treatment with either chlorsulfuron or bromoxynil plus MCPA alone also increased yields in 1 of 3 yr. Fall-applied dicamba alone at either 1.7 or 2.2 kg ha^{-1} increased yield in 1 of 3 yr in trial 2, in contrast with results obtained in trial 1. It must be noted that persistent phytotoxic herbicide residues of fall-applied dicamba may limit rotational crop options in the northern Great Plains.

Yields never achieved their full potential according to North Dakota State University fertilizer recommendations, probably because drought and Canada thistle limited yield more than did nitrogen availability (Table 4).

Net Returns and Risk Preferences

The present value of net returns for the 10 treatment sequences are summarized for each trial (Table 4). Because no wheat was harvested in year 1 (1983), the present value of net returns was negative for all treatments in trial 1 that year. After net returns were subjected to stochastic dominance analysis with respect to a function (SDWF), projected farmer preferences for alternative herbicide sequences were reported for each trial for three risk-preference cases: risk neutrality, moderate risk aversion, and high risk aversion (Tables 5–7).

According to SDWF for trial 1, three sequences of herbicide treatments were preferred to the untreated check at a discount rate of 6% in all three risk-aversion cases: (*i*) fall-applied 2,4-D at 1.7 kg ha^{-1}, (*ii*) spring-applied 2,4-D at 560 g ha^{-1} in wheat, and (*iii*) a sequence of (*i*) followed by (*ii*) above (Table 5). This occurred because the present value of net return for the untreated check was more negative than these three herbicide treatments. The untreated check was preferred to the other six herbicide treatments at a 6% discount rate. All other herbicide treatments were preferred to the fall-applied dicamba at 2.2 kg ha^{-1} followed by chlorsulfuron at 30 g ha^{-1} treatment.

In trial 1 predicted preference for various 2,4-D sequences compared to other treatments depended on the risk-aversion case, in contrast with other herbicide treatments that were independent of the risk-aversion case (Table 5). Fall-applied 2,4-D at 1.7 kg ha^{-1} for 2 yr was calculated to be preferred to all other herbicide treatments by risk-neutral or moderately risk-averse farmers. Strongly risk-averse farmers probably would prefer sequences of 2,4-D applied in-crop at 560 g ha^{-1} to fall-applied 2,4-D at 1.7 kg ha^{-1} either with or without 2,4-D in-crop at 560 g ha^{-1}.

When the discount rate was increased from 6 to 8% preference for trial 1, orderings among herbicide treatments remained unchanged for the three risk cases (unpublished data). However, the ordering of preferences was slightly different at the 8% discount rate compared with the 6% rate . For all three risk cases, the untreated check was preferred to fall-applied 2,4-D at 1.7 kg ha^{-1} plus 2,4-D at 560 g ha^{-1} applied in wheat. For the risk-neutral case, 2,4-D at 560 g ha^{-1} applied in wheat was less preferred to fall-applied 2,4-D at 1.7 kg ha^{-1}, whereas preference ordering is indeterminate for the moderately risk-averse case.

In trial 2, several preference rankings for herbicide treatments remained the same for all three risk cases at a 6% discount rate (Table 6). The untreated check was preferred to all herbicide treatments except MCPA plus bromoxynil at 280 plus 280 g ha^{-1}, respectively, and 2,4-D plus clopyralid at 280 plus 70 g ha^{-1}, respectively, regardless of risk preference. MCPA plus bromoxynil would be preferred to 2,4-D plus clopyralid by moderately and strongly risk-averse farmers. Chlorsulfuron at 30 g ha^{-1} was preferred to all other treatment sequences, except the untreated check, MCPA plus bromoxynil at 280 plus 280 g ha^{-1}, respectively, and 2,4-D plus clopyralid at 280 plus 70 g ha^{-1}, respectively. All other treatments were preferred to the sequence of fall-applied dicamba at 2.2 kg ha^{-1} followed by chlorsulfuron at 30 g ha^{-1}, as in trial 1.

In trial 2, treatment sequences of MCPA plus bromoxynil and 2,4-D plus clopyralid were the only treatments preferred over the untreated check when the discount rate was increased from 6 to 8% (unpublished data). MCPA plus bromoxynil at 280 plus 280 g ha^{-1}, respectively, would likely be preferred to 2,4-D plus clopyralid at 280 plus 70 g ha^{-1}, respectively, by moderately and strongly risk-averse farmers. There were minor differences in treatment preferences across the three risk cases at the 8% discount rate in trial 2, but these differences were limited to treatment sequences that were not preferred to the untreated check.

Herbicide preferences were summarized by ranking each herbicide treatment sequence by how often it was preferred to all other treatments (Table 7). Although the absolute ranking of the five treatments that were common to both trials differed, the relative ranking was quite similar, namely, untreated check, chlorsulfuron at 30 g ha^{-1}, dicamba at either 1.7 or 2.2 kg ha^{-1} (rank reverses between trials 1 and 2), and dicamba at 2.2 kg ha^{-1} followed by chlorsulfuron at 30 g ha^{-1}. Only two treatments are preferred to the untreated check in both trials, namely 2,4-D at 560 g ha^{-1} applied in wheat and fall-applied 2,4-D at 1.7 kg ha^{-1} in trial 1 and MCPA plus bromoxynil at 280 plus 280 g ha^{-1}, respectively, and 2,4-D plus clopyralid at 280 plus 70 g ha^{-1}, respectively, in trial 2. Treatments including dicamba and/or chlorsulfuron were preferred less than the untreated check in trial 1 (Table 5). Treatments that included dicamba, glyphosate, or chlorsulfuron were less preferred than the untreated check in trial 2 (Table 6).

Table 7. Overall ranking of herbicide treatments for trials 1 and 2[z]

Ranking	Trial 1	Trial 2
1	2,4-D 560	MCPA 280 + bromoxynil 280
2	2,4-D 1.7	2,4-D 280 + clopyralid 70
3	Untreated check[y] and 2,4-D 1.7 + 2,4-D 560[x]	Untreated check[y]
4	Chlorsulfuron 30[y]	Chlorsulfuron 30[y]
5	Dicamba 1.7 + 2,4-D 560	Dicamba 2.2[y]
6	Dicamba 2.2 + 2,4-D 560	Dicamba 1.7[y]
7	Dicamba 1.7[y]	Dicamba 1.7 + MCPA + bromoxynil
8	Dicamba 2.2[y]	Glyphosate 1.7
9	Dicamba 2.2 + chlorsulfuron 30[y]	Glyphosate 1.7 + MCPA + bromoxynil
10	—	Dicamba 2.2 + chlorsulfuron 30[y]

[z] Numbers with a decimal following treatment refer to kilograms active ingredient or acid equivalent ha^{-1}, and those without to g a.i. or a.e. ha^{-1}.
[y] Treatments common to both trials.
[x] Both treatments tied for third place.

This research provides farmers with information on the limitations of multiple-year strategies incorporating fall-applied herbicides for controlling Canada thistle in reduced-till spring wheat. There was little value in using fall-applied herbicides, such as dicamba, glyphosate, or 2,4-D at high rates, for long-term Canada thistle control when certain in-crop herbicides, such as chlorsulfuron, MCPA plus bromoxynil, or 2,4-D plus clopyralid, were applied for general weed control. Although some herbicide sequences reduced the severity of this perennial weed over time, fall-applied dicamba at high rates or spring-applied chlorsulfuron may limit rotational crop options. Fall-applied dicamba or glyphosate at high rates may not be profitable for low-valued crops, like spring wheat. These fall-applied herbicides may have value for higher valued crops that lack selective herbicides for Canada thistle control yet can tolerate potentially phytotoxic herbicide residues. Rotation of sulfonylurea herbicides with other effective herbicide combinations, such as clopyralid plus 2,4-D, would be preferable to slow the development of herbicide-resistant annual weed populations in wheat. Changes in Canada thistle shoot density provide additional support for the contention that drought can enhance the efficacy of repeated annual herbicide treatment for Canada thistle control, as suggested earlier (Carlson and Donald 1988; Donald and Prato 1992).

ACKNOWLEDGMENT

We thank R. Hoerauf and numerous hourly workers for technical assistance.

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