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Zone herbicide application controls annual weeds and reduces residual herbicide use in corn

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To minimize the chance of surface water contamination by herbicides, farmers need alternative ways to manage weeds in field crops, such as field corn, that reduce herbicide use. Zone herbicide application (ZHA) reduces herbicide use compared with conventional broadcast herbicide application by (1) banding low herbicide rates between corn rows (≤ 1× normal broadcast registered rate), (2) managing crops to favor crop competition, and (3) banding very low herbicide rates over crop rows (≪ 1× normal rate). The research goal was to compare the relative effectiveness of reduced-rate ZHA with broadcast herbicide application on in-row (IR) and between-row (BR) summer annual weed cover (chiefly giant foxtail and waterhemp species), grain yields, and net returns resulting from herbicide application in field corn. Preemergence ZHA of atrazine + metolachlor + clopyralid + flumesulam was made in zones (i.e., even width bands) at different rates between and over crop rows for three site-years in Missouri, and the 1× rate was 2.24 + 1.75 + 0.211 + 0.067 kg ai ha^{-1}, respectively. Best ZHA treatments (0.29× to 0.30× IR herbicide rates + 0.74× to 0.80× BR herbicide rates) outperformed all reduced-rate broadcast herbicide treatments (0.25×, 0.5×, and 0.75×) based on net returns in partial budget analysis. Yields for highest yielding ZHA could not be distinguished from the 1× broadcast treatments in two of three site-years. Net returns due to herbicide application for the highest yielding ZHA were comparable with the 1× broadcast treatment in all three site-years. For the best ZHA, the 3-yr average for total herbicide applied per unit was 53% of the 1× broadcast rate. ZHA may provide row crop farmers with a new generic option for reducing herbicide rates and input costs while maintaining net returns and reducing the chance of surface water contamination by herbicides.

Nomenclature: Atrazine; clopyralid; flumetsulam; glufosinate; metolachlor; giant foxtail, *Setaria faberii* (L.) Beauv. SETFA; common waterhemp, *Amaranthus rudis* Sauer AMATA; corn, *Zea mays* L., ‘Pioneer 33G28’.

Key words: Banded herbicide, reduced rates, zone herbicide application, sprayer, weed management.

In the Midwestern United States, corn producers rely on herbicides to manage weeds rather than field cultivation (Anonymous 2000; Missouri Agricultural Statistics Service 2001; Rikoon et al. 1996). However, throughout the Midwest herbicides routinely contaminate surface water (i.e., they are present in water) and can pollute it (i.e., make it unfit for its intended uses) (Brock 1982; Gaynor et al. 1995; Larson et al. 1997; Logan et al. 1987; Mutchler and Greer 1984). Corn is produced in northern Missouri on extensive areas of claypan soils (Jamison et al. 1968; Missouri Agricultural Statistics Service 2001). Because claypan layers restrict downward water and herbicide movement through the subsoil, herbicides seldom contaminate groundwater in northern Missouri on these soil types (Blanchard and Donald 1997). Unfortunately, claypan soils increase the likelihood that herbicides will contaminate surface water due to slow water permeability through clay soils and runoff to surface water (Blanchard and Lerch 2000; Donald et al. 1998). Consequently, several atrazine- or cyanazine-contaminated lakes and reservoirs are included in the Proposed Final Missouri Section 303 (d) list for the federal Clean Water Act (Missouri Department of Natural Resources 2002).

New best management practices are needed to reduce offsite herbicide, nutrient, and sediment movement in runoff (Logan et al. 1987; Logan 1993; Nelson and Jones 1994) and minimize herbicide contamination of surface and ground water (Fawcett 1998) without compromising farmers’ economic or soil conservation goals. Moreover, if best management practices are to be adopted and used, they must be practical and acceptable to farmers (Rikoon et al. 1996). Surveys have established that most Missouri farmers reject band herbicide application plus field cultivation between rows as a best management strategy for reducing herbicide contamination of water (Rikoon et al. 1996).

Unpredictable, severe rainfall events soon after herbicide application cause significant offsite herbicide movement in runoff and contamination of surface water in broadcast herbicide weed management systems (Larson et al. 1997; Logan et al. 1987). Therefore, new best management practices are needed to reduce total soil residual herbicide use, decrease the area treated with herbicides, or both, to minimize herbicide contamination of surface and ground water. Weed control efficacy of broadcast soil residual herbicides at reduced rates, chiefly triazine and chloracetamide herbicides, has been researched for more than 15 yr in corn by several research groups (Buhler et al. 1995; Bussan and Boerboom 2001; Hamill and Zhang 1995; Lin et al. 1995; O’Sullivan and Bouw 1993; Zhang et al. 2000). For some herbicides,

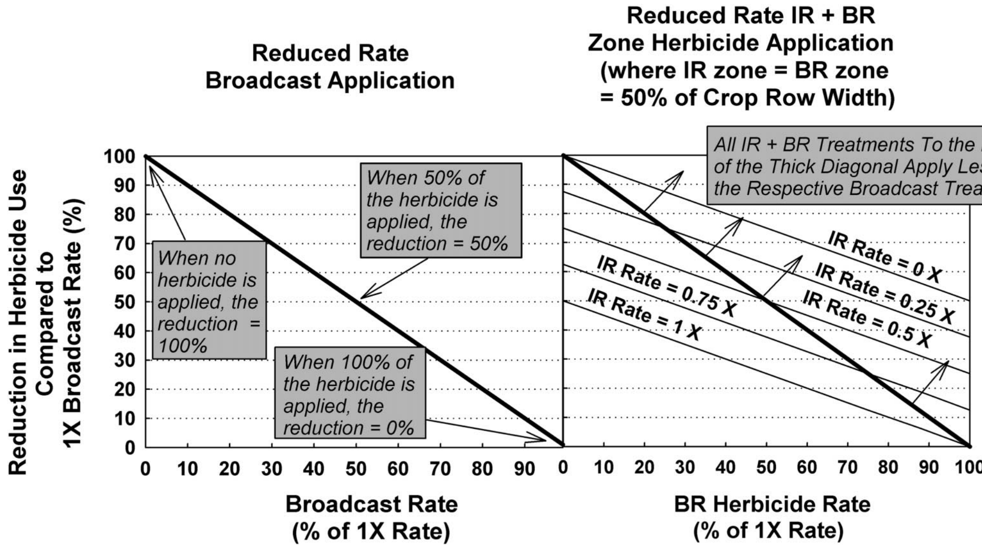

FIGURE 1. The relative extent to which reduced-rate broadcast and zone herbicide application (ZHA) decrease total herbicide applied per unit area. The percent reduction in total herbicide applied per unit area is graphed for broadcast application rate (left panel) and selected combinations of in-row (IR) + between-row (BR) ZHA in terms of relative rate, the percentage of the 1× rate (right panel). Some combinations of reduced-rate IR + BR ZHA (i.e., those with thin arrows pointing to the right of the diagonal in the right panel) apply less total herbicide per unit area than the respective reduced-rate broadcast application.

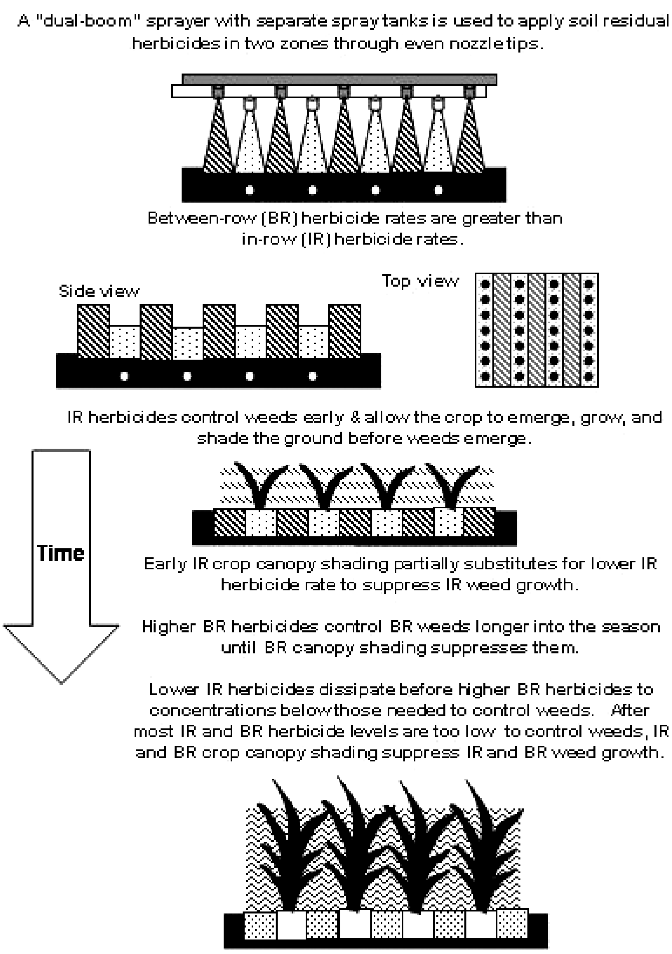

FIGURE 2. A qualitative, pictorial hypothesis of how PRE soil residual herbicides control weeds in competitive row crops using zone herbicide application (ZHA). Herbicide rates in rows are less than between rows. Consequently, the relative contribution of crop interference (i.e., such as shading) and herbicide efficacy to weed control differs in and between crop rows and changes as the growing season progresses and the crop canopy closes.

soil types, and environments, soil residual herbicides controlled targeted weeds at some reduced rates.

Zone herbicide application (ZHA) is a previously unreported, novel, integrated weed management practice to reduce total herbicide applied per unit area, that uses (1) banding low herbicide rates between corn rows ($\leq$ 1× normal broadcast registered rate), (2) managing crops to favor crop competitiveness with weeds, and (3) banding very low herbicide rates over crop rows ($\ll$ 1× normal rate). Reduced-rate ZHA is different from other weed management methods, such as mechanical tillage, band herbicide application plus mechanical tillage, and reduced-rate broadcast herbicide application. Reduced-rate ZHA has neither been tested before nor compared with reduced-rate broadcast herbicide application to reduce total herbicide use per area. A 2002 search of the scientific literature found no references for this technology. In addition, ZHA was not mentioned by McWhorter and Gebhardt (1987) or Matthews (2000) in their books on herbicide application technology.

Some reduced-rate ZHAs of different combinations of in-row (IR) + between-row (BR) rates apply less total herbicide per unit area than reduced-rate broadcast application (Figure 1, arrows to the right of the diagonal line in the right panel). Figure 2 presents a qualitative hypothesis to explain how preemergence (PRE) soil residual herbicides combined with crop interference control weeds using ZHA. In this integrated weed management system, crop interference (shading, etc.) likely contributes to herbicide efficacy to control weeds earlier and more effectively in crop rows than between crop rows. Thus, the relative contribution of crop shading or interference to herbicide efficacy in ZHA depends on weed distribution relative to crop rows and changes as the growing season progresses (Donald et al. 2004). In this hypothesis, competitive crops are assumed to close canopy. Less herbicide is needed in crop rows than between crop rows because competitive crops shade and suppress emerging weed seedlings more quickly in rows than between rows. Therefore, ZHA can reduce total herbicide use for some

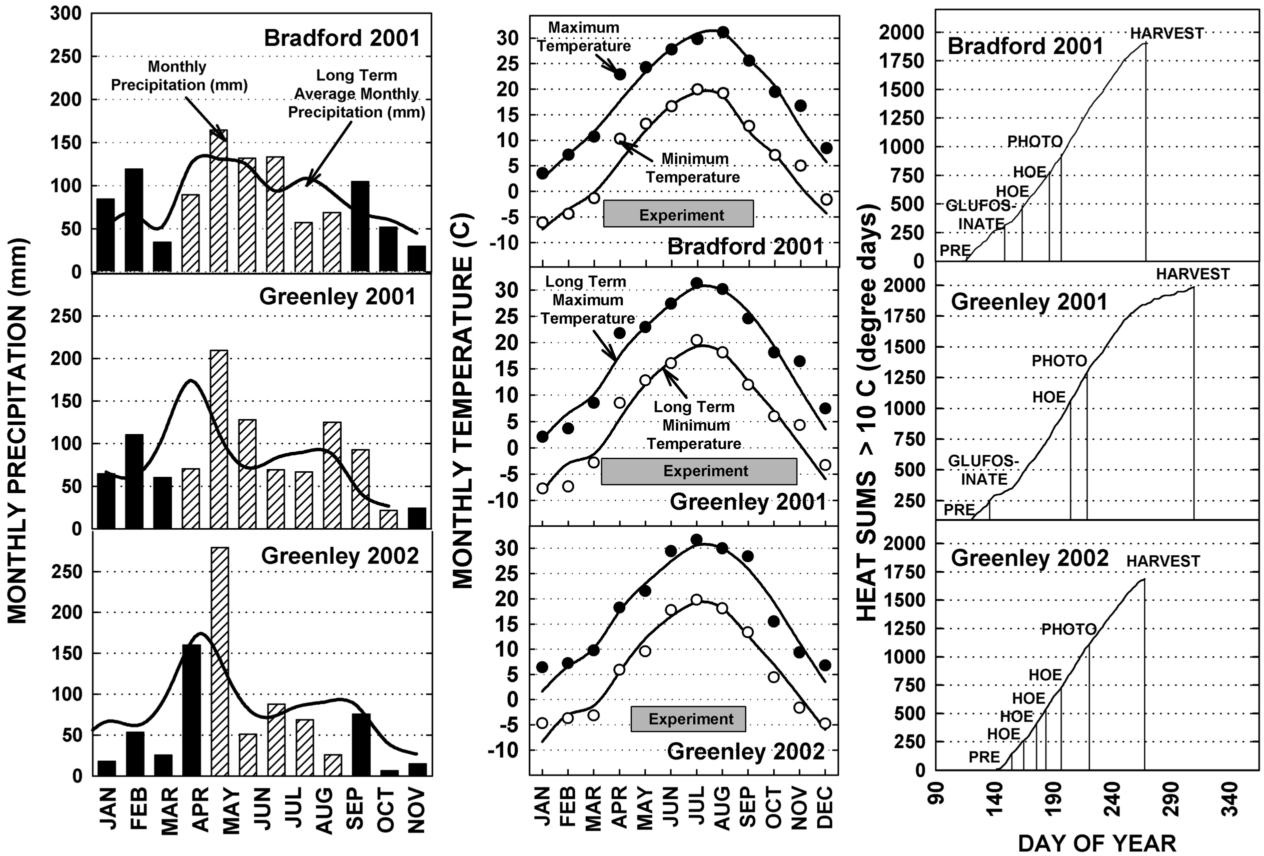

Figure 3. Monthly precipitation (hatched and black bars) and the long-term average monthly precipitation (lines) are graphed vs. month of the year at Bradford in 2001 and Greenley in 2001 and 2002 (left panels). The long-term averages were 9 yr (1993 to 2001) for Bradford and 6 yr (1996 to 2001) for Greenley. Monthly average maximum and minimum air temperatures (solid and open circles) and long-term averages (lines) are graphed vs. month of the year (middle panels). The duration of the experiment is indicated as either hatched or gray bars (left panels) or a horizontal bar "experiment" (middle panels). Cumulative heat sums > 10 C (i.e., growing degree days) after planting are graphed vs. day of the year (right panels). Major events are indicated (PRE = PRE herbicide applied; weed-free plots were either hoed [HOE] or sprayed [glufosinate]; PHOTO = photographs taken; HARVEST).

combinations of relatively "low" IR rates + "high" BR herbicide rates compared with broadcast-applied herbicides at reduced rates (Figures 1 and 2). It is assumed that herbicides at reduced rate using ZHA control weeds more consistently than do broadcast-applied herbicides at equivalent reduced rates. In the ZHA hypothesis, there is no advantage in applying herbicides at high rates over crop rows and low rates between crop rows. This qualitative hypothesis is the logical outgrowth of previous research on crop interference and soil residual herbicides (Donald and Johnson 2004; Donald et al. 2004). One research objective was to test the expectation from the ZHA hypothesis that total herbicide use per area could be reduced without decreasing weed control using reduced-rate ZHA compared with either equivalent reduced-rate or 1× broadcast herbicide applications.

Much published weed control research has focused on maximizing yields by minimizing weed interference. However, yields of the best ZHA and 1× broadcast treatments were expected to be equivalent in this research. By reducing herbicide input costs while maintaining yields, the best ZHA treatment was expected to increase net returns above the 1× broadcast treatment. Consequently, a second research objective was to test the null hypothesis that PRE soil residual herbicides applied at reduced rates by ZHA would control annual weeds, increase grain yields and net returns above the weedy check, and maintain grain yields and net returns as well as the 1× broadcast application in field corn. The alternative hypothesis was that reduced-rate ZHA would be superior to equivalent reduced-rate broadcast applications based on these criteria.

Materials and Methods

Herbicide Treatments

Atrazine[1] + s-metolachlor + clopyralid + flumetsulam were applied PRE by either ZHA or broadcast application (Table 1; Figure 3, "PRE" in right panel). BR and IR zone widths were 50% of the corn row width (i.e., even band widths), 76 cm, and were created using even spray nozzle tips with limited spray overlap (about one-eighth swath width overlap). The 1× rate of atrazine[1] + s-metolachlor + clopyralid + flumetsulam[1] was 2.24 + 1.75 + 0.211 + 0.067 kg ai ha^{-1}, respectively. In 2001, the BR + IR zone herbicide treatments were applied at 0× (i.e., weedy check), 0.25, 0.5, 0.75, and 1× in all possible BR + IR zone combinations. In 2002, only those ZHA combinations in which the BR rate equaled or exceeded the IR rate were applied. Treatments were arranged in a randomized complete block design with five or six blocks (Gomez and Gomez 1984; Hoshmand 1994). Individual plots measured 3 by 13.7 m at the Bradford Research and Extension Center, near Columbia, and 3 by 9.1 m at the Greenley Research Center near Novelty, MO.

Table 1. Dates for field operations, treatments, or measurements at Bradford or Greenley.

Field operation or measurement	Bradford 2001[a]			Greenley 2001[a]			Greenley 2002[a]		
	Date	DAP	DAE	Date	DAP	DAE	Date	DAP	DAE
Disk soil	November 10, 2000	—	—	November 12, 2000	—	—	November 23, 2001	—	—
Apply glyphosate	—	—	—	—	—	—	May 20, 2002	−2	—
Plant crop	April 26, 2001	0	—	April 20, 2001	0	—	May 22, 2002	0	—
Apply atrazine + s-metolachlor + clopyralid + flumetsulam	April 30, 2001	4	—	April 24, 2001	4	—	June 4, 2002	13	2
Crop emergence	May 3, 2001	3	0	April 29, 2001	5	0	June 2, 2002	11	0
Measure crop stand	May 23, 2001	27	20	May 16, 2001	26	7	June 14, 2002	23	12
Weed-free check only:	—	—	—	—	—	—	—	—	—
Apply glufosinate	May 29, 2001	29	26	May 16, 2001	22	18	—	—	—
Hoeing and hand-pulling weeds	June 13, 2001	44	41	July 24, 2001	91	87	June 14, 2002	23	12
Hoeing and hand-pulling weeds	June 14, 2001	45	42	—	—	—	June 25, 2002	34	23
Hoeing and hand-pulling weeds	July 6, 2001	67	64	—	—	—	July 16, 2002	55	44
Hoeing and hand-pulling weeds	—	—	—	—	—	—	August 9, 2002	79	68
Photograph weed cover	July 16 to 17, 2001	77	74	July 11, 2001	78	74	July 2, 2002	41	30
	July 30, 2001	—	—	August 7, 2001	—	—	—	—	—
Harvest corn	September 27, 2001	150	147	November 6, 2001	196	192	September 25, 2002	126	115

[a] Abbreviations: DAP, days after planting; DAE, days after corn emergence.

A backpack sprayer with flat-fan nozzle tips[2] spaced 76.2 cm apart on a spray boom was used for broadcast herbicide treatments with a spray volume of 168 L ha^{-1} using compressed CO_2 at 193 kPa as a propellant and a ground speed of 1.6 km h^{-1}. A dual-boom backpack sprayer with even spray nozzle tips[3] spaced 76.2 cm apart on two separate spray booms held adjacent to each another on a frame was used for ZHA. The adjacent dual booms of the ZHA sprayer were offset 38.1 cm from each other, so that BR and IR even nozzle tips were spaced 38.1 cm apart. Each dual boom applied a carrier volume of 166 L ha^{-1} through separate compressed CO_2 propellant systems at the same pressure and ground speed as above. To maintain uniform BR and IR zone widths, the boom height above the ground was held constant by suspending the booms from guy lines that ran from each end of the boom to the top of backpack frame holding the sprayer. The guy lines suspended the weight of the boom from the applicator's back, rather than the applicator's arms, thus minimizing applicator fatigue and variation in boom height during the course of spraying in the experiment. The boom heights were about 84 and 34 cm above the ground for broadcast and ZHA dual-boom sprayers, respectively.

Seedbed preparation killed the weeds present before planting. Weed-free checks were created with a sequence of postemergence (POST) broadcast-applied glufosinate at 0.28 kg ai ha^{-1} followed by hoeing and hand-pulling weeds several times during the growing season (Table 1; Figure 3, right panel). Later-emerging weeds were controlled with repeated shallow hand hoeing until corn silking. Although these "hand-weeded" plots were not completely "weed-free" by harvest, weeds emerging after silking and canopy closure do not reduce corn grain yields (Bedmar et al. 1999; Hall et al. 1992).

Agronomic Practices

Field corn was planted after soybeans [*Glycine max* (L.) Merr.] at two sites: (1) the University of Missouri's Bradford Research and Extension Center in north-central Missouri near Columbia (38°53′43.5″N, 92°12′37.9″W, 269 m altitude) in 2001 and (2) the University of Missouri's Greenley Memorial Research Center in northern Missouri near Novelty (40°0′45″N, 92°12′29″W, 254 m altitude) in 2001 and 2002. The Bradford site was on a Mexico silty clay loam (fine, smectitic, mesic Aeric Vertic Epiaqualf), whereas the Greenley site was a Putnam silt loam (fine, montmorillonitic, mesic Vertic Albaqualf). Soil pHs are salt pH values that run approximately 0.5 units lower than the customary water pH values. The soil at Bradford had 18 to 20% sand, 46 to 48% silt, 34% clay, 2.9 to 3.4% organic matter, and pHs of 5.5 to 5.7, whereas the soil at Greenley had 12 to 16% sand, 52 to 54% silt, 30 to 36% clay, 3 to 3.4% organic matter, and a pHs of 6. Early-season rainfall occurred soon after herbicide application at both locations (Figure 3).

Dates for field operations, treatments, and measurements are summarized (Figure 3; Table 1). Each site was shallowly disked in spring to redistribute residue and facilitate degradation, as well as for seedbed preparation. Corn was fertilized with N–P–K for a grain yield goal of 10,000 kg ha^{-1} based on soil tests and recommendations of the University of Missouri soil testing lab. N-P-K was broadcast before planting at 160:69:93 kg ha^{-1} at Bradford in 2001 and 180:56:112 kg ha^{-1} at Greenley in 2001 and 2002 and was incorporated by disking. Glufosinate-resistant 'Pioneer 33G28' corn seed was planted 1.3 to 1.9 cm deep in 76-cm rows at 68,000 seed ha^{-1}.

Historical weather data were collected at the Bradford farm (Figure 3). However, 1995 data from the nearby Sanborn Experimental Field and 2001 data from the University of Missouri South Farm were substituted in 1995 and 2001 because weather data in those years were incomplete at Bradford. A shorter continuous weather record was used from Greenley. Heat sums for corn were calculated from planting until harvest using a base temperature of 10 C (Ruiz et al. 1998).

Giant foxtail was the major weed present at both sites. At Bradford, common waterhemp was the major broadleaf weed present, followed by scattered, sparse Pennsylvania smartweed (*Polygonum pensylvanicum* L.) and common ragweed (*Ambrosia artemisiifolia* L.). At Greenley, common waterhemp was the major broadleaf weed present followed by sparse common cocklebur (*Xanthium strumarium* L.), ladysthumb smartweed (*Polygonum persicaria* L.), Pennsylvania smartweed, and velvetleaf (*Abutilon theophrasti* Medik.).

Measurements

Corn stands were determined after full emergence by counting all plants in the two center rows of four-row plots (Table 1). After cutting borders at either end of all plots, corn was combine harvested from the two center rows in an area measuring 1.5 by 10.6 and 1.5 by 8.2 m at Bradford and Greenley, respectively, and grain yields were adjusted to 15% moisture content.

Projected ground cover ("cover" hereafter) of grass weeds, broadleaf weeds, and total weeds (i.e., grass + broadleaf weed cover) (%) was measured from photographs taken over crop rows and between crop rows to document the effect of the treatments on weeds, rather than predicting yield loss from weeds (Figure 3; Table 1). Crop cover was not measured. Corn foliage overhanging and obscuring the BR and IR zones was pulled back with 1-m^2 wooden frame panels covered with black cloth, and an orange-colored dowel was extended at 90° 19 cm out from the crop row at the soil surface toward the row middle to indicate the IR zone width in the photographs. Before taking photographs in 2002, IR and BR weed cover were separated from each another using black panels extended to the soil surface to prevent foliage overhanging from adjacent zones from obscuring IR and BR weed cover. Four photographs per zone per plot were taken vertically (i.e., camera facing toward the soil surface, nadir) with a digital camera[4] at a height of 132 cm in four and five blocks in 2001 and 2002, respectively. Each photograph corresponded to 1.1 m^2 at the soil surface based on photographs of a 30- by 30-cm orange calibration plate. Maximum weed canopy height was measured for each photograph. Photographs (640 by 512 pixels = 327,680 pixels per photograph in 2001 and 1600 by 1200 pixels = 1,920,000 pixels per photograph in 2002) were saved as JPG files for image analysis. Image analysis software[5] was used to crop BR and IR zones and automatically superimpose a 20- by 20-pixel grid over each cropped photograph. In 2001, total weed cover (WC) was calculated using the following equation:

$$WC = (n/N)100, \qquad [1]$$

where WC = grass + broadleaf projected weed cover (%), n = number of grid intersections in the grass or broadleaf weed cover categories, and N = total number of grid line intersections per cropped photograph.

In 2002, all photographs were taken under the shade of an umbrella to minimize contrast between brightly lit and heavily shaded spots and ensure uniform diffuse light intensity for photographs on 1 d. This allowed total weed cover to be determined using the software's automated measurement capacity to distinguish "green" from other colors. Total weed cover (%) was calculated as the ratio of green pixels to total pixels per photograph multiplied by 100. In both years, total weed cover measurements are the average of four photographs per plot in either BR or IR zones. Weed cover determined by automated green pixel counting using software[6] was linearly related to weed cover determined by visual grid point intersection counting, with an X intercept of 0 and a slope of 1.

Economic Analysis

The net returns due to herbicide applications (hereafter, "net return") of alternative herbicide treatments were estimated using a partial budget analysis. Changes in net returns for each treatment were calculated relative to the weedy (untreated) check using the estimated yield response surfaces and the following equation:

$$\begin{aligned}\text{Net return } (\$\ \text{ha}^{-1}) = {} & [(\text{treated grain yield in kg ha}^{-1}) \\ & - (\text{weedy check grain yield in kg ha}^{-1})] \\ & \times (\text{grain price in } \$\ \text{kg}^{-1}) \\ & - \text{herbicide cost } (\$\ \text{ha}^{-1}) \\ & - \text{herbicide application cost } (\$\ \text{ha}^{-1}) \qquad [2]\end{aligned}$$

In Equation 2, net return represents the net economic benefit of alternative herbicide treatments, with a positive net return indicating an increase in returns due to herbicide application and a negative net return indicating a decrease in returns due to herbicide application. The 1× herbicide cost of \$115.60 ha^{-1} was based on herbicide prices published by Kansas State University (2002). A herbicide application cost of \$10.60 ha^{-1} was based on Missouri custom rates (Plain et al. 2001). The average, minimum, and maximum prices for corn for Missouri marketing years were \$9.29 Mg^{-1}, \$7.01 Mg^{-1}, and \$13.70 Mg^{-1}, respectively, averaged from 1993 to 2002 (National Agricultural Statistics Service 2003). The average, minimum, and maximum prices were used to evaluate the sensitivity of results to changes in corn price. Software was used to prepare 2-D contour graphs of the net returns for each site-year using the average corn price. Nonlinear optimization was used to select the herbicide treatment that maximized net returns for each site-year under each of the corn price scenarios.

Herbicide application decisions must be made by producers before a specific yield response is known. For ZHA to be economically feasible, it is necessary not only that there is a ZHA treatment that does well in a single year but

TABLE 2. The data were tested using the following alternative polynomial equations in response surface analysis. Dependent variables (Z = IR weed cover, BR weed cover, or yield) were regressed on IR relative herbicide rate (X) and BR relative herbicide rate (Y).

Polynomial equations	Equation number
$Z = a + bX + eY$	[3]
$Z = a + bX + eY + fY^2$	[4]
$Z = a + bX + fY^2$	[5]
$Z = a + bX + cX^2 + eY$	[6]
$Z = a + bX + cX^2 + eY + fY^2$	[7]
$Z = a + cX^2 + eY$	[8]
$Z = a + cX^2 + eY + fY^2$	[9]
$Z = a + cX^2 + fY^2$	[10]
$Z = a + bX + eY + hXY$	[11]
$Z = a + bX + eY + fY^2 + hXY$	[12]
$Z = a + bX + fY^2 + hXY$	[13]
$Z = a + bX + cX^2 + eY + hXY$	[14]
$Z = a + bX + cX^2 + eY + fY^2 + hXY$	[15]
$Z = a + cX^2 + eY + hXY$	[16]
$Z = a + cX^2 + eY + fY^2 + hXY$	[17]
$Z = a + cX^2 + fY^2 + hXY$	[18]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2$	[19]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + gY^3$	[20]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + hXY$	[21]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + gY^3 + hXY$	[22]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + hXY + iX^2Y$	[23]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + gY^3 + hXY + iX^2Y$	[24]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + iX^2Y$	[25]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + gY^3 + iX^2Y$	[26]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + hXY + iX^2Y + jXY^2$	[27]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + gY^3 + hXY + iX^2Y + jXY^2$	[28]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + iX^2Y + jXY^2$	[29]
$Z = a + bX + cX^2 + dX^3 + eY + fY^2 + gY^3 + iX^2Y + jXY^2$	[30]

that there is a ZHA treatment that consistently performs well over a range of conditions. To analyze the economic feasibility of selecting a treatment before the yield response was known, an expected net return response surface was estimated by the average of the three site-year response curves. Software was used to prepare a 2-D contour graph of the expected net returns, and nonlinear optimization was used to select the herbicide treatment that maximized expected net returns for each of the corn price scenarios.

Statistical Analysis

Data for each site-year were subjected to response surface regression (Myers and Montgomery 2002; SPSS 2001). Least squares regression software[6] was used to fit dependent variables (Z), other than net return, on the independent variables, IR (X) and BR (Y) relative herbicide rate, with rates expressed as a fraction of the 1× rate. Response surface equations for grain yields were used to calculate response surfaces for net returns. In preliminary analyses, polynomial equations (Table 2) were determined using means of the dependent variables, and the resulting polynomial equations were sorted by r^2 adjusted for the number of variables in the equation. Because F values for all equations, except those for corn stand, were significant (P = 0.05 or better), simplest parsimonious equations were selected that had both the (1) highest adjusted r^2 and (2) coefficients for X and Y terms that were different from zero. Equation suitability was evaluated on the basis of lack of fit statistics, adjusted r^2, and visual inspection of the distribution of residuals vs. independent variables. After a suitable equation was selected, the regression analysis was rerun using all data, not just the means. The equations resulting from these analyses were tabulated (Table 3). Software[7] was used to prepare 2-D contour graphs of the equations after smoothing contour lines. Smoothed contour line intervals were arbitrarily chosen and should not be interpreted as statistically different from one another (Figures 4–7).

Results and Discussion

BR and IR Total Weed Ground Cover

By mid-season in weedy check plots, BR total weed cover ("weed cover") exceeded IR weed cover (Donald et al. 2004). This difference also was verified in all three site-years. By mid-season BR and IR total weed cover were 74 (± 3)% (mean ± standard error) and 57 (± 11)% of the ground cover, respectively, in the weedy checks at Greenley in 2001 and 83 (± 7)% and 59 (± 7)%, respectively, at Bradford in 2001. In contrast, the total BR and IR weed cover were 67 (± 6)% and 60 (± 5)%, respectively, at Greenley in 2002. The corn canopy had not yet closed and shaded the ground when photographs were taken in 2002 in contrast to 2001 (Table 1). When BR and IR total weed cover of a subset of treatments was measured later in the 2002 growing season, BR weed cover exceeded IR weed cover (Donald et al. 2004). Consequently, some time must elapse before corn interference causes BR and IR total weed cover to become different.

By mid-season, giant foxtail, the chief weed present, accounted for most BR and IR total weed cover in weedy

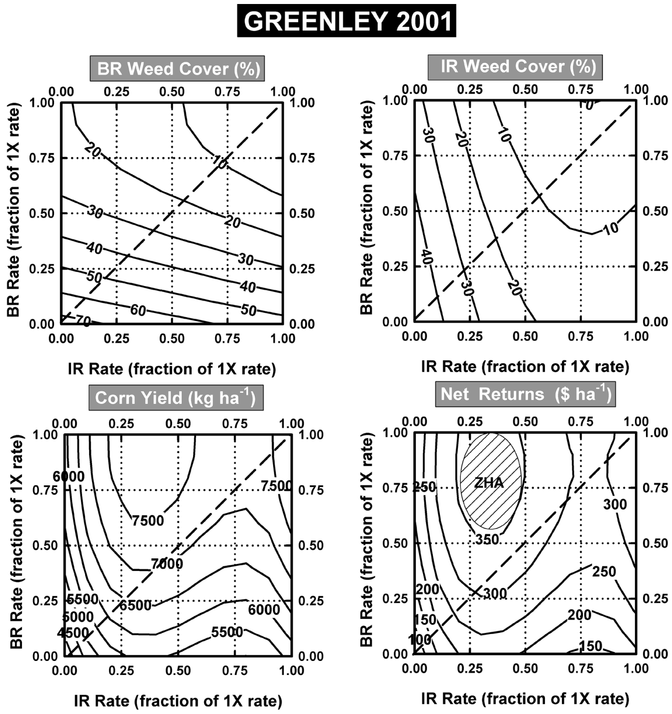

FIGURE 4. Contour graphs of between-row (BR) total weed cover (%), in-row (IR) total weed cover (%), corn yield (kg ha^{-1}), and net returns vs. IR + BR herbicide rate, expressed as a fraction of the 1× rate, at Greenley in 2001. Dotted line intersections correspond to various combinations of IR + BR herbicide rates. The thick dashed diagonal line running across the contour graphs represents the broadcast treatment where IR = BR herbicide rates. Contour lines intervals are arbitrary and should not be interpreted as being statistically different from one another. The shaded oval corresponds to the region of optimum ZHA. Equations are presented in Table 3.

checks at all site-years (Figures 4–6). Common waterhemp accounted for most remaining weed cover. When giant foxtail cover was expressed as a percentage of total weed cover at mid-season, rather than ground cover, BR and IR giant foxtail cover were similar in all three site-years. At Greenley in 2001, giant foxtail was 82% of total BR weed cover and 81% of total IR weed cover in weedy checks. At Bradford in 2001, giant foxtail accounted for 63 and 61% of total BR and IR weed cover, respectively, in weedy checks. At Greenley in 2002, giant foxtail accounted for 64 and 65% of BR and IR total weed cover, respectively, in weedy checks.

The 1× broadcast herbicide treatment minimized BR and IR total weed cover at all three site-years (Figures 4–6). By mid-season in 2001 at Greenley, the BR and IR weed cover were 2 (± 1)% and 1 (± 1)% of ground cover, respectively, for the 1× broadcast herbicide treatment. In 2002 at Greenley, the BR and IR weed cover for this treatment were 4 (± 1)% and 11 (± 6)% of total ground cover, respectively. In 2001 at Bradford, the BR and IR weed cover were 21 (± 7)% and 12 (± 3)% of total ground cover, respectively. Photographs were taken slightly later at Bradford than at Greenley in 2001 and 2002 (Figure 3; Table 1), allowing more time for extended emergence of summer and winter annual broadleaf weeds. June and July rainfall in 2001 at Bradford also exceeded that at Greenley in either 2001 or 2002 (Figure 3). This may have both hastened herbicide degradation and, consequently, favored greater mid- to late-season broadleaf weed emergence and weed cover growth despite PRE herbicide treatment.

The BR Weed Cover Null Hypothesis

With ZHA, BR weed cover was expected to be inversely related to BR herbicide rate and independent of IR herbicide rate. According to this BR null hypothesis, contour lines of equal BR weed cover were expected to (1) extend at right angles from the BR herbicide rate axis, (2) be parallel to the IR herbicide rate axis (i.e., the coefficient for IR herbicide rate in the regression equation = 0), and (3) be parallel to one another.

All elements of this null hypothesis were not fully confirmed at any site-year (Figures 4–6; Table 3). At Greenley in 2001, contour lines of BR weed cover were more consistent with the BR null hypothesis at high cover (i.e., low BR herbicide rate) than at low cover (i.e., high BR and IR herbicide rate). Although nonlinear polynomial equations with both IR + BR herbicide rate ZHA accounted for 49% of data variability in BR weed cover at Greenley in 2001, BR herbicide rate contributed more to BR weed cover than IR herbicide rate by mid-season (i.e., $Y + Y^2$ terms contribute more than the X term to Z) (Figure 4; Table 3). At Greenley in 2002, BR weed cover was a linear function of BR + IR herbicide rate, rather than a nonlinear equation as in 2001, and the equation accounted for 54% of data variability (Figure 5; Table 3). Although the BR null hypothesis was not verified at Greenley in 2002, observations were more consistent with the BR null hypothesis than in 2001 (e.g., contour lines were parallel), probably because modified methodology minimized artifacts from IR weed foliage overhanging into the BR zone (see Materials and Methods). At Bradford in 2001, BR weed cover was a nonlinear polynomial function of BR + IR herbicide rate, and the equation accounted for 42% of data variability (Figure 6; Table 3). However, this equation was rejected because the coefficient for IR herbicide rate was nonsignificant and, consequently, this model failed to adequately fit the data. When BR weed cover was regressed on BR relative herbicide rate alone, a nonlinear equation accounted for 64% of data variability and adequately fit the data (Table 3). This latter equation was consistent with part of the BR null hypothesis (i.e., coefficient for IR herbicide rate = 0).

Departures from the BR null hypothesis are likely due to both plant biology and methodological artifacts. BR weed cover can be subdivided into the product of (1) weed density and (2) projected cover per plant for each species, summed for all species present, although only projected total weed cover per unit area was measured. Regression equations for weed density or cover per plant differ vs. herbicide rate for each species. In addition, corn, other BR weeds, and IR weeds interfere with BR weeds. BR weed interference decreases as BR herbicide rate increases. Likewise, both IR weed interference and corn interference with BR weed cover vary with both IR and BR herbicide rates. In the presence of corn interference, BR weed cover exceeds IR weed cover (Donald and Johnson 2004; Donald et al. 2004). The relative impacts of these interacting factors on BR weed cover also changes as the growing season advances. BR herbicide is less likely to control BR weed cover as the growing season progresses because the herbicide degrades, whereas corn interference is likely to increase.

Departures from the BR null hypothesis may be partially due to flaws in methodology in 2001. Methods used for separating BR and IR zones in photographs were changed

TABLE 3. Dependent variables (Z) as functions of IR herbicide rate (X) + BR herbicide rate (Y) (both as fraction of the 1 × rate). Regression analyses were significant at P = 0.0001. X and Y coefficients were rounded to whole numbers (± standard errors) and were significantly different from zero at P ≤ 0.05, except where noted (by P > 0.05, NS, or NA). Degree of freedom–adjusted r^2 is presented.[a]

Figure	Site-year	Dependent variables (Z)	Equation	P > F	Lack of fit	r^2
4	Greenley, 2001	BR weed cover (%)	$Z = a + bX + eY + fY^2$ a = 74 (± 5) b = −20 (± 6) e = −108 (± 21) f = 55 (± 20)	< 0.0001	0.0416	0.49
4	Greenley, 2001	IR weed cover (%)	$Z = a + bX + cX^2 + eY$ a = 50 (± 4) b = −84 (± 16) c = 53 (± 15) e = −17 (± 5)	< 0.0001	0.0732	0.41
4	Greenley, 2001	Corn grain yield (kg ha^{-1})	$Z = a + bX + cX^2 + dX^3 + eY + fY^2$ a = 3,629 (± 381) b = 13,231 (± 2,908) c = −27,398 (± 7,365) d = 16,235 (± 4,840) e = 4,595 (± 1,289) f = −2,358 (± 1,235) (P = 0.058)	< 0.0001	0.5579	0.31
5	Greenley, 2002	BR weed cover (%)	$Z = a + bX + eY$ a = 57 (± 3) b = −9 (± 5) (P = 0.0554) e = −44 (± 4)	< 0.0001	0	0.54
5	Greenley, 2002	IR weed cover (%)	$Z = a + bX + cX^2 + eY$ a = 57 (± 3) b = −64 (± 11) c = 47 (± 11) e = −33 (± 3)	< 0.0001	0.0001	0.63
5	Greenley, 2002	Corn grain yield (kg ha^{-1})	$Z = a + bX + cX^2 + dX^3 + eY + fY^2$ a = 3,051 (± 428) b = 13,484 (± 3,329) c = −27,903 (± 8,953) d = 17,299 (± 6,143) e = 6,621 (± 1,669) f = −3,164 (± 1,638) (P = 0.056)	< 0.0001	0.6552	0.47
6	Bradford, 2001	BR weed cover (%)	$Z = a + bX + fY^2$ a = 69 (± 4) b = −6 (± 6) NS f = −45 (± 6)	< 0.0001	0.0306	0.42
6	Bradford, 2001	BR weed cover (%)	$Z = a + fY^2$ a = 67 (± 3) f = −44 (± 7)	< 0.0001	0.7942	0.64
6	Bradford, 2001	IR weed cover (%)	$Z = a + bX + fY^2$ a = 58 (± 3) b = −16 (± 5) f = −35 (± 5)	< 0.0001	0.0184	0.45

[a] Abbreviations: NS, not significant, NA, not applicable; BR, between-row; IR, in-row.

Table 3. Continued.

Figure	Site-year	Dependent variables (Z)	Equation	P > F	Lack of fit	r^2
6	Bradford, 2001	Corn grain yield (kg ha^{-1})	$Z = a + bX + cY + dX^2 + eY^2 + fXY + gX^3 + hXY^2 + iX^2Y$	< 0.0001	0.5831	0.31
			a = 4,332 (± 554)			
			b = 15,425 (± 3,356)			
			c = −22,957 (± 7,247)			
			d = 11,992 (± 4,618)			
			e = 12,725 (± 2,221)			
			f = −8,722 (± 2,057)			
			g = −20,713 (± 4,911)			
			h = 6,338 (± 3,341)			
			i = 11,875 (± 3,341)			

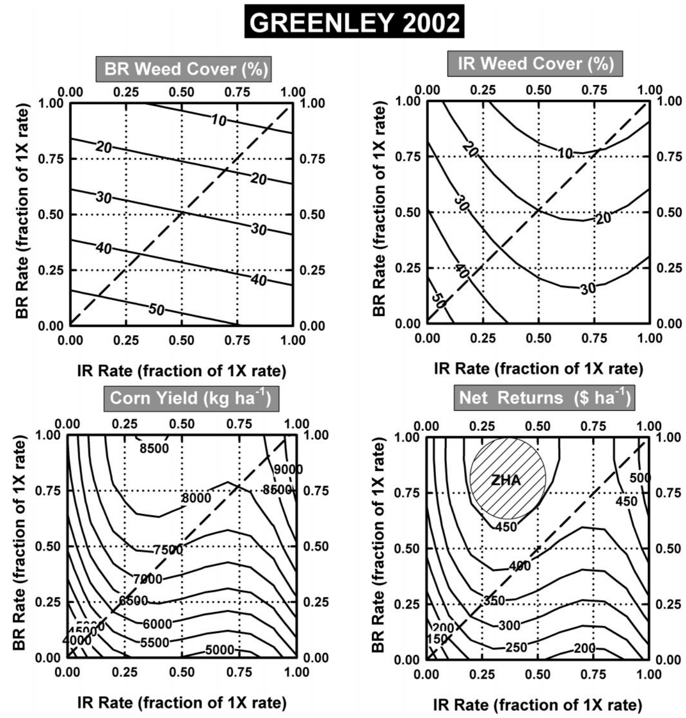

Figure 5. Contour graphs of between-row (BR) total weed cover (%), in-row (IR) total weed cover (%), corn yield (kg ha^{-1}) , and net returns vs. IR + BR herbicide rate, expressed as a fraction of the 1× rate, at Greenley in 2002. Dotted line intersections correspond to various combinations of IR + BR herbicide rates (see Figure 4). The thick dashed diagonal line running across the contour graphs represents the broadcast treatment where IR = BR herbicide rates. Contour lines intervals are arbitrary and should not be interpreted as being statistically different from one another. The shaded oval corresponds to the region of optimum ZHA. Equations are presented in Table 3.

from 2001 to 2002 to minimize these flaws. In 2002, BR weed foliage overhanging IR zones and IR foliage over BR zones was physically separated using dark cloth–covered panels extended to the soil surface before taking photographs. In contrast, corn foliage was pulled back with panels, but the BR and IR zones were not physically separated from each other with panels in 2001. Later, BR and IR zones in photographs were cropped before image analysis. BR weed cover could be accurately measured with this approach because all IR weed foliage overhanging the BR zone could be completely cropped from photographs. In addition, corn suppressed IR weed growth and foliage overhanging into the BR zone, especially at high IR herbicide rates.

The IR Weed Cover Null Hypothesis

The IR weed cover null hypothesis is analogous to the BR weed cover null hypothesis. IR weed cover was expected to be inversely related to IR herbicide rates, but not BR herbicide rates. However, results did not support the IR null hypothesis for any site-year (Figures 4–6; Table 3).

At Greenley in 2001, IR weed cover was more consistent with the IR null hypothesis at high cover (i.e., low IR herbicide rate) than at low cover (i.e., high BR and IR herbicide rate) (Figure 4; Table 3). Although nonlinear polynomial equations with both BR + IR herbicide rates as independent variables accounted for 41% of data variability, IR herbicide

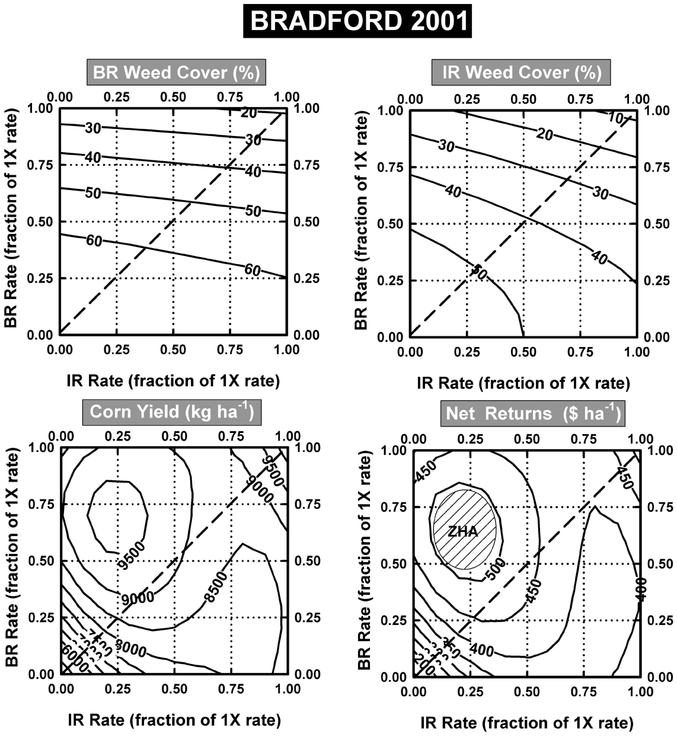

FIGURE 6. Contour graphs of between-row (BR) total weed cover (%), in-row (IR) total weed cover (%), corn yield (kg ha^{-1}), and net returns vs. IR + BR herbicide rate, expressed as a fraction of the 1× rate, at Bradford in 2001. Dotted line intersections correspond to various combinations of IR + BR herbicide rates (see Figure 4). The thick dashed diagonal line running across the contour graphs represents the broadcast treatment where IR = BR herbicide rates. Contour lines intervals are arbitrary and should not be interpreted as being statistically different from one another. The shaded oval corresponds to the region of optimum ZHA. Equations are presented in Table 3.

rates largely determined IR weed cover by mid-season. Across all combinations of IR + BR herbicide rate, the maximum IR weed cover (54%) was less than the maximum BR weed cover (73%) and is likely due to corn interference (Donald and Johnson 2004).

At Greenley in 2002, IR weed cover was a nonlinear function of BR + IR herbicide rate, and the equation accounted for 63% of data variability (Figure 5; Table 3). IR herbicide rate also largely determined IR weed cover by mid-season. The maximum IR weed cover (64%) was similar to the maximum BR weed cover (58%) across all IR + BR herbicide rates in 2002, in contrast to 2001. Photographs were taken earlier in 2002 than in 2001, before corn canopy closure and shading were complete. For differences between BR and IR weed cover to develop in response to crop interference, more time may need to elapse before the effects of crop interference are reflected in weed cover.

At Bradford in 2001, IR weed cover was a nonlinear polynomial function of BR + IR herbicide rate, and the equation accounted for 45% of data variability (Figure 6; Table 3). The large contribution of BR herbicide rate to the equation is hard to explain. Photographs were taken later at Bradford than at Greenley in 2001. The relationship between IR weed cover and IR herbicide rates may have been obscured if IR herbicide had degraded to nonphytotoxic levels and summer weed had continued to emerge and produce cover into late summer, despite crop shading when photographed. At mid-season, the maximum IR weed cover (67%) was less than the maximum BR weed cover (80%).

Departures from the IR null hypothesis and the BR null hypothesis probably have similar biological explanations. Methodological artifacts described for BR weed cover also are likely to be greater for IR weed cover because BR weed foliage overhanging the IR zone could not be completely cropped from photographs in 2001. Overhanging BR foliage also decreased as BR herbicide rate increased. In 2002, this flaw was minimized by modifying the methodology and by taking photographs earlier when there was less weed foliage and overlap between BR and IR zones.

Corn Grain Yield

Relative Yield Losses in Weedy Checks

As expected, weeds greatly reduced corn yields in the weedy check, as reflected in the ratio of the weedy check yield to the weed-free check yield. This ratio, expressed as a percentage, was 40, 42, and 29% at Bradford and Greenley in 2001 and at Greenley in 2002, respectively. Absolute corn yields in check treatments varied between site-years. At Bradford in 2001, the corn grain yield was 3,337 (± 508) kg ha^{-1} in the weedy check, which was 36% of the grain yield for the broadcast 1× rate (9,393 [± 544] kg ha^{-1}) and 40% of the weed-free check (8,411 [± 432] kg ha^{-1}). At Greenley in 2001, the corn grain yield was 2,908 (± 662) kg ha^{-1} in the weedy check, which was 43% of the grain yield for the broadcast 1× rate (6,708 [± 453] kg ha^{-1}) and 42% of the weed-free check (6,986 [± 310] kg ha^{-1}). At Greenley in 2002, the corn grain yield was 2,346 (± 602) kg ha^{-1} in the weedy check, which was 26% of the grain yield for the broadcast 1× rate (9,048 [± 326] kg ha^{-1}) and 29% of that for the weed-free check (8,217 [± 543] kg ha^{-1}).

Although corn yields are very sensitive to reduced stands (Hoeft et al. 2000), herbicide treatments did not reduce stands for any site-year (not presented). Corn yields of the weed-free and 1× broadcast herbicide treatments could not be distinguished from one another at all three site-years (see reported yields above). The 1× broadcast herbicide treatment, the highest rate applied, did not damage corn on the basis of either crop stand or yield in any site-year.

Yield Response Surface Equations

At all three site-years, corn grain yields were nonlinear functions of IR + BR ZHA rates, and these equations differed between site-years (Figures 4–6; Table 3). These functions were expected to differ between site-years because the upper (i.e., weed-free) and lower (i.e., weedy) yields differed between site-years. These equations showed that estimated yield gradually increased as BR + IR herbicide rate increased, except where BR, IR, or BR + IR herbicide rates were 0×. For ZHA, corn grain yields increased more as BR herbicide rate increased, while holding IR rates = 0, than as IR rates increased, holding BR herbicide rates = 0.

The nonlinear yield equations accounted for different amounts of data variability (Figures 4–6; Table 3). Equations accounted for 31% of data variability at Greenley and Bradford in 2001 and 47% at Greenley in 2002.

TABLE 4. Net returns and optimum zone herbicide application (ZHA) rates.

Scenario	1 × Broadcast		Optimum ZHA			
	Net returns Estimate	Standard error	Net returns Estimate	IR herbicide rate	BR herbicide rate	Average herbicide rate
	$ ha^{-1}			fraction of 1 × rate		
Bradford, 2001						
Average corn price	520	51	528	0.21	0.64	0.43
Low corn price	361	38	383	0.21	0.63	0.42
High corn price	827	75	807	0.22	0.66	0.44
Greenley, 2001						
Average corn price	341	42	376	0.32	0.84	0.58
Low corn price	226	32	264	0.31	0.80	0.56
High corn price	562	62	592	0.33	0.88	0.61
Greenley, 2002						
Average corn price	528	30	489	0.33	0.95	0.64
Low corn price	367	23	348	0.33	0.92	0.63
High corn price	838	45	762	0.34	0.98	0.66
Combined site-years						
Average corn price	463		454	0.29	0.77	0.53
Low corn price	318		325	0.29	0.74	0.51
High corn price	742		705	0.30	0.80	0.55

Best Broadcast vs. ZHA Treatments

At all three site-years, the greatest calculated yield from response equations was achieved with the 1× broadcast treatment (Figures 4–6; Table 3). In two of three site-years, the maximum measured yield also was achieved with the 1× broadcast treatment. For all three site-years, the highest yielding ZHA treatments could not be distinguished from the 1× broadcast treatment. At Greenley in 2001, the greatest measured yield was close to the 1× broadcast treatment (i.e., 1× IR + 0.75× BR ZHA) (Figure 4; Table 3). Using the equation, the calculated corn grain yield was greatest for the 1× broadcast rate, but this calculated yield could not be distinguished from that of the calculated optimum ZHA treatment[8] (i.e., 0.351× IR + 0.974× BR ZHA). At Greenley in 2002, the corn yield was greatest for the 1× broadcast rate, whether determined using the equation (Figure 5; Table 3) or measured means. The calculated yield also could not be distinguished from that of the calculated best ZHA using the equation (i.e., 0.367× IR + 1× BR ZHA). Likewise, at Bradford in 2001, the corn yield was greatest for the 1× broadcast rate, whether determined using the equation (Figure 6; Table 3) or observed means. This yield also could not be distinguished from that of the optimum ZHA using the equation (i.e., 0.237× IR + 0.692× BR ZHA).

Net Returns

In partial budget analysis, net returns were positive over the entire range of herbicide treatments for each of three corn price scenarios, indicating an economic benefit of herbicide application for all three site-years (Figures 4–7; Table 4). Optimum ZHA net returns exceeded the 0.25, 0.50, and 0.75× broadcast reduced-rate treatments for each of the corn price scenarios for all three site-years. At Greenley in 2001, the 1× broadcast rate returns were $341 ha^{-1} (± $42) for the average corn price scenario (Figure 4; Table 4). However, net returns were maximized for ZHA treatments of 0.31× to 0.33× IR + 0.80× to 0.88× BR for all corn price scenarios (Table 4).

For Greenley in 2002, net returns were maximized near the 1× broadcast rate with a 1× IR + 0.95× BR ZHA rate for the average corn price scenario (Figures 5; Table 4). Net returns for this ZHA was $529 compared with the 1× broadcast net returns of $528 ha^{-1} (± 30) (Table 4). The net returns of an "interior" optimum ZHA of 0.33× IR + 0.95× BR herbicide rate was $489, which was not significantly different from the 1× broadcast rate. Results were similar for the high and low corn price scenarios, with the optimum herbicide treatments near the 1× broadcast rate. Moreover, net returns for ZHA rates of 0.31× to 0.33× IR + 0.92× to 0.98× BR were not significantly different from the 1× broadcast rate for the three price scenarios (Table 4).

For Bradford in 2001 and the average corn price, net returns were maximized at the 0.21× IR + 0.64× BR ZHA rate with a net return of $528 ha^{-1} (± 51), which was not significantly different from the 1× broadcast net return of $521 ha^{-1} (Figure 6; Table 4). For the high and low corn price scenarios, net returns were maximized at the 1× broadcast rate and the 0.21× IR + 0.63× BR ZHA rates, respectively. Optimum ZHA net returns exceeded the 0.25, 0.50, and 0.75× broadcast reduced-rate treatments for each of the corn price scenarios.

Expected Net Returns

For the average and high corn price scenarios, expected net returns were maximized at the 1× broadcast rate (Figure 7; Table 4). For the low corn price scenario, expected net returns were maximized at a ZHA rate of 0.29× IR + 0.74× BR. However, ZHA rates of 0.29× to 0.30× IR + 0.74× to 0.80× BR generated net returns comparable with the 1× broadcast rate for all price scenarios. The optimum ZHA expected net returns also exceeded those of the 0.25, 0.50, and 0.75× reduced-rate broadcast treatments for each

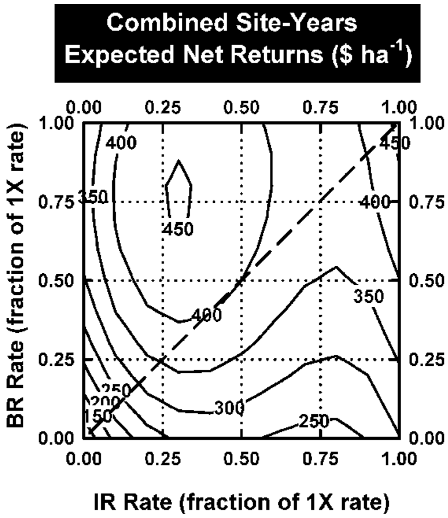

FIGURE 7. Contour graphs of expected net returns ($ ha^{-1}) vs. in-row (IR) + between-row (BR) herbicide rate, expressed as a fraction of the 1× rate, averaged over three site-years. Dotted line intersections correspond to various combinations of IR + BR herbicide rates. The thick dashed diagonal line running across the contour graphs represents the broadcast treatment where IR = BR herbicide rates. Contour lines intervals are arbitrary and should not be interpreted as being statistically different from one another.

of the corn price scenarios. This supports the idea that an economically feasible PRE ZHA treatment could be selected that would perform well across a range of conditions.

Practical Implications of ZHA

ZHA Reduces Herbicide Use

If ZHA of 0.29× to 0.30× IR + 0.74× to 0.80× BR herbicide rates of atrazine + s-metolachlor + flumesulam + clopyralid were used to control weeds and prevent corn yield loss, then total soil residual herbicide applied per unit area could be reduced an average of 47% compared with broadcast 1× herbicide rates (Figures 4–6) or 43, 58, and 64% of the 1× broadcast rate at Bradford in 2001, Greenley in 2001, and Greenley in 2002, respectively. Giant foxtail and common waterhemp were likely controlled by atrazine + s-metolachlor in the mixture, although flumetsulam + clopyralid was added to the mixture to control some minor weeds.

ZHA Is Generic

ZHA is not limited to certain herbicides or crops, such as atrazine + s-metolachlor in field corn. ZHA is a generic herbicide application technique that may help reduce use of other persistent, soil residual herbicides, such as acetanilide, acetamide, triazine, or dinitroaniline herbicides in corn and other competitive annual row crops, such as grain sorghum [*Sorghum bicolor* (L.) Moench]. However, this possibility must be verified by field testing. Planter-mounted sprayers could be used for ZHA of soil-active, residual, PRE herbicides, as was done for herbicide banding in the past. ZHA may have more immediate potential use with PRE soil residual herbicides than POST herbicides. Because POST herbicide efficacy varies with carrier volume and other application variables, the weed control efficacy of POST ZHA must be tested and optimized, and new even nozzle tips may be required that are specifically designed for POST ZHA.

Sprayer Modifications for Using ZHA Are Inexpensive

ZHA has potential for reducing herbicide input cost after minor and inexpensive modification of existing ground herbicide sprayers. In this research, BR and IR herbicide rates were varied using a dual-boom zone herbicide sprayer to keep other sprayer parameters constant (e.g., carrier volume). However, dual-boom herbicide sprayers for ZHA are complicated, expensive, and double equipment costs for farmers. If farmers used single-boom ZHA sprayers instead, they could modify existing sprayers cheaply for ZHA. For single-boom ZHA of different BR and IR herbicide rates of the same herbicide mixture (1) the number of nozzles on one boom could be doubled, (2) the between-nozzle spacing could be halved, and (3) two different even nozzle tips could be alternated on the same sprayer boom. Different BR and IR herbicide rates could be achieved by varying (1) BR and IR even nozzle tips to change BR and IR carrier volume and (2) herbicide concentration in the spray tank, after suitable calibration and spray pattern checks. New even nozzle tips may be needed to reduce the total carrier volume applied and allow greater boom height. Input cost savings for herbicides over time should dwarf initial costs for modifying sprayers for single-boom ZHA. If single-boom ZHA is successful, reduced herbicide input costs would likely drive adoption of ZHA without the need for government subsidies. In addition, ZHA is independent of scale and could be used on many different sized farms.

ZHA Reduces the Chance of Crop Injury by Herbicides

ZHA may improve crop selectivity for some soil residual herbicides that can damage crops, especially under environmental stress, such as low temperature and high soil moisture content, during emergence and seedling establishment (Boldt and Barrett 1989; Kunkel et al. 1996). By reducing IR herbicide rates, ZHA decreases the chance of herbicide phytotoxicity to crops so that crop growth and interference with weeds are maximized. Lower total herbicide use with ZHA also minimizes soil residual herbicide carryover and potential damage to susceptible rotational crops. It may also shorten the time interval required before planting susceptible species after some residual herbicides if planted back into the IR zone.

ZHA Reduces the Chance of Water Contamination by Herbicides

By reducing total herbicide applied per unit area an average of 47% without sacrificing weed control, yield, or net returns, ZHA could help reduce the risk of surface water contamination by soil residual herbicides. ZHA may be compatible with no-till farming methods that also help minimize soil erosion and sediment contamination of surface water. Thus, ZHA can help farmers reduce non–point source pollution and improve environmental stewardship. ZHA may also contribute to the long-term economic viability or sustainability of our agricultural production system by reducing input costs. ZHA also may provide new economic opportunities for herbicide sprayer or sprayer parts manufacturers, custom herbicide applicators, and crop consultants.

Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the products, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.

Sources of Materials

[1] Bicep II Magnum (atrazine + s-metolachlor) is manufactured by Syngenta, Greensboro, NC 27419-8300, and Hornet (clopyralid + flumetsulam) is produced by Dow AgroSciences LLC, Indianapolis, IN 46268-3033.

[2] Teejet 6501 flat-fan nozzle tip, Spraying Systems Co., North Avenue at Schmale Road, Wheaton, IL 60188.

[3] Teejet 4001E even nozzle tip, Spraying Systems Co., North Avenue at Schmale Road, Wheaton, IL 60188.

[4] Olympus D-620 L digital camera in 2001 and Olympus C4040 zoom digital camera in 2002, Olympus America Inc., Melville, NY 11747-3157.

[5] Sigma Scan Pro version 5 software, SPSS Science, SPSS Inc., 233 South Wacker Drive, 11th Floor, Chicago, IL 60606-6307.

[6] Table Curve 3D version 3 software, SPSS Inc., 444 North Michigan Avenue, Chicago, IL 60611.

[7] SigmaPlot 2000 software, SPSS Inc., 444 North Michigan Avenue, Chicago, IL 60611.

[8] The constrained nonlinear optimization quick sheet, MathCAD 2000 software, Mathsoft Inc., 101 Main Street, Cambridge MA 02142.

Acknowledgments

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