Weed Science, 1992. Volume 40:590–598

# Yield Loss Assessment for Spring Wheat (*Triticum aestivum*) Infested with Canada Thistle (*Cirsium arvense*)[1]

WILLIAM W. DONALD and MOHAMMAD KHAN[2]

*Abstract.* **In eight of nine trials spanning 5 yr, relative yield of semidwarf hard red spring wheat (yield expressed as a percent of estimated weed-free yield) decreased linearly as Canada thistle shoot density increased when measured in late July to early August in the northern Great Plains. Differences between yield loss assessment (YLA) equations could not be distinguished statistically between no-tillage and chisel-plowed production systems. Multiple linear regression equations of relative wheat yield versus wheat density plus Canada thistle shoot density accounted for more variability in YLA equations than simple linear regression equations of wheat yield versus Canada thistle shoot density alone. Estimated weed-free wheat yield and negative slope (b) for yield loss assessment equations increased as cumulative growing-season (April to August) rainfall increased. Thus, relative wheat yield was decreased more by increasing Canada thistle density (slope b became more negative) in years of greater growing-season rainfall. Nomenclature: Canada thistle, *Cirsium arvense* (L.) Scop. #[3] CIRAR; wheat, *Triticum aestivum* L. 'Wheaton' and 'Len'.**
*Additional index words.* **Chisel plow, competition, interference, no-tillage, reduced tillage, tillage.**

## INTRODUCTION

Methodology for crop yield loss assessment (YLA)[4] for crop diseases and insects has been reviewed (15). In YLA for annual weeds, decreases in yield are related to some measure of increasing weed growth such as density or biomass. Alternatively, YLA may be expressed as relative decreases in yield as a percent of the weed-free yield versus some measure of increasing weed growth. YLA has value for describing the impact of weeds on crop production. Economic analyses of YLA relationships could help estimate profitability of weed control measures in break-even analyses. Much descriptive YLA of weeds has been misnamed "competition" (16) research, which actually deals with physiological, ecological, and biochemical mechanisms responsible for plant interactions.

Few crop YLA studies have been conducted with perennial weeds (16). The extent to which increasing densities of Canada thistle reduce yield of winter and spring wheat, barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), rapeseed (*Brassica napus* L.), and alfalfa (*Medicago sativa* L.) in conventional production systems has been reviewed (3). However, older published research (3, 6, 12) on spring wheat YLA due to Canada thistle has several limitations: modern statistical methods, such as least square regression analysis, were not used, which makes economic analyses difficult for older data; agronomic practices were not completely described; results using older agronomic practices, such as moldboard plowing, are not completely transferable to current reduced-tillage agronomic practices; and Canada thistle probably would reduce yields of current semidwarf varieties of spring wheat more than older standard-height varieties.

Wheat YLA for modern semidwarf spring wheat infested with Canada thistle grown under reduced tillage, such as chisel plowing or no-tillage, has not been described in the literature. Reduced-tillage production practices may increase Canada thistle growth and competitive ability because the root system is less disturbed by reduced tillage than by moldboard plowing (3). Objectives of this research were to: determine whether linear or multiple linear regression equations best described functional relationships between spring wheat yield and Canada thistle shoot density, Canada thistle shoot dry weight, and/or wheat density; determine whether estimated wheat yield or negative slope from YLA equations of wheat yield versus Canada thistle density at harvest were related to either monthly or cumulative growing season rainfall; determine whether Canada thistle shoot density in spring estimated wheat yield loss better than shoot density measured in late summer (plot experiments only); and determine whether wheat yield loss due to increasing Canada thistle shoot density was greater in no-tillage than in chisel-plowed cropping systems (plot experiments only).

## MATERIALS AND METHODS

**Wheat YLA in quadrats.** *General methods.* Treatments were various Canada thistle shoot densities from 0 to 230 shoots $m^{-2}$ across a naturally established patch infesting hard red spring wheat in a chisel plow production system. It is more valid to use the term "shoot density" than "plant density"

[1]Received for publication October 17, 1991, and in revised form June 3, 1992. Contribution of the Cropping Syst. Water Quality Res. Unit, USDA-ARS. Published with the approval of the Director, Agric. Exp. Stn., North Dakota State Univ. as J. Art. No. 2000.

[2]Res. Agron., Cropping Systems and Water Quality Res. Unit, USDA-ARS, 244 Agric. Engr. Bldg., UMC, Columbia, MO 65211 and Plant Physiol., Agric. Res. Inst., Tarnab (Peshawar) NWFP, Pakistan. Addresses of authors when research was conducted: USDA-ARS Biosciences Res. Lab. and Dep. Crop and Weed Sci., North Dakota State Univ., Fargo, ND 58105.

[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: $D_h$, late July to early August counts of Canada thistle shoot density $m^{-2}$; $D_o$, early June counts of Canada thistle shoot density $m^{-2}$; W, wheat plant density $m^{-2}$ in spring; X, Canada thistle shoot dry weight $m^{-2}$ in late July to early August; Y, wheat yield in kg $ha^{-1}$; and YLA, yield loss assessment.

because one established Canada thistle plant (genet) may produce several new adventitious shoots (ramets) from adventitious root buds on the interconnected roots of this perennial weed (3). In 1987, 1988, and 1989, 47 to 60 0.75-$m^2$ quadrats were placed at random shortly after wheat planting, but before Canada thistle shoot emergence, both in and adjacent to a natural patch of Canada thistle [subspecies 'arvense' (Wimm. and Grab.)] (9). Only adventitious shoots of Canada thistle arising from adventitious root buds were counted in early June ($D_o$)[4] and immediately before wheat harvest ($D_h$)[4] because seedlings were rare (Table 1). Canada thistle shoots were harvested in early August, washed free of soil, and dried at 70 C for at least 3 d before shoot dry weight determination. Wheat seed was hand harvested from each quadrat in early August, air dried, cleaned, and weighed (Table 1). Net wheat yields were calculated based on grain weight adjusted to 13% moisture content.

The experiment was located on the North Dakota State University Experimental Farm in Fargo (40° 16.36 N, 96° 14.54 W, 272-m altitude). The soil type was a Fargo silty clay (fine, montmorillonitic, frigid Vertic Haplaquolls) with 2.5% sand, 51.7% silt, 45.8% clay, 4.8% organic matter, and a pH of 7.9. Dates of significant field events are summarized in Table 1. The site had been mechanically fallowed in 1986 and was chisel plowed in the fall of 1987 and 1988.

Emerged annual broadleaf and grass weeds present before planting were controlled by field cultivation-harrowing for seedbed preparation. Wheaton semidwarf hard red spring wheat was planted with a no-tillage double-disc grain drill[5] at 100, 120, and 90 kg $ha^{-1}$ 3.8 to 5 cm deep in rows spaced 17.5 cm apart in 1987, 1988, and 1989, respectively. In 1987, 1988, and 1989 wheat density averaged 170, 140, and 110 plants $m^{-2}$, respectively, after establishment.

Nitrogen was applied each year for a 2690 kg $ha^{-1}$ wheat yield goal as recommended by North Dakota State University from tests on soil samples collected in late fall. Nitrogen as urea was banded at planting approximately 6 cm deep in 35-cm rows halfway between wheat rows at 60, 120, and 80 kg N $ha^{-1}$ in 1987, 1988, and 1989, respectively. No other mineral nutrients were recommended or applied.

Diclofop {(±)-2-[4-(2,4-dichlorophenoxy)-phenoxy]propanoic acid} at 1.1 kg ae $ha^{-1}$ plus thifensulfuron {3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid} at 2 g ai $ha^{-1}$ plus nonionic surfactant[6] at 0.25% by vol were applied to the entire experiment during the second week of June in 1987 and 1988 for annual grass and broadleaf weed control, respectively, after wheat began tillering (Table 1). Herbicides were applied with a tractor-drawn garden sprayer calibrated to deliver 140 to 190 L $ha^{-1}$ of water carrier at 140 to 170 kPa. The sprayer was equipped with flat-fan nozzles[7] spaced 50 cm apart on a 3.1-m boom drawn at 5.5 to 6.1 km $h^{-1}$. Treatments eliminated sparse, scattered wild oats (*Avena fatua* L. # AVEFA), green foxtail [*Setaria viridis* (L.) Beauv. # SETVI], and yellow foxtail (*Setaria glauca* L.). Sparse stands of kochia [*Kochia scoparia* (L.) Schrad. # KCHSC] and wild mustard (*Brassica kaber* L. # SINAR) seedlings that emerged with Canada thistle after wheat planting were controlled 90%. Diclofop (10) and thifensulfuron (2) applied postemergence at commercial rates do not influence wheat yield or Canada thistle growth.

*Table 1.* Dates on which significant field operations were performed at Fargo, ND.

| Operation | Dates | | |
|---|---|---|---|
| | Trial 1 | Trial 2 | Trial 3 |
| Fall chisel plowed | No | 10/7/87 | 10/10/88 |
| Seedbed prepared by field cultivation-harrowing | 4/17/87 | 5/16/88 | 4/28/89 |
| Wheat planted and fertilized | 4/28/87 | 5/17/88 | 5/1/89 |
| Wheat density determined | 6/3/87 | 6/7–8/88 | 6/2/89 |
| Diclofop and thifensulfuron applied | 6/15/87 | 6/10/88 | No |
| Canada thistle shoot density determined: | | | |
| In early June | 6/11/87 | 6/8/88 | 6/8/89 |
| In late July to early August | 7/23/87 | 7/22/88 | 8/2/89 |
| Canada thistle shoot dry weight determined | 8/4/87 | 7/27–8/1/88 | 8/9/89 |
| Wheat harvested | 8/6/87 | 7/27–8/1/88 | 8/9/89 |

*Experimental design and statistical analysis.* A completely randomized design was used, and the experiment was repeated from 1987 to 1989. Data were subjected to single and multiple least squares regression analyses using SPSS/PC+ software[8] (13, 14). Equations were calculated for relationships between wheat yield (Y), the dependent variable, and Canada thistle shoot density ($D_h$ in no. $m^{-2}$) or shoot dry weight (X in g $m^{-2}$) in late July to early August, and wheat density in early June (W in no. $m^{-2}$) in all combinations. Equations were calculated for absolute wheat yield as a function of increasing Canada thistle shoot density from $Y = a - b^*D_h$, where Y = wheat yield in kg $ha^{-1}$, a = Y intercept (estimated weed-free wheat yield at zero Canada thistle shoot density), b = slope, and $D_h$ = Canada thistle shoot density in no. $m^{-2}$ in late July to early August. Equations for relative wheat yield (yield loss expressed as a percent of the weed-free yield) were derived from these latter equations using $Y(\%) = ((a_i/a)^*100) - ((b/a)^*D_h^*100)$, where $Y(\%)$ = wheat yield as a percent of estimated weed-free wheat, and $a_i$ = estimated yield observations at zero Canada thistle shoot density, and a, b, and $D_h$ were described above.

The Y-axis intercept of the least squares regression equation for wheat yield as a linear function of Canada thistle shoot density in late summer was used to estimate weed-free wheat yield. Two other methods were compared for

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

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

[7]Teejet 8003 flat-fan spray nozzle. Spraying Systems Co., Wheaton, IL 60187.

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

estimating weed-free yield of wheat infested with Canada thistle: wheat was kept weed free by handweeding quadrats placed within a natural patch, and wheat was sampled from naturally weed-free quadrats placed outside of a patch. Yields were compared by t-tests (13).

Adequacy of least squares regression equations was determined by calculating coefficients of determination ($r^2$) and inspection of plots of residuals versus the independent variable(s) of regression equations. The coefficients for the Y-axis intercept and slope were calculated for regression equations having the greatest $r^2$ and were tested for the null hypothesis that they were not different than zero. F- or t-tests were performed on $r^2$ values, depending upon sample size, to determine whether adding variables in multivariate equations increased the $r^2$ values (8, 14). Z- or t-test statistics were calculated to determine whether equations were parallel [i.e., whether pairs of slopes of regression equations were significantly different from one another (8)].

**Wheat YLA in plots.** *General methods.* Data were reanalyzed for this research from previously described experiments on herbicides for Canada thistle control in semidwarf wheat in fall chisel-plowed (5) or no-tillage (4) production systems. No-tillage plots did not receive any prior primary or secondary tillage. Semidwarf Len hard red wheat was planted in 1984 and 1985 and genetically related semidwarf Wheaton wheat was planted thereafter.

*Experimental design and statistical analysis.* These experiments were arranged in a randomized complete block design with three blocks and were conducted concurrently on immediately adjacent land (4, 5). Three herbicide treatments that were common to both experiments were pooled for analysis. In this approach, herbicides were assumed to be nonphytotoxic to wheat and influenced wheat yield only indirectly by reducing Canada thistle shoot density. Wheat was not visibly damaged by herbicide treatment (4, 5). Least squares regression equations were calculated for relationships between wheat yield and Canada thistle shoot density at either the time of broadleaf herbicide application in early June and in late July to early August just before wheat harvest. The adequacy of least squares regression equations was determined by calculating $r^2$ values and inspection of plots of residuals versus the independent variable(s) of regression equations. Coefficients for Y-axis intercept and slope were calculated for regression equations having the greatest $r^2$ and were tested for the null hypothesis that they were not different than zero.

Total cumulative rainfall was calculated for the following time periods each year: April, May, June, July; April through May; April through June; April through July; May through June; May through July; and June through July. Estimated weed-free yield (a) and negative slopes (b) of YLA equations were regressed on total cumulative monthly rainfall for all YLA relationships between wheat yield and Canada thistle shoot density in late summer. Adequacy of least squares regression equations was determined by calculating $r^2$ values and inspection of plots of residuals versus the independent variable(s) of regression equations. The coefficients of the Y-axis intercept and slope were calculated for regression equations having the greatest $r^2$ and were tested for the null hypothesis that they were not different than zero.

## RESULTS AND DISCUSSION

**Spring wheat YLA in quadrats.** Spring wheat yield (Table 2) or relative yield (Figure 1) decreased linearly with increasing Canada thistle shoot density or shoot dry weight in a fall chisel-plowed production system. Values of $r^2$ for YLA equations of wheat yield as a function of increasing Canada thistle shoot density in late July to early August were 0.47, 0.29, and 0.63 in 1987, 1988, and 1989, respectively (Figure 1 and Table 2). These relatively low $r^2$ reflect data variability, rather than lack of fit to a linear model.

Often, relative crop yield is related only to weed density in YLA, although other measures of weed growth could be used. Hume (7) reported that weed shoot dry weight $m^{-2}$ estimated relative spring wheat yield due to annual weeds better than did weed density. However, O'Sullivan et al. (11) observed that for Canada thistle infesting barley, Canada thistle shoot density estimated wheat yield better than shoot dry weight $m^{-2}$.

Estimating wheat yield from Canada thistle shoot dry weight had no advantage over using Canada thistle shoot density (Table 2). For Canada thistle infesting wheat, $r^2$ values for relationships between wheat yield and either Canada thistle shoot density or Canada thistle shoot dry weight $m^{-2}$ alone could not be distinguished from one another by the Z statistic. Thus, both functional relationships accounted for equivalent amounts of data variability. However, from a practical standpoint Canada thistle shoot density is preferable to shoot dry weight $m^{-2}$ for estimating relative wheat yield (Figure 2) because determination of shoot density is nondestructive, inexpensive, and relatively quick.

Including crop density in addition to weed growth as independent variables in multivariate YLA equations has been suggested to improve model fit (1, 7). Wheat yield was expressed as a function of wheat density, Canada thistle shoot density, and/or Canada thistle shoot dry weight as independent variables using multiple linear regression and compared with simple linear regression models using these respective independent variables alone to determine whether additional independent variables helped estimate wheat yield more precisely (Table 2). Values for $r^2$ were less than 0.8 for all linear relationships between wheat yield and single independent variables. Multivariate relationships between wheat yield and two independent variables increased values of $r^2$ above the $r^2$ values for relationships between wheat yield and the corresponding single variables in all 3 yr, as indicated by Z statistics for various comparisons of $r^2$ values. Multivariate relationships between wheat yield and all three independent variables taken together never increased $r^2$ values above those for multivariate relationships including two independent variables.

Multivariate relationships between wheat yield and wheat density plus Canada thistle shoot density accounted for more model variability than relationships between wheat yield and Canada thistle density alone all 3 yr, as indicated by Z

*Table 2*. Linear least squares regression equations[a] describing the functional relationship between spring wheat yield (Y in kg $ha^{-1}$) and Canada thistle shoot density ($D_h$ in no. $m^{-2}$), Canada thistle shoot dry weight (X in g $m^{-2}$), and spring wheat density (W in no. $m^{-2}$) based on quadrats in a fall chisel-plowed production system at Fargo, ND.

| Year | Functional relationship[b] | n[c] | $r^2$[d] |
|---|---|---|---|
| 1987 | Y = 1636 (± 151)*** − 12.8 (± 2.0)*** $D_h$ | 47 | 0.47 |
| | Y = 1922 (± 132)*** − 4.4 (± 0.5)*** X | 47 | 0.66 |
| | Y = −602 (± 127)*** + 17.7 (± 1.4)*** W | 47 | 0.79 |
| | Y = −237 (± 237)NS − 3.1 (± 1.7)NS $D_h$ + 15.5 ( ± 1.8)*** W | 47 | 0.79 |
| | Y = 75 (± 127)NS − 1.4 (± 0.6)*** X + 13.5 ( ± 2.4)* W | 47 | 0.79 |
| 1988 | Y = 475 (± 33)*** − 2.5 (± 0.5)*** $D_h$ | 60 | 0.29 |
| | Y = 461 (± 33)*** − 2.0 (± 0.5)*** X | 60 | 0.24 |
| | Y = −260 (± 66)*** + 2.5 (± 0.3)*** W | 60 | 0.62 |
| | Y = −168 (± 92)NS − 0.6 (± 0.5)NS $D_h$ + 2.3 ( ± 0.3)*** W | 60 | 0.62 |
| | Y = −171 (± 84)* − 0.6 (± 0.4)NS X + 2.3 ( ± 0.3)*** W | 60 | 0.64 |
| 1989 | Y = 1492 (± 90)*** − 16.7 (± 1.9)*** $D_h$ | 47 | 0.63 |
| | Y = 1414 (± 93)*** − 6.0 (± 0.8)*** X | 47 | 0.56 |
| | Y = −321 (± 157)* + 11.2 (± 1.4)*** W | 47 | 0.60 |
| | Y = 607 (± 259)* − 10.3 (± 2.5)** $D_h$ + 6.1 ( ± 1.7)*** W | 47 | 0.70 |
| | Y = 417 (± 260)NS − 3.3 (± 1.0)** X + 7.0 ( ± 1.7)** W | 47 | 0.68 |

| Year | Comparison of pairs of $r^2$ for the following relationships: | P ≥ F for Z statistic (n > 25) or t test (n < 25) |
|---|---|---|
| 1987 | Y = X versus Y = W | NS |
| | Y = X versus Y = $D_h$ | NS |
| | Y = $D_h$ versus Y = W | ** |
| | Y = W versus Y = W + $D_h$ | NS |
| | Y = $D_h$ versus Y = W + $D_h$ | * |
| | Y = W versus Y = W + X | NS |
| | Y = X versus Y = W * X | NS |
| | Y = X + W versus Y = X + W + $D_h$ | NS |
| | Y = $D_h$ + W versus Y = X + W + $D_h$ | NS |
| 1988 | Y = X versus Y = W | NS |
| | Y = X versus Y = $D_h$ | NS |
| | Y = $D_h$ versus Y = W | NS |
| | Y = W versus Y = W + $D_h$ | NS |
| | Y = $D_h$ versus Y = W + $D_h$ | * |
| | Y = W versus Y = W + X | NS |
| | Y = X versus Y = W * X | NS |
| | Y = X + W versus Y = X + W + $D_h$ | NS |
| | Y = $D_h$ + W versus Y = X + W + $D_h$ | NS |
| 1989 | Y = X versus Y = W | NS |
| | Y = X versus Y = $D_h$ | NS |
| | Y = $D_h$ versus Y = W | NS |
| | Y = W versus Y = W + $D_h$ | NS |
| | Y = $D_h$ versus Y = W + $D_h$ | * |

*(continued)*

*Table 2. (continued)* Linear least squares regression equations[a] describing the functional relationship between spring wheat yield (Y in kg $ha^{-1}$) and Canada thistle shoot density ($D_h$ in no. $m^{-2}$), Canada thistle shoot dry weight (X in g $m^{-2}$), and spring wheat density (W in no. $m^{-2}$) based on quadrats in a fall chisel-plowed production system at Fargo, ND.

| | |
|---|---|
| Y = W versus Y = W + X | NS |
| Y = X versus Y = W * X | NS |
| Y = X + W versus Y = X + W + $D_h$ | NS |
| Y = $D_h$ + W versus Y = X + W + $D_h$ | NS |

[a]p ≥ F = 0.0001 for all trial and year interactions.

[b]Means (± standard error) are presented for equation intercepts (a) and slope (b). Intercepts and slopes were either not different from zero (= NS), or significantly different at P = 0.01 to 0.05 (= *), P = 0.001 to 0.01 (= **), or P = 0.0001 to 0.001 (= ***).

[c]n = number of observations.

[d]$r^2$ = coefficient of determination.

statistics for comparison of $r^2$ values (Table 2). The multivariate relationship between wheat yield and wheat density plus Canada thistle density accounted for just as much model variability as the relationship between wheat yield and wheat density alone. However, the multivariate equation between wheat yield and wheat density plus Canada thistle density was probably "overspecified" because the coefficients for the Canada thistle density term in this multivariate equation could not be distinguished from zero in 2 of 3 yr (1987 and 1988). The relationship between wheat yield and wheat density plus Canada thistle shoot dry weight also accounted for just as much model variability as the relationship between wheat yield and wheat density alone in 2 of 3 yr (1987 and 1989), as indicated by Z statistics for $r^2$ values.

YLA equations for Canada thistle infesting wheat (Table 2) support Hume (7) and Cousens (1) who suggested that both weed density and crop density should be included in YLA equations to improve yield estimates compared with simple linear regression equations between crop yield and weed density alone. In all 3 yr, the $r^2$ for the relationship between wheat yield and wheat density plus Canada thistle shoot density was greater than the $r^2$ for the relationship between wheat yield and Canada thistle density alone.

The $r^2$ values and Z statistics showed that the relationship between wheat yield and wheat density accounted for as much data variability in 1988 and 1989, or more data variability in 1987, than multivariate relationships between wheat yield and wheat density plus either Canada thistle shoot density or dry weight (Table 2). Canada thistle emerges with or slightly before spring wheat in reduced-tillage cropping systems (3, 4, 5) and is so highly competitive with wheat that wheat stands can be reduced, especially within Canada thistle patches (3). If yield component compensation of surviving wheat plants is not great enough to overcome the effect of both reduced wheat stand and season-long competition from Canada thistle on wheat yield, this may explain why the relationship between wheat yield and wheat density described as much or more data variability as the relationships between wheat yield and wheat density plus either Canada thistle shoot density or dry weight.

**Paired quadrats for estimating weed-free wheat yield.** Hume (7) suggested that paired quadrats of weedy and weed-free wheat, achieved by handweeding, could be used to estimate yield loss due to annual weeds while minimizing differences in wheat density from site to site in a field. Hume's paired quadrat method, however, did not adequately estimate weed-free yield of wheat infested with Canada thistle (Table 3). The wheat yield determined from weed-free quadrats sampled outside a Canada thistle patch was greater than the yield from handweeded quadrats sampled within a patch just a few meters away in 2 yr.

There are several explanations for this yield difference. Repeated handweeding was required at weekly intervals throughout the growing season to prevent Canada thistle shoot establishment. Removing Canada thistle shoots encouraged additional emergence of Canada thistle shoots from adventitious root buds on perennial roots (3). Weed-free quadrats within a Canada thistle patch also could not be handweeded without damaging some wheat shoots although handweeding did not reduce wheat stand (Table 3). Canada

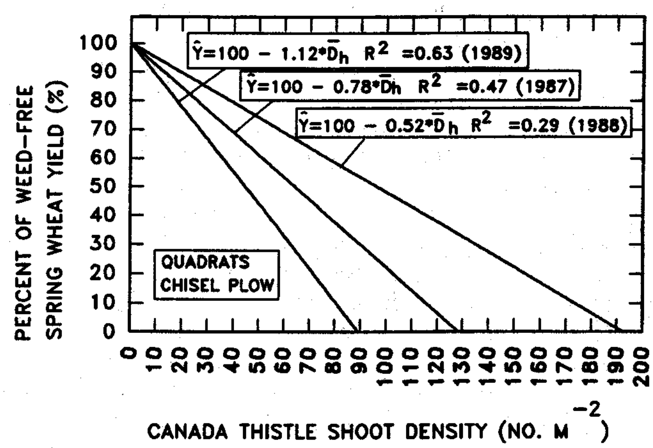


*Figure 1.* Functional relationship between relative spring wheat yield [yield as a percent of estimated weed-free yield] and Canada thistle shoot density ($D_h$) in late July to early August for hand-harvested quadrats over several years. Intercepts and slopes were significantly different from zero for all equations presented (at least P = 0.05). Sample size for regression equations was 47 in 1987 and 1989 and 60 in 1988.

thistle surrounding wheat in handweeded quadrats within patches also may have reduced weed-free wheat yield by limiting available resources within the patch, such as moisture or nutrients, and creating an area-of-influence effect unique to the patch. Hume's paired quadrat method may have greater application for sparse stands of annual weeds on which it was first used than for dense stands of highly competitive perennial weeds, such as Canada thistle.

**Spring wheat YLA in plots.** Relative spring wheat yield decreased linearly with increasing Canada thistle shoot density in late summer in mechanically harvested plots (Figure 2), as observed for wheat YLA equations from hand-harvested quadrats (Figure 1). Slopes for YLA relationships were less negative for hand-harvested quadrats (Figure 1) than for mechanically harvested plots even when chisel-plowed wheat is considered alone (top two panels of Figure 2).

Less negative slopes in YLA equations suggest that greater Canada thistle densities were required to cause an equivalent percent yield loss in hand-harvested quadrats (Figure 1) than in combine-harvested plots. However, differences in YLA equation slope may be an artifact of harvest method, in part. An area 20 times greater was harvested by combine for plots than by hand for quadrats. Combined yield was related to average Canada thistle shoot density for plots, whereas hand-harvested yield was related to specific Canada thistle shoot density for the same quadrats. Hand-harvesting allowed almost all wheat to be gathered from quadrats and probably reflects the direct impact of Canada thistle on spring wheat yield production potential, assuming that preharvest losses, such as shattering or consumption by insects, can be ignored. In contrast, combining plots may have harvested less grain than was produced because green Canada thistle shoots and chaff going through the combine probably interfered with separation of grain from residue and increased harvest losses. Plots with more Canada thistle shoots probably would be more affected in this way by combining than weed-free plots. Thus, the more negative slopes of YLA equations for plots than for quadrats probably reflect both the impact of Canada thistle density on yield production potential and harvesting efficiency in plots. More research is required to demonstrate that harvest method affects YLA equations for weeds.

Negative slopes for the relationship between wheat yield and Canada thistle shoot density became progressively more negative as a linear function of increasing estimated weed-free wheat yield (Figure 3) for pooled quadrat and plot YLA equations. Apparently, as weed-free wheat yield potential increased, Canada thistle caused greater yield losses, as indicated by progressively more negative slopes.

*YLA in relation to cumulative rainfall.* As discussed above, harvest method (hand-harvested quadrats versus mechanically harvested plots) probably influenced the magnitude of slopes for linear YLA equations. However, year-to-year differences in growing season rainfall (Figure 4) may have also contributed to differences in slopes for YLA equations. Plots received cumulative seasonal rainfall (April to August) similar to or greater than the 30-yr average in 2 of 3 yr, whereas cumulative seasonal rainfall was less than the

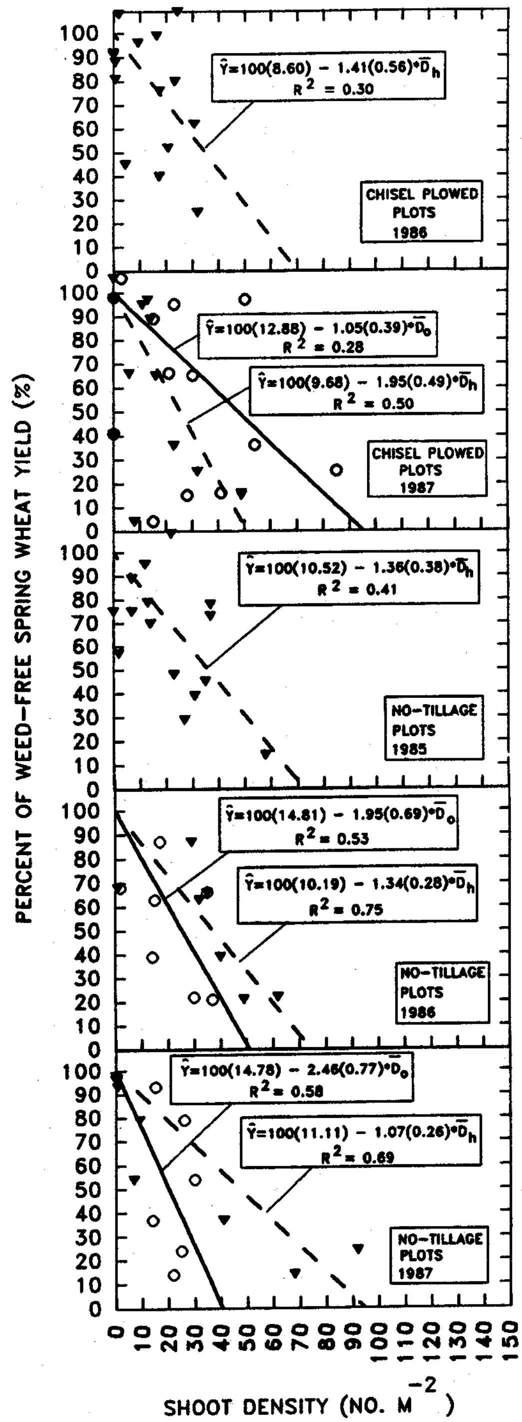


*Figure 2.* Functional relationship between spring wheat yield (Y) as a percentage of weed-free wheat versus Canada thistle shoot density measured in early June before spraying ($D_o$) (open circles) or in late July to early August before spring wheat harvest ($D_h$) (solid triangles). Intercepts and slopes were significantly different from zero for all equations presented (at least P = 0.05). Sample size for regression equations was 18 for chisel-plowed plots in 1986 and 1987, and 9 for no-tillage plots from 1985 to 1987.

*Table 3.* Weed-free spring wheat yield determined using two different methods.

| Method of estimating weed-free yield | Number of observations 1988 | Number of observations 1989 | Wheat stand[a] 1988 | Wheat stand[a] 1989 | Yield[a] 1988 | Yield[a] 1989 |
|---|---|---|---|---|---|---|
| | | | no. $m^{-1}$ | | kg $ha^{-1}$ | |
| Handweeded quadrats sampled within a Canada thistle patch | 24 | 24 | 270 (± 10) | 160 (± 10) | 370 (± 40) | 1210 (± 80) |
| Weed-free quadrats sampled outside of a Canada thistle patch | 10 | 6 | 290 (± 20) | 140 (± 10) | 520 (± 70) | 1640 (± 310) |
| t-test P ≥ F | — | — | NS | NS | 0.063 | 0.064 |

[a]Means (± standard errors) are presented.

30-yr average for all 3 yr that the quadrat experiment was conducted.

Estimated weed-free wheat yield increased linearly as cumulative April to August rainfall increased for pooled quadrat plus plot YLA equations (Figure 5), as expected. Cumulative April to August rainfall accounted for most of the year-to-year variation in estimated weed-free wheat yield ($r^2$ = 0.96) calculated from YLA equations (Table 2). Spring wheat yields often are limited by soil moisture in the northern Great Plains.

Negative slopes for the YLA relationship between wheat yield and increasing Canada thistle density became progressively more negative as cumulative April to August rainfall increased for pooled quadrat plus plot YLA data (Figure 6). Thus, the decrease in spring wheat yield per increase in Canada thistle density (slope) was greater in wet than in dry years.

Cumulative April to August rainfall also accounted for most of the year-to-year variation in negative slope ($r^2$ = 0.92) of YLA equations (Figure 6). Canada thistle likely had greater access to soil moisture reserves than did wheat because Canada thistle's perennial root system is more extensive and extends deeper into the soil profile than does that of wheat (3). If harvest method was entirely responsible for the functional relationship observed in Figure 6, then quadrat and plot data points should be clumped. However, harvest method probably was not indirectly responsible for this functional relationship because the respective data were not clumped.

*YLA versus time of density determination.* Relative wheat yield decreased as a linear function of increasing Canada thistle shoot density measured either in early June at the time of broadleaf herbicide application ($D_o$) or just prior to wheat harvest in late July to early August ($D_h$) in both chisel-plowed and no-tillage spring wheat production systems (Figure 2). However, relative wheat yield was related to early June Canada thistle shoot density in 1 of 3 yr (1987) for chisel-plowed wheat and in 2 or 3 yr (1986 and 1987) for no-tillage wheat (data not presented in Figure 2). In contrast, relative wheat yield decreased as a linear function of increasing Canada thistle shoot density in late July to early August in 2 or 3 yr for chisel-plowed wheat and in all 3 yr for no-tillage wheat. Slopes for YLA equations were more negative using $D_o$ than $D_h$ in 2 of 3 yr for no-tillage, but not for chisel-plowed spring wheat (Figure 2 and Table 4).

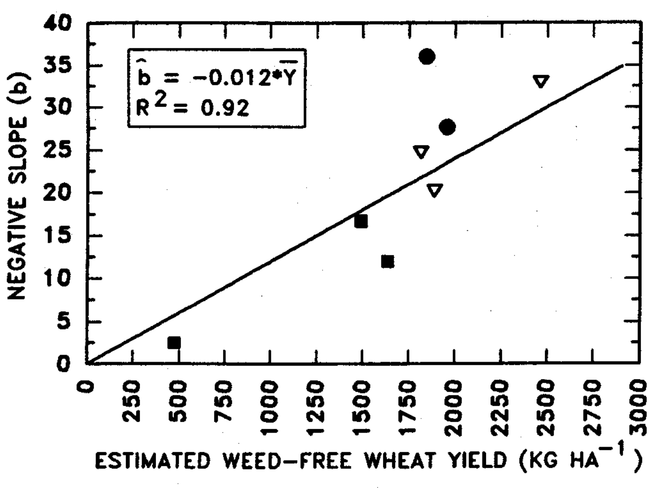


*Figure 3.* Functional relationship between the negative slopes (b) and estimated weed-free spring wheat yield (Y) [from YLA equations of spring wheat yield versus increasing Canada thistle density ($D_h$)] forced through the origin (solid squares = chisel plow quadrats; solid circle = chisel plow plots; open triangles = no-tillage plots).

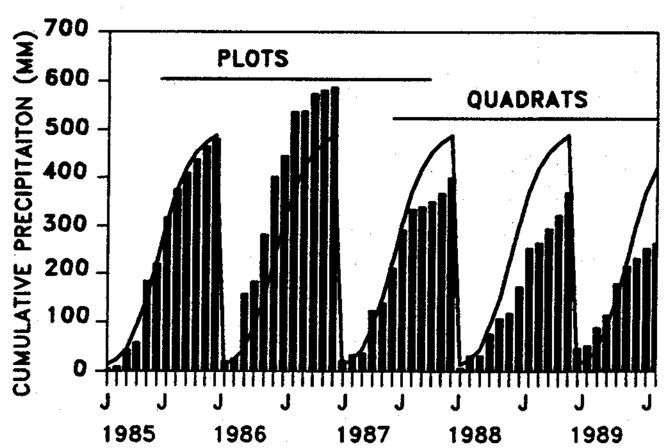


*Figure 4.* Cumulative monthly precipitation (= bars) from 1985 to 1989 and the 30-yr average cumulative monthly precipitation (= solid line) for the Hector Airport Weather Station, Fargo, ND.

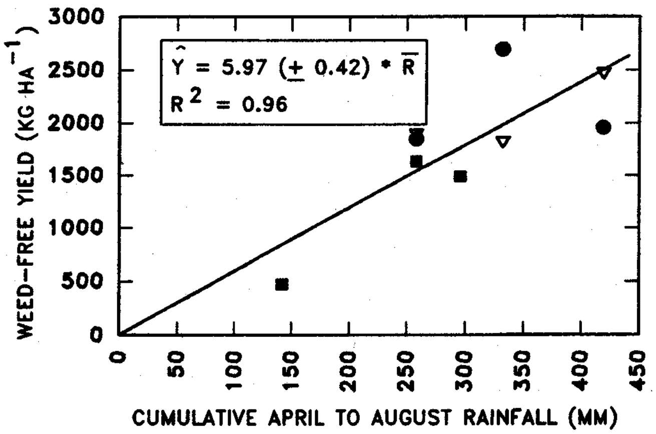


*Figure 5*. Functional relationship between estimated weed-free spring wheat yield (Y) [from the YLA equations for wheat yield versus increasing Canada thistle shoot density] and cumulative April to August rainfall (R in mm) forced through the origin (solid squares = chisel plow quadrats; solid circle = chisel plow plots; open triangles = no-tillage plots).

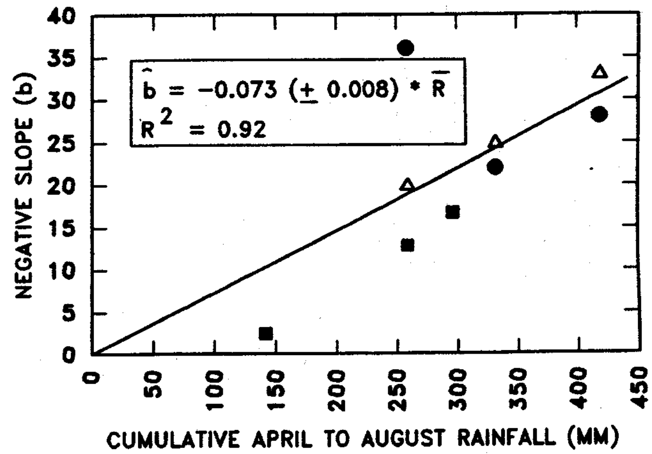


*Figure 6*. Functional relationship between negative slopes (b) [from the YLA equation for yield versus increasing Canada thistle shoot density] and cumulative April to August rainfall forced through the origin (R in mm) (solid squares = chisel plow quadrats; solid circle = chisel plow plots; open triangles = no-tillage plots).

YLA equations employing $D_h$ estimated wheat yield losses better by accounting for more variability (i.e., greater $r^2$) than those employing $D_o$ (Figure 2). Nevertheless, the YLA equations using $D_o$ combined with actual observations of Canada thistle stand made in spring on commercial fields may be used to help farmers make economic choices regarding alternative control measures before treatment in break-even analyses.

*Tillage effects on YLA*. Increasing Canada thistle shoot densities measured in late July to early August progressively reduced relative wheat yield in 2 of 3 yr for chisel-plowed wheat and in all 3 yr for no-tillage wheat (Figure 2 and Table 4). Negative slopes were not consistently greater for one tillage system than the other and varied from year to year (Table 4). Thus, Canada thistle reduced wheat yield to an equal extent for both chisel-plowed and no-tillage systems.

The $r^2$ for linear relationships between wheat yield and Canada thistle shoot density in late summer varied from 0.30 to 0.50 for chisel-plowed wheat (Figure 2), when significant, and from 0.41 to 0.75 for no-tillage wheat over time. Greater $r^2$ values for YLA equations for no-tillage indicated that these equations accounted for more data variability than comparable YLA equations for chisel-plowed wheat all 3 yr.

There are few studies describing YLA for crops infested with perennial weeds. Methods used for annual weeds, such as periodically thinning weed infestations to known densities, cannot be used for studying established perennial weeds, for the reasons described above. Hume's (7) paired quadrat approach cannot be used for holding crop density constant in YLA of spring wheat infested with perennials, such as Canada thistle. In this research, YLA equations have been

*Table 4*. t-tests for equality of slope for linear least squares regression equations for the functional relationship between spring wheat yield (Y in kg ha$^{-1}$) and Canada thistle shoot density at spraying in spring ($D_o$ in no. m$^{-2}$) and in late summer ($D_h$ in no. m$^{-2}$) based on mechanical harvesting of small plots in either fall chisel-plowed or no-tillage production systems.

| Grouping of data | | Comparison of slopes (b) for: | t-test for equality of slopes (b) |
|---|---|---|---|
| No-tillage for | 1985 | $Y = D_o$ versus $Y = D_h$ | NS |
| | 1986 | $Y = D_o$ versus $Y = D_h$ | * |
| | 1987 | $Y = D_o$ versus $Y = D_h$ | * |
| Chisel plow for | 1985 | $Y = D_o$ versus $Y = D_h$ | NS |
| | 1986 | $Y = D_o$ versus $Y = D_h$ | NS |
| | 1987 | $Y = D_o$ versus $Y = D_h$ | * |
| 1985 | | $Y = D_o$ for chisel plow versus no-tillage | NS |
| | | $Y = D_h$ for chisel plow versus no-tillage | NS |
| 1986 | | $Y = D_o$ for chisel plow versus no-tillage | NS |
| | | $Y = D_h$ for chisel plow versus no-tillage | * |
| 1987 | | $Y = D_o$ for chisel plow versus no-tillage | * |
| | | $Y = D_h$ for chisel plow versus no-tillage | * |

determined for the first time for Canada thistle infesting modern semidwarf spring wheat grown using either chisel-plowed or no-tillage wheat production systems. Canada thistle infesting wheat apparently reduced wheat yield as a function of increasing Canada thistle shoot density to the same extent in both reduced-tillage systems. Multiple linear regression equations of wheat yield as a function of wheat density plus Canada thistle shoot density accounted for more variability in estimated wheat yield than simple linear regression equations of wheat yield versus Canada thistle shoot density alone but requires more effort for data collection. Most year-to-year variation in the estimated weed-free wheat yield and negative slope for YLA equations (i.e., wheat yield versus Canada thistle shoot density) was accounted for by cumulative growing season (April to August) rainfall.

## ACKNOWLEDGMENTS

We thank R. Hoerauf and numerous workers for their assistance, and Drs. C. Messersmith, A. Ogg, K. Renner, and J. Sachs, as well as two unknown reviewers, for their critical review of this manuscript.

## LITERATURE CITED

1. Cousens, R. 1985. An empirical model relating crop yield to weed and crop density and a statistical comparison with other models. J. Agric. Sci. 105:513–521.
2. Donald, W. W. 1990. Sulfonylurea herbicides. Pages 423–477 *in* W. W. Donald, ed. Systems of Weed Control in Wheat in North America. Weed Sci. Soc. Am., Champaign, IL.
3. Donald, W. W. 1990. Management and control of Canada thistle (*Cirsium arvense*). Rev. Weed Sci. 5:193–250.
4. Donald, W. W. and T. Prato. 1992. Efficacy and economics of herbicides for Canada thistle (*Cirsium arvense*) control in no-till spring wheat (*Triticum aestivum*). Weed Sci. 40:233–240.
5. Donald, W. W. and T. Prato. 1992. Efficacy and economics of sequences of fall- and in-crop-applied herbicides for Canada thistle (*Cirsium arvense*) control in spring wheat (*Triticum aestivum*). Can. J. Plant Sci. 72:599–618.
6. Hodgson, J. M. 1968. The nature, ecology, and control of Canada thistle. U. S. Dep. Agric. Tech. Bull. 1386. 32 pp.
7. Hume, L. 1985. Crop losses in wheat (*Triticum aestivum*) as determined using weeded and nonweeded quadrats. Weed Sci. 33: 734–740.
8. Kleinbaum, D. G. and L. L. Kupper. 1978. Pages 101–102 *in* Applied Regression Analysis and Other Multivariate Methods. Duxbury Press, North Scituate, MA.
9. Moore, R. J. and C. Frankton. 1974. The Thistles of Canada. Can. Dep. Agric. Monogr. 10.
10. O'Sullivan, P. A. 1990. Diclofop. Pages 321–346 *in* W. W. Donald, ed. Systems of Weed Control in Wheat in North America. Weed Sci. Soc. Am., Champaign, IL.
11. O'Sullivan, P. A., V. C. Kossatz, G. M. Weiss, and D. A. Dew. 1982. An approach to estimating yield loss of barley due to Canada thistle. Can. J. Plant Sci. 62:725–731.
12. Peschken, D. P., J. H. Hunter, and A. G. Thomas. 1980. Damage in dollars caused by Canada thistle in wheat in Saskatchewan. Pages 37–43 *in* Canada Thistle Symp. Agric. Can., Regina Res. Stn.
13. Sokal, R. R. and F. J. Rohlf. 1969. Pages 16–19 *in* Biometry. The Principles and Practice of Statistics in Biological Research. W. H. Freeman and Co., San Francisco.
14. SPSS Inc. 1990. Pages B94–B97 *in* SPSS/PC$^+$ Statistics 4.0 for the IBM PC/XT/AT and PS/2. SPSS, Inc., Chicago, IL.
15. Teng, P. S. 1987. Crop Loss Assessment and Pest Management. American Phytopathology Society Press, St. Paul, MN. 270 pp.
16. Zimdahl, R. L. 1980. Weed-Crop Competition, a Review. Int. Plant Prot. Ctr., Oregon State Univ., Corvallis. 195 pp.