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Common lambsquarters (*Chenopodium album*) interference with corn across the northcentral United States

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Variation in crop–weed interference relationships has been shown for a number of crop–weed mixtures and may have an important influence on weed management decision-making. Field experiments were conducted at seven locations over 2 yr to evaluate variation in common lambsquarters interference in field corn and whether a single set of model parameters could be used to estimate corn grain yield loss throughout the northcentral United States. Two coefficients (*I* and *A*) of a rectangular hyperbola were estimated for each data set using nonlinear regression analysis. The *I* coefficient represents corn yield loss as weed density approaches zero, and *A* represents maximum percent yield loss. Estimates of both coefficients varied between years at Wisconsin, and *I* varied between years at Michigan. When locations with similar sample variances were combined, estimates of both *I* and *A* varied. Common lambsquarters interference caused the greatest corn yield reduction in Michigan (100%) and had the least effect in Minnesota, Nebraska, and Indiana (0% yield loss). Variation in *I* and *A* parameters resulted in variation in estimates of a single-year economic threshold (0.32 to 4.17 plants m^{-1} of row). Results of this study fail to support the use of a common yield loss–weed density function for all locations.

Nomenclature: Common lambsquarters, *Chenopodium album* L. CHEAL; corn, *Zea mays* L. 'DK404SR', 'DK493SR', 'DK592SR', 'Asgrow RX602SR'.

Key words: Bioeconomic model, common lambsquarters, corn, interference, yield loss.

Reducing herbicide inputs is a primary concern in agriculture today (Ngouajio et al. 1999). Application of thresholds in weed management decision-making may contribute to a rationalization of herbicide use (Lotz et al. 1996). A single-year economic threshold (T_e) is the weed density at which the cost of weed control equals the value of predicted crop yield loss if the weed is not controlled (Coble and Mortensen 1992; Lindquist et al. 1999). T_e can be estimated using (Marra and Carlson 1983)

$$T_e = C/(Y_{wf}PE_fY_{L,O} - Y_{L,M}), \qquad [1]$$

where C is the total cost of the management tactic and its application (\$ ha^{-1}), Y_{wf} the weed-free crop yield (kg ha^{-1}), P the crop price (\$ kg^{-1}), and Y_L the proportional yield loss at a given density. Yield loss can be estimated from experimental data using (Cousens 1985)

$$Y_L = IN/(1 + IN/A), \qquad [2]$$

where I is yield loss as weed density (N) approaches zero, and A is the asymptote or the estimated maximum yield loss. $Y_{L,O}$ is yield loss without management, and $Y_{L,M}$ is yield loss after management removed E_fN weeds where E_f is herbicide efficiency. Substitution of Equation 1 into Equation 2 and rearrangement results in a quadratic equation

$$0 = (1 - E_f)(T_eI/A)^2 + (2 - E_f - Y_{wf}PAE_f/C)(T_eI/A) + 1, \qquad [3]$$

which can be solved algebraically for T_e (Cardina et al. 1995; Lindquist et al. 1999). Ideally, variation in T_e would result primarily from changes in crop price, cost of management, and weed-free crop yield. However, estimates of I and A from Equation 2 must be obtained from experimental data and, therefore, may vary across environments. Implementation of a threshold-based weed management program requires a thorough assessment of the potential variation in estimated T_e within a region.

Common lambsquarters is one of the world's worst weeds (Holm et al. 1977). Common lambsquarters germinates at lower temperatures than many other weed species (Chu et

TABLE 1. Corn hybrid, planting date, seeding rate, and mean weed-free yields at each location.

Location	Year	Hybrid	Planting date	Seeding rate	Weed-free yield[a]
				seeds ha^{-1}	kg ha^{-1}
Colorado	1996	DK592SR	May 6	74,000	9,820 ± 810
	1997	DK592SR	May 9	74,000	8,990 ± 750
Illinois	1996	DK592SR	April 18	69,400	9,590 ± 930
	1997	DK592SR	April 29	69,200	10,540 ± 1,110
Indiana	1996	DK592SR	May 20	69,100	10,670 ± 340
	1997	DK592SR	April 27	69,100	10,410 ± 1,350
Minnesota	1996	DK404SR	May 21	79,000	10,070 ± 1,550
	1997	DK493SR	May 6	79,000	10,490 ± 610
Michigan	1996	DK404SR	May 7	60,500	8,180 ± 740
	1997	DK493SR	May 5	55,600	9,170 ± 520
Wisconsin	1995	DK404SR	May 1	80,000	8,440 ± 630
	1996	RX602SR	May 3	80,000	9,700 ± 650
	1997	DK493SR	April 29	80,000	9,120 ± 190
Nebraska	1997	DK592SR	May 7	54,600	7,500 ± 600

[a] Weed-free yield ± 1 SD.

al. 1978; Weaver et al. 1988; Wiese and Binning 1987). Therefore, it has a competitive advantage by emerging early in the season, typically before crop emergence. Common lambsquarters may produce large numbers of seed (Holm et al. 1977) that remain viable in soil for many years (Conn and Deck 1995) and contribute to future populations. Competitiveness of common lambsquarters is determined by density, relative time of crop and weed emergence, and environmental conditions (Kempenaar et al. 1996). Corn yield loss because of common lambsquarters interference was studied by several researchers who measured losses in the range of 0% in The Netherlands (Spitters et al. 1989), 12% in Illinois (Beckett et al. 1988), 38% in Quebec, Canada (Ngouajio et al. 1999), and 58% in Ontario, Canada (Sibuga and Bandeen 1980). These results were obtained from a wide range of environments using different weed densities. Therefore, it remains unclear whether the relationship between corn yield loss and common lambsquarters density varies among environments.

The objectives of our research were to evaluate (1) the stability of corn–common lambsquarters interference relationships across the northcentral United States and (2) how variation in estimates of I and A from Equation 2 influence T_e.

Materials and Methods

Experimental Procedures

Field experiments were conducted at seven locations (East Lansing, MI; West Lafayette, IN; Champaign, IL; Waseca, MN; Fort Collins, CO; Lincoln, NE; and Arlington, WI) to evaluate the influence of common lambsquarters interference on corn yield. Each experiment was established as a randomized complete block design with four replications. A sethoxydim-resistant corn hybrid with a maturity appropriate for each specific location was selected to facilitate grass weed control within the experiment. Corn was seeded in rows spaced 0.76 m apart at a locally recommended population density (Table 1), and fertilizer was applied according to local soil test recommendations each year.

Common lambsquarters populations were established using natural soil seed banks at Wisconsin, Michigan, and Illinois, whereas supplemental seeding within the corn row was used at all other locations. Common lambsquarters was seeded several weeks before corn planting at Minnesota in 1997, seeded immediately after planting in 1996 and 1997 at Indiana and Colorado and in 1996 at Minnesota, and seeded 5 d after corn planting at Nebraska. Common lambsquarters density treatments (0, 1, 3, 9, and 18 plants per linear m of crop row) were established in the center four rows of six-row plots at most locations. However, four-row plots were used with densities established in all four rows in Michigan. Plots were initially overseeded, then thinned to the desired densities when common lambsquarters seedlings reached 2 to 5 cm in height. All other broadleaf weeds and late-emerging common lambsquarters seedlings were removed biweekly by hand. Grass weeds were controlled with postemergent sethoxydim at all locations except Nebraska. Plots at Nebraska were treated with alachlor at 1.68 kg ai ha^{-1} 6 d after corn was planted.

After common lambsquarters densities were established, a 5-m section of one of the middle two rows of each plot was randomly selected for data collection. All corn and common lambsquarters plants within the 5-m section were counted biweekly from establishment until corn pollination. Common lambsquarters plants from 1 m of row were collected from within the 5-m section of each plot after seed set and dried to constant weight. Corn yield at maturity was determined by harvesting the center two rows of each plot. Grain weight was corrected to 15.5% moisture content.

Statistical Analyses

Yield Loss Estimates

Corn yield loss was calculated by dividing yield from weedy plots by the mean weed-free yield for that environment and then regressed on target weed density using least squares nonlinear regression of Equation 2. Observed common lambsquarters densities counted at seed set, including losses because of intra and interspecific competition, resulted in a better fit than target density or common lambsquarters biomass at Wisconsin and were thus used in the analysis for that location. Approximate F-tests were conducted to eval-

TABLE 2. Fit of corn yield loss on common lambsquarters density,[a] and calculated single-year economic threshold weed density (T_e) for data sets collected in six states.

Location	Year	Coefficient estimate[b]					T_e[c]
		df	MSE	I	A	r^2	
							plants m^{-1}
Colorado	1996	18	65.3	3.54 (1.43)	71.21 (41.43)	0.90	0.89
Colorado	1997	18	52.0	4.24 (2.26)	31.42 (11.22)	0.86	0.87
Illinois	1997	22	80.6	6.36 (2.27)	53.47 (10.76)	0.93	0.47
Indiana	1996	14	19.9	8.06 (10.59)	7.68 (3.14)	0.77	0.56
Indiana	1997	18	132.5	0.70 (1.25)	100	0.72	4.17
Minnesota	1997	22	28.0	4.69 (2.09)	22.34 (3.95)	0.91	0.69
Michigan	1996	22	189.2	3.67 (2.66)	61.30 (54.73)	0.80	1.05
Michigan	1997	22	159.5	10.46 (2.92)	100	0.94	0.32
Wisconsin	1995	22	87.1	2.71 (0.61)	100	0.92	1.34
Wisconsin	1996	22	45.5	2.07 (0.94)	43.38 (29.96)	0.85	1.59
Wisconsin	1997	22	47.6	5.85 (1.63)	58.62 (13.61)	0.93	0.59

[a] Fit obtained using Equation 2: $Y_L = (IN)/(1 + (IN)/A)$.
[b] Estimate (± 1 asymptotic SE).
[c] Single-year economic threshold (Equation 3): $0 = (1 - E_f)(T_e I/A)^2 + (2 - E_f - Y_{wf}PAE_f/C)(T_e I/A) + 1$, where C = \$24.70 ha^{-1}, P = \$0.0881 kg^{-1}, E_f = 0.95. Values are in U.S. dollars.

uate goodness of fit. Homogeneity of variance for the residuals was tested to determine whether data sets could be pooled for further analysis. Stability of yield loss–weed density relationships was then tested using the extra sum of squares principle outlined by Lindquist et al. (1996) and Ratkowsky (1983).

To determine whether weed biomass served as a better predictor of crop loss across environments than weed density, corn yield loss was regressed on the late-season common lambsquarters biomass using least squares nonlinear regression analysis of Equation 2 or linear regression, whichever provided the best fit. A greater r^2 value for the fit of yield loss on biomass than on density would indicate weed biomass was a better predictor of yield loss.

Variation in T_e

The influence of variation in *I, A*, and weed-free yield on single-year T_e common lambsquarters density was determined by calculating T_e using the mean estimates of *I* and *A* for each data set as reported in Table 2. Cost of the management tactic, price of the crop, and efficacy of the management tactic were set to constant values of \$24.70 ha^{-1}, \$0.0881 kg^{-1}, and 0.95 (95% of the plants removed), respectively. The weed-free crop yield was set to the value reported in Table 1 for each data set. All values are in U.S. dollars.

Results and Discussion

Location, year, hybrid, planting date, seeding rate, and weed-free yield for each location are shown in Table 1. Equation 2 resulted in a reasonable fit (approximate $r^2 >$ 0.70) to all data sets, except those collected in Illinois and Minnesota in 1996 and in Nebraska in 1997 (statistics not shown). A linear equation failed to adequately describe the data at Illinois and Minnesota in 1996 and Nebraska in 1997, indicating that yield was not reduced at any of the observed densities in those environments (Figure 1). Wet weather at the Illinois and Minnesota locations in 1996 may have slowed emergence, or early-season common lambsquarters growth, or both, contributing to the lack of interference effects at these locations. The application of alachlor and delayed common lambsquarters seeding most likely resulted in delayed emergence and reduced vigor of common lambsquarters at Nebraska in 1997.

Stability Between Years

Estimates of the *I* and *A* coefficients from Equation 2 were compared among years for those locations where results were obtained over more than 1 yr. The absence of a relationship between common lambsquarters density and grain yield loss at Minnesota and Illinois in 1996 prevented statistical comparisons between years at those locations. However, because a significant relationship was observed for these locations in 1997, differences between years did occur (Figure 1). Homogeneity of variance tests indicated similar variances between years within a location at Colorado, Michigan, and Wisconsin but not Indiana. The null hypothesis that parameters do not differ between years was rejected at all locations (α = 0.10; Table 3). Further tests indicated that both *I* and *A* differed at Wisconsin, and only *I* differed at Michigan. Results were inconclusive as to the parameter causing differences at Colorado. This suggests that the relationship between weed density and yield loss changes between years. Therefore, a single parameter value is not valid over years within a location.

Stability Among Locations

Because parameters differed between years within a location, all location by year data sets were treated individually. Homogeneity of variance tests showed that the 1996 data set from Wisconsin and the 1997 data sets from Colorado, Indiana, Minnesota, and Wisconsin had similar residual variance. Stability of *I* and *A* parameters was tested for these five data sets. The null hypothesis that parameter values do not differ between locations was rejected at an alpha level of 0.01. Further tests indicated that both *I* and

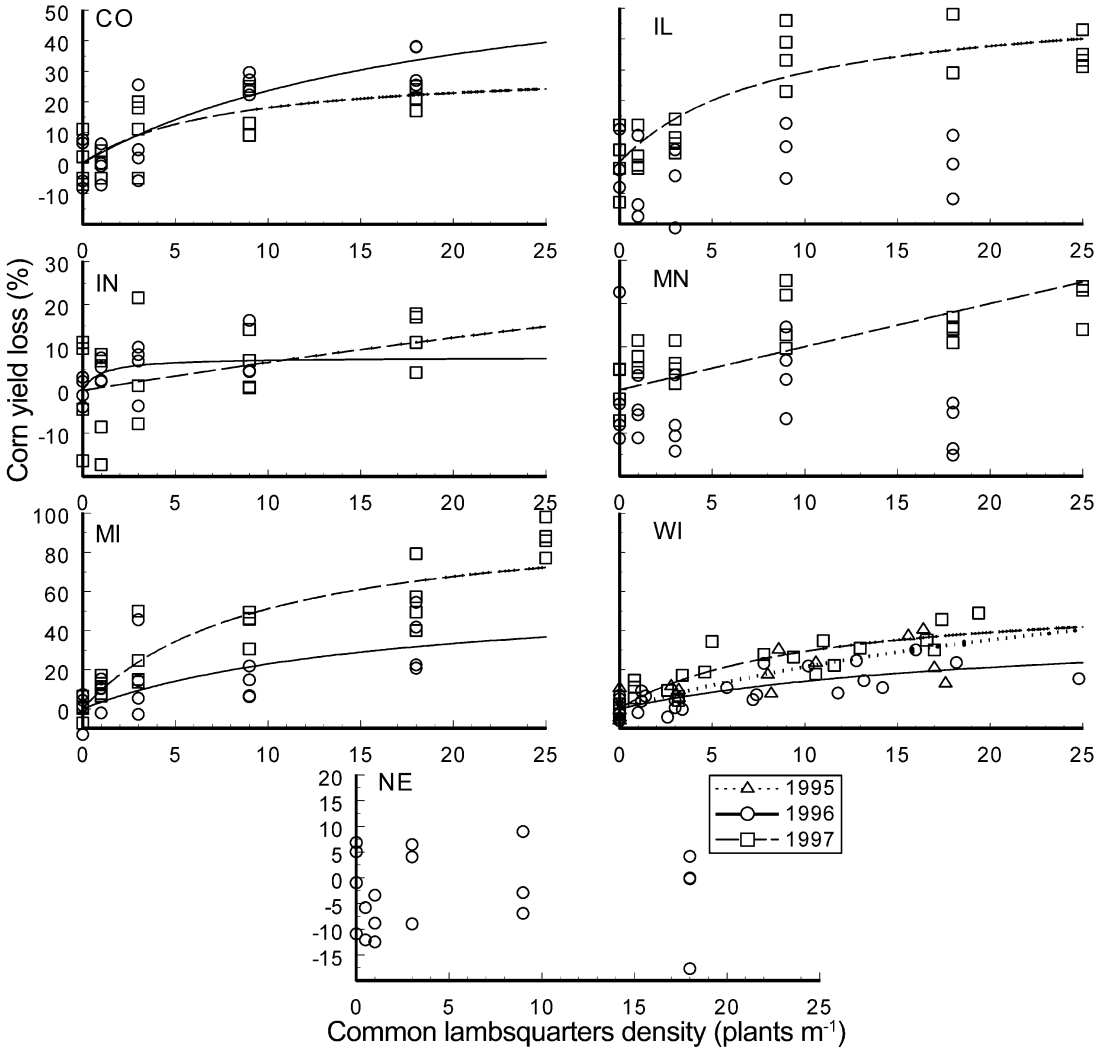

FIGURE 1. Relationship between corn yield loss and common lambsquarters density for 14 data sets from seven locations. Individual data sets and best fit lines from Equation 2. Common lambsquarters densities are reported as number of plants per linear meter of row.

A differed among locations at the 0.01 level (Table 4). Greatest predicted corn yield losses (*A* coefficient) occurred at Colorado (71%), Michigan (100%), and Wisconsin (100%) (Table 4). Sample variances (mean square error) were smallest for the Minnesota and Colorado data sets.

Although Equation 2 explained 72 to 94% of the variation in 11 of the 14 data sets, the observed differences in *I* and *A* indicate the need for additional information to accurately predict yield over sites and years. Additional environmental or growth data may be required to accurately predict the interference effects of common lambsquarters on corn grain yield loss across locations.

TABLE 3. Stability of corn–common lambsquarters interference relationships across years within a single location.

Location	Null hypothesis	df_1[a]	df_2[b]	Variance ratio[c]
Fort Collins, CO, (1996 and 1997)	*I*, *A*, or both, do not vary	2	36	2.67*
	I does not vary	1	36	0.06 NS
	A does not vary	1	36	1.91 NS
East Lansing, MI, (1996 and 1997)	*I*, *A*, or both, do not vary	2	41	14.26***
	I does not vary	1	41	11.49***
	A does not vary	1	41	0.04 NS
Arlington, WI, (1995, 1996, and 1997)	*I*, *A*, or both, do not vary	2	44	7.25***
	I does not vary	1	44	9.33***
	A does not vary	1	44	2.97*

[a] Abbreviation: df_1, numerator degrees of freedom obtained from the regression sum of squares.
[b] Abbreviation: df_2, denominator degrees of freedom obtained from the residual sum of squares.
[c] Abbreviation: NS, not significant at $P > 0.10$.
* $P < 0.10$; *** $P < 0.01$.

TABLE 4. Stability of corn–common lambsquarters interference relationships among experiments in 1996 at Wisconsin and in 1997 at Colorado, Indiana, Michigan, and Wisconsin.

Null hypothesis	df_1[a]	df_2[b]	Variance ratio[c]
I, *A*, or both, do not vary	7	103	16.66***
I does not vary	4	103	14.38***
A does not vary	4	103	11.45***

[a] Abbreviation: df_1, numerator degrees of freedom obtained from the regression sum of squares.
[b] Abbreviation: df_2, denominator degrees of freedom obtained from the residual sum of squares.
[c] Abbreviation: NS, not significant at $P > 0.10$.
*** $P < 0.01$.

Biomass Production

To evaluate whether weed biomass was a better predictor of corn yield loss across locations, corn yield loss was regressed on common lambsquarters biomass for those data sets with similar residual variance. The relationship between yield loss and common lambsquarters biomass was generally more linear than hyperbolic. Therefore, mean square error for the fit of yield loss on biomass using Equation 2 was greater than for those shown in Table 4 (results not shown). Homogeneity of variance tests showed similar residual variance among the 1996 data from Illinois, Minnesota, and Wisconsin and 1997 data from Colorado, Indiana, Minnesota, Nebraska, and Wisconsin. Results indicated that the yield loss–common lambsquarters biomass relationship was no more stable among years or locations than the yield loss–density relationship (data not shown). Linear regression of corn yield loss on common lambsquarters biomass provided little added benefit because only 33 to 64% of the variation in yield loss was explained with the linear model (data not shown).

Differences in T_e

Estimated single-year T_e varied from 0.32 plants m^{-1} row at Michigan in 1997 to 4.17 plants m^{-1} row at Indiana in 1997, to an infinite number of common lambsquarters plants for the three data sets where yield loss was not observed (Figure 1; Table 4). Although T_e estimates appear to be consistent at Colorado over years, T_e estimates at Indiana, Michigan, and Wisconsin had substantial differences between years. As with results found by Lindquist et al. (1999), management decisions based on T_e are risky. On the basis of the results of this study, the most conservative management approach would be to control common lambsquarters at densities greater than one plant every 2 to 3 m of crop row. However, this T_e does not account for the contribution of uncontrolled plants to future common lambsquarters populations by seed production. Nor would this approach account for loss in revenue that would occur in years when herbicides are applied when no control is needed.

As producers begin to base weed management decisions on economic thresholds, effects of individual growing practices on crop–weed interactions will need to be predicted. Although weed density is an important factor in determining crop loss, many other factors will also influence potential yield loss. Total common lambsquarters biomass produced—possibly reflective of relative time of emergence—corn seeding rate, corn planting date, field latitude, and uncontrollable weather events, all influence corn yield loss from common lambsquarters interference. If future multilocation experiments are to be conducted on weed–crop interference, a number of factors must be standardized. These include crop density, weed seed source and weed establishment methods, and relative time of crop and weed emergence. Results of our research indicate that these factors, as well as environmental conditions, should be considered when quantifying effects of weeds on crop yields.

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