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MAIZE GRAIN YIELD RESPONSE TO VARIABLE ROW NITROGEN FERTILIZATION

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□ *Crop yields are affected by the rate and method of nitrogen (N) fertilizer application. This study was conducted to determine the effects of applying variable N rates by row on maize grain yields. The effects of variable rates and row application were investigated at the R.L. Westerman Irrigation Research Facility near Stillwater, Oklahoma on a Port-Oscar silt loam (fine-silty, mixed, super active, thermic Cumulic Haplustolls) and at Hennessey, Oklahoma on a Bethany silt loam (fine, mixed, thermic Pachic Paleustolls). For 2005 that was characterized by high yields, significant yield differences occurred in non-fertilized rows adjacent to N (67, 100, 134 kg N ha^{-1}) fertilized rows, but not when adjacent to low N [34 and 67 (some cases) kg N ha^{-1}]. In 2006, which had a dry growing season, grain yields were significantly lower than those produced in 2005. With few exceptions, rows receiving N did not produce significantly higher yields in 2006. In 2007, trends were similar to those observed in 2005. Excluding 2006, all site-years showed a significant reduction in yield when N fertilizer was not applied to each row. In order to maximize corn grain yields, N fertilizer should be applied by row, while alternate row N application should be avoided.*

Keywords: corn, precision agriculture, soil fertility

INTRODUCTION

Maize is an important crop grown as food for humans and feed for livestock in the United States and the world. Under current production,

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maize is the largest crop produced in the world with 695,228,280 metric tons (MT) produced in 2006 (FAO, 2007). For 2006, production in the United States (U.S.) was 267,598,000 MT, placing maize as the largest crop grown in the U.S. (FAO, 2007). Compared to 1996, these values represent an increase in maize production of 105,768,241 MT (18%) and 234,527,008 MT (14%) in the world and the U.S., respectively. Production increases can be attributed to increased land under maize cultivation in the world, higher yields per land area (FAO, 2007), improved hybrids, management, and fertilization strategies (Pingali, 2000). Because of the importance of maize in the U.S. and the world, it is important to evaluate production inputs, i.e., fertilizer, irrigation, pesticide applications, etc., that may increase yield or decrease the cost of production. After water, nitrogen (N) fertilizer is considered to be the most limiting factor for cereal crop production, including maize. The fertilizer component that plants require in greatest amounts and whose availability often limits plant productivity is N (Bloom et al., 2003). In addition, the greatest competition between plants is usually for N, and thus it is the major nutrient input farmers utilize to increase crop yield (Patterson, 1995; Raun and Johnson, 1999).

The importance of N fertilizer placement varies with crop yield potential, soil N level, the amount and timing of rainfall, tillage system, and environmental conditions (Blackshaw et al., 2002). With such influential factors, placing N fertilizer in the fertilization zone at the correct rate and optimum time should limit the impact of each input feature. As a result, nitrogen use efficiency (NUE) would be expected to increase through the appropriate placement of N fertilizer through split applications (Lehrsch et al., 2000). For maize, N fertilization occurs on a variety of scales – surface broadcasting, sidedressing between rows, banding, knife injection, etc. – for preplant, starter, and topdressing applications. Of the various application methods, banding and sidedressing are particularly advantageous when producing maize in N depleted soils; however, if adequate N is present in the soil as a starter fertilizer for growth through mid-season, then 100 percent of the additional N fertilizer needed, applied as a sidedress application, may increase NUE and yield (Lehrsch et al., 2000). Banding resolution of N in maize, i.e., every row, between row, every other row, etc. has been shown to be satisfactory in producing no reduction in yield by applying N in the middle of every other row instead of every inter-row (Durst and Beegle, 1999; Hefner and Tracy, 1995; Murrell, 2006; Lehrsch et al., 2000; Stecker, 1993; Vitosh et al., 1995). Durst and Beegle (1999) and Stecker (1993) considered this application best practiced as a sidedress application when maize rows are visible so that the bands of N can be precisely placed between the rows to eliminate the potential decline in yield to the row furthest from the N source. However, this is contradictory to work by others.

TABLE 1 Initial soil test results (0–15 cm) for LCB 2005 and HEN 2007

			mg kg^{-1}			
Location	Year	pH	NH_4-N	NO_3-N	P	K
LCB	2005	5.54	22.6	3.8	33.6	129
Classification: Port-Oscar silt loam (fine-silty, mixed, super active, thermic Cumulic Haplustolls)						
HEN	2007	5.26	2.03	3.2	63.1	391
Classification: Bethany silt loam (fine, mixed, thermic Pachic Paleustolls)						

*pH - 1:1 soil:water; P and K - Mehlich III; NH_4-N and NO_3-N - 2 M KCl extraction.

In maize, N is predominantly used by the individual row to which it is applied when spatial diversity is minimized near the point of application (Johnson and Kurtz, 1974; Jokela and Randall, 1987; Sanchez et al., 1987; Blaylock et al., 1990). Further studies conducted in Iowa, U.S. showed labeled N was recovered chiefly by the row to which it was applied with little N recovery observed in either adjacent maize row, suggesting that maize derives little of its N from that applied to adjacent rows (Ghaffarzadeh et al., 1998). From a logical standpoint, this makes sense because the roots of a maize plant occupy a relatively small area in comparison to the width of a normal row spacing of 0.76 m.

Spatially and temporally, N in the soil is extremely heterogeneous (Miller and Cramer, 2004; Raun et al., 2002). Various studies have indicated that N is primarily recovered by the maize row to which it is applied and therefore, row-by-row precision applications of N fertilizer (Ghaffarzadeh et al., 1998) or finer resolutions, i.e., by plant N fertilizer application, seem to be an appropriate management tool for improving NUE, increasing yield, reducing input costs, lowering the risk of potential N losses, and the detrimental impacts to the environment caused by excess N applications.

The objective of this study was to determine maize (*Zea mays* L.) grain yield response to variable row N fertilization at varying rates when liquid N fertilizer was placed at the base of each maize row.

MATERIALS AND METHODS

Experimental sites were established at the R. L. Westerman Irrigation Research Center at Lake Carl Blackwell (LCB), west of Stillwater, OK, in 2005 and at Hennessey (HEN), OK in 2007. Initial soil test results (0–15 cm) for each location are reported in Table 1. Each site was planted to maize (*Zea mays* L.), using Pioneer® 33B51 (2005 and 2006; Pioneer, Johnston, IA, USA) and DeKalb® DKC 66–23 (2007) at LCB and DeKalb® 50–20 at HEN. The irrigated site was planted at a population of 79,000 seeds ha^{-1} for all

TABLE 2 Treatment structure employed for N row study at Lake Carl Blackwell 2005 and 2006 on resultant maize grain yields

	Sidedress application kg N ha^{-1}						
Treatment	Border	Row 1	Row 2	Row 3	Row 4	Row 5	Border
1	134	134	134	0	0	0	0
2	100	100	100	0	0	0	0
3	67	67	67	0	0	0	0
4	34	34	34	0	0	0	0
5	134	134	0	0	0	0	0
6	134	134	34	0	0	0	0
7	134	134	67	0	0	0	0
8	0	0	67	0	0	0	0
9	0	0	0	0	0	0	0
10	134	134	134	134	134	0	0
11	134	134	0	134	0	0	0

years and the rainfed Hennessey site was planted at a population of 53,100 seeds ha^{-1}. Both sites were planted with a row spacing of 0.76 m.

The study consisted of 11 treatments arranged in a completely randomized block design with three replications (LCB 2005 and 2006) and modified for the 2007 season to 11 treatments arranged in a completely randomized design consisting of three replications in four ranges. The treatment structure employed at LCB for 2005 and 2006 (Table 2) was modified slightly in 2007 (Table 3) to allow for better interpretation of change in yield and influence of N fertilizer applied to specific rows and its lateral movement, if any. Plots were 3 meters long by seven rows (0.76 m row spacing). Nineteen

TABLE 3 Treatment structure employed for N row study at Lake Carl Blackwell, and Hennessey, 2007 on resultant maize grain yields

	Sidedress application kg N ha^{-1}						
Treatment	Border	Row 1	Row 2	Row 3	Row 4	Row 5	Border
1	134	134	134	0	0	0	0
2	100	100	100	0	0	0	0
3	67	67	67	0	0	0	0
4	34	34	34	0	0	0	0
5	134	134	0	0	0	0	0
6	134	134	34	0	0	0	0
7	134	134	67	0	0	0	0
8	67	67	0	67	0	0	0
9	0	0	0	0	0	0	0
10	134	134	134	134	134	0	0
11	134	134	0	134	0	0	0

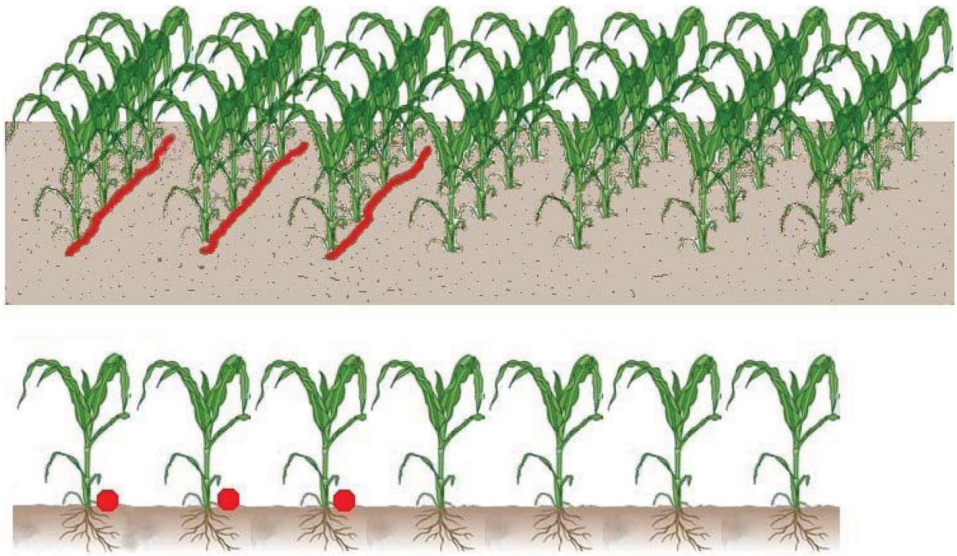

FIGURE 1 Nitrogen fertilization placement employed for this study to determine maize grain yield response to variable row N fertilization (Color figure available online).

liters ha^{-1} of 10-15-0 starter liquid fertilizer was applied at planting at the irrigated site for 2006 and 2007. No starter or pre-plant fertilizer was applied at the rain-fed site. Top-dress N rates of 34, 67, 100, and 134 kg N ha^{-1} were applied at V6–V8 growth stages to the base of individual rows (Figure 1) based on treatment structure. The V6–V8 growth stages are known as the time when the tassel/growing point comes above the soil surface and corresponding rapid growth of the plant, ear shoot initiation, and kernel row determination (Hanway, 1963). Syringes were used to apply the N fertilizer at the base of the plant in each fertilized row.

At harvest, ears from each plant of the first five rows (2005 and 2006) and the five middle rows (2007) in each plot were hand harvested. The ear weight (grain on cob) of each row was recorded. Ears were dried at 75°C for seven days using a forced air drying oven, re-weighed, and ears shelled using a hand mechanical sheller. Grain weight for each row was recorded. Statistical analysis at the 0.05 probability level, using Duncan's Multiple Range Test was performed using SAS (SAS Institute, Cary, NC, USA).

RESULTS

At LCB, in 2005, significant yield differences occurred in non-fertilized rows adjacent to mid to higher N fertilized rows receiving 67, 100, or 134 kg N ha^{-1}; lower rates of 34 and 67 (some cases) kg N ha^{-1} did not result in significant yield differences in adjacent rows receiving no N (Table 4). For

TABLE 4 Treatment mean grain yields for LCB, 2005 and 2006 (See Table 2 for treatment structure)

Treatment means by row			Grain yield mg ha^{-1}				
Year	LOC	TRT	Border row	Row 1	Row 2	Row 3	Row 4
2005	LCB	1	12.4	11.6	10.3	7.4 a, b	5.6 a, b, c
		2	10.2	10.5	11.0	7.3 c	7.5 c
		3	10.5	10.3	8.7	6.8 a, b	6.0 a, b
		4	8.4	8.3	8.4	7.9	7.9
		5	8.8	8.5	5.3 a	5.6	5.6
		6	13.0	13.0	9.5 a, b	8.5 a, b	8.5 a, b
		7	11.1	11.6	9.1	7.4 a, b	7.1 a, b
		8	6.1	5.7	8.6	6.2	6.3
		9	9.4	8.7	9.9	9.2	9.8
		10	11.1	11.0	9.4	10.3	11.3
		11	12.3	12.0	9.6	11.3	8.2 a, b
2006	LCB	1	7.8	5.2 a	4.7 a	4.7 a	5.9
		2	6.0	4.6	4.2	3.3 a	4.8
		3	5.0	4.6	3.4	3.6	3.6
		4	3.2	3.1	3.1	2.4	3.0
		5	3.4	3.8	3.0	3.0	3.1
		6	4.5	4.0	3.9	3.7	3.6
		7	7.3	5.7	5.4	5.3	4.6 a
		8	5.3	4.9	4.0	4.0	5.1
		9	4.0	4.7	5.1	4.4	4.4
		10	5.3	5.8	6.4	5.1	5.5
		11	4.9	7.0	4.7 b	4.4 b	4.6 b

Means in a row followed by a letter indicate significantly different means at the 0.05 probability level using Duncan's multiple range test in the following manner: a - to border row, b - to row 1, c - to row 2.

each treatment, fertilized rows produced higher yields than non-fertilized rows even though this difference in yield was not always significant.

Differences in yield by row can be attributed to the rate of N received by each row. When the first three rows received N and the next two rows received no N (Table 2), the resultant grain yields showed differences between fertilized and non-fertilized rows. In each case, the fertilized rows produced yields that were not significantly different from each other; however, the yield of the fertilized row adjacent to the non-fertilized row was depressed from that of the other two fertilized rows. The yield of the last fertilized row in the sequence was not significantly different than the non-fertilized rows, but the non-fertilized rows were significantly different compared to the first fertilized rows in the sequence (Table 4). In each scenario, the fertilized row's yield depression may be attributed to competition from the adjacent non-fertilized row, indicating some lateral movement of N fertilizer.

In the case of one row receiving N (67 kg N ha^{-1}) and the two adjacent rows on either side receiving no N, the fertilized row produced a higher grain yield, indicating the benefit of N fertilizer (Table 2). However, the increase in yield was not significantly different than the yields of rows receiving no N

(Table 4). Similarly, when the first two rows and the fourth row received N (134 kg ha^{-1}) and the third and fifth rows received no N (Table 2), grain yields were depressed in the non-fertilized rows. However, grain yield in the fertilized row, between two non-fertilized rows, was the only yield that was significantly different (Table 4). The yield for row two was depressed from that of either of its neighbor rows, but this indicates that some lateral movement may have occurred to allow this yield to be higher than that of row four.

At LCB, in 2006, yields were significantly lower than those produced in 2005. For 2006, response to mid-season application of N fertilizer was limited and as a result, rows receiving N (34, 67, 100, and 134 kg N ha^{-1}) did not produce significantly higher yields when compared to rows receiving no N fertilizer (Table 4). The few instances where significant yield differences occurred did not follow the same trend as 2005. The check (all five rows receiving 0 kg N ha^{-1}) on average yielded more than four of the fertilized treatments, and produced yields nearly identical to two other fertilized treatments. This illustrates a limited response to N except for isolated cases (Table 4); however, the depressed yields produced for this site year show that yield was less impacted with rate of N applied and was more influenced by low moisture availability and high temperature.

Combining site years 2005 and 2006 resulted in trends similar to those found for 2005; however, overall yields were depressed due to low yields obtained in 2006. Significant yield differences occurred between non-fertilized rows adjacent to rows receiving higher rates of N (67, 100, and 134 kg N ha^{-1}); low rates of N (34 kg N ha^{-1}) did not result in significant yield differences when compared to adjacent rows (Table 5). Fertilized rows yielded more than non-fertilized rows across treatments.

TABLE 5 Mean treatment grain yields over site-years LCB, 2005 and 2006

Treatment means by row			Grain yield mg ha^{-1}				
Year	LOC	TRT	Border row	Row 1	Row 2	Row 3	Row 4
2005 and 2006	LCB	1	10.1	8.4	7.5 a	6.1 a, b	5.7 a, b
		2	8.1	7.5	7.6	5.3 a, b, c	6.1
		3	7.7	7.5	6.1	5.2 a, b	4.8 a, b
		4	5.8	5.7	5.8	5.1	5.4
		5	6.1	6.2	4.1	4.3	4.4
		6	8.7	8.5	6.7*a*	6.1 a, b	6.1 a, b
		7	9.2	8.7	7.2	6.3 a, b	5.8 a, b
		8	5.7	5.3	6.3	5.1	5.7
		9	6.7	6.7	7.5	6.8	7.1
		10	8.2	8.4	7.9	7.7	8.4
		11	8.6	9.5	7.2*b*	7.9	6.4 a, b

Means in a row followed by a letter indicate significantly different means at the 0.05 probability level using Duncan's multiple range test in the following manner: a - to row 1, b - to row 2, c - to row 3.

TABLE 6 Treatment mean grain yields for LCB and HEN, 2007 (see Table 3 for treatment structure)

Treatment means by row			Grain yield mg ha^{-1}				
Year	LOC	TRT	Row 1	Row 2	Row 3	Row 4	Row 5
2007	LCB	1	7.3	6.9	5.9	3.7 a, b	4.4 a
		2	9.2	9.7	5.1 a, b	4.2 a, b	5.2 a, b
		3	7.5	8.2	3.6 a, b	3.9 a, b	3.4 a, b
		4	5.6	4.9	4.4	5.3	4.2
		5	9.4	4.8 a	4.4 a	5.5 a	4.0 a
		6	6.2	4.7	3.5 a	4.5	3.5 a
		7	7.5	6.6	5.0	3.2 a, b	3.5 a, b
		8	7.3	5.0	6.5	4.9	4.1 a
		9	5.4	3.9	3.4	3.9	4.5
		10	8.8	9.1	8.2	8.9	4.6 a, b, c, d
		11	7.5	4.6	6.6	3.3 a, c	2.9 a, c
2007	HEN	1	7.5	8.4	6.9	6.1 b	6.2 b
		2	8.7	9.0	6.9 b	6.5 a, b	7.0 b
		3	5.4	5.7	5.0	4.0	4.0
		4	7.8	7.4	6.9	5.7 a	7.1
		5	8.6	7.2	5.4 a	5.5 a	6.6 a
		6	8.4	7.0	8.4	6.4 a, c	6.7
		7	8.6	6.8 a	5.2 a	5.6 a	5.8 a
		8	7.0	6.5	7.3	4.8 a, c	6.4
		9	5.4	4.8	4.6	5.3	6.1
		10	8.8	9.1	9.4	10.1	8.3 d
		11	7.0	5.7	7.4	5.9	4.8 a, c

Means in a row followed by a letter indicate significantly different means at the 0.05 probability level using Duncan's multiple range test in the following manner: a - to row 1, b - to row 2, c - to row 3, d - to row 4.

With slight modifications to the treatment structure for 2007, the results for LCB were more revealing of variable N row fertilization. Significant yield differences occurred between N fertilized rows (67, 100, 134 kg N ha^{-1}) and non-fertilized rows. Rows fertilized with the lower N rate (34 kg N ha^{-1}) did not produce yields significantly different than non-fertilized rows (Table 6). For all treatments, excluding treatment four, fertilized rows produced higher yields than non-fertilized rows.

In the case where the first two rows were fertilized (134 kg N ha^{-1}) and the next three rows were not fertilized (Table 3), results show a significant yield difference from the fertilized rows compared to the non-fertilized rows (Table 6). The third row, having received no N, had a depressed yield from that of either of the two fertilized rows, but it had a higher yield than either of the other two non-fertilized rows, suggesting that some lateral movement of N may have occurred as this row was in competition for nutrients with the adjacent fertilized row. Additionally, every non-fertilized row had a significantly lower yield than the fertilized rows (100 and 67 kg N ha^{-1}) (Table 6). The two fertilized rows had significantly higher yields than the non-fertilized rows, suggesting in this case that no lateral movement of N occurred, nor were rows at this spacing (0.76 m) in competition with one another for nutrients. Likewise, when the first row was the only fertilized row, receiving 134 kg N ha^{-1}, and the four subsequent rows received no N fertilizer, each of the non-fertilized rows produced a significantly lower yield than the fertilized row. Additionally, the non-fertilized row immediately adjacent to the fertilized row did not have a higher yield than the non-fertilized row adjacent on the other side (Table 6). Reversing the treatment, in which the first four rows were fertilized (134 kg N ha^{-1}) and row five was not fertilized (Table 3), the non-fertilized row's yield was significantly lower than that of the fertilized rows (Table 6), indicating that no lateral movement of N occurred.

It could be argued that competition for nutrients or lateral movement of N did occur, as was the case when rows four and five (0 kg N ha^{-1}) had significantly lower yields than rows one or two which received 134 kg N ha^{-1}, but was not significantly different than row three which also received no N. Row two's yield was depressed from that of row one, but higher than that of row three; likewise, row three's yield was higher than that of rows four and five. A non-fertilized row between two fertilized rows may help to increase the yield of the non-fertilized row. The non-fertilized row between two fertilized rows (67 or 134 kg N ha^{-1}) resulted in a higher yield in the non-fertilized row when compared to the other non-fertilized rows within the treatment (Table 6). Furthermore, in some cases, any non-fertilized row adjacent to a fertilized row benefited from the fertilizer applied. Only those rows not adjacent to a fertilized row resulted in significantly lower yields. In other cases, only rows between two fertilized rows benefited from fertilizer application, while adjacent rows, even to fertilized rows, produced significantly lower yields if the row was not between two fertilized rows. (Table 6).

The HEN site produced significantly different yields between fertilized and non-fertilized rows (Table 6). Rows with higher N rates (100 and 134 kg N ha^{-1}) produced yields significantly different than rows receiving no N, while lower N rates (34 and 67 kg N ha^{-1}) did not produce significantly different yields when compared to rows receiving no N. With the exception of treatment six, all treatments followed a similar trend. All fertilized rows yielded higher, although not always significantly, than non-fertilized rows.

Results indicate that some lateral movement or competition for N among rows existed. In some cases, a row having received no N, but adjacent to a fertilized row, produced a higher yield than the other rows receiving no N; however, the yield was still lower than the fertilized row (134 kg N ha^{-1}). This suggests that the non-fertilized row adjacent to the fertilized row received some benefit from the applied N. In the case of varying N rate from row to row, non-fertilized rows yielded significantly lower than the row with the highest fertilizer rate (134 kg N ha^{-1}), but not to the row receiving 67 kg

TABLE 7 Mean treatment grain yields over site-years HEN and LCB, 2007

Treatment means by row			Grain yield mg ha^{-1}				
Year	LOC	TRT	Row 1	Row 2	Row 3	Row 4	Row 5
2007	HEN and LCB	1	7.4	7.6	6.4	4.9 a, b	5.3 a, b
		2	8.9	9.3	6.0 a, b	5.3 a, b	6.1 a, b
		3	6.5	6.9	4.3 a, b	3.9 a, b	3.7 a, b
		4	6.7	6.2	5.6	5.5	5.6
		5	9.0	6.0 a	4.9 a	5.5 a	5.3 a
		6	7.3	5.8	5.9	5.4 a	5.1 a
		7	8.1	6.7	5.1 *a, b*	4.4 *a, b*	4.6 *a, b*
		8	7.2	5.7	6.9	4.8 a, c	5.3 a, c
		9	5.4	4.4	4.0	4.6	5.3
		10	8.8	9.1	8.8	9.5	6.4 a, b, c, d
		11	7.2	5.2 a	7.0 b	4.6 a, c	3.9 a, c

Means in a row followed by a letter indicate significantly different means at the 0.05 probability level using Duncan's multiple range test in the following manner: a - to row 1, b - to row 2, c - to row 3, d - to row 4.

N ha^{-1}. However, the yield of the row receiving 67 kg N ha^{-1} was higher than that of the non-fertilized rows, suggesting a response to the N applied (Table 6).

A non-fertilized row between fertilized rows may receive some benefit from the fertilized rows. The yield of the non-fertilized row was lower than that of the fertilized row, but higher than that of the other non-fertilized rows. However, the non-fertilized row adjacent to the fertilized row yielded significantly lower than the fertilized rows (Table 6). Additionally, a non-fertilized row between fertilized rows and adjacent to fertilized rows produced a lower yield, though not significantly lower. However, a non-fertilized row next to another non-fertilized row produced a yield significantly lower than either of the fertilized rows (Table 6), suggesting that the non-fertilized rows between or adjacent to fertilized rows may receive some benefit from the N applied.

Combining site years LCB and HEN 2007 resulted in trends similar to those found for each site year. Significant yield differences occurred between non-fertilized rows adjacent to rows receiving higher rates of N (67, 100, and 134 kg N ha^{-1}); low rates of N (34 kg N ha^{-1}) did not result in significant yield differences when compared to adjacent rows (Table 7). Fertilized rows yielded more than non-fertilized rows across all treatments.

DISCUSSION AND CONCLUSIONS

This study reports the effects of applying different N rates to different rows and the ensuing by-row maize grain yields. Low by-row rates of N (34 kg N ha^{-1}) did not produce significantly different yields for any site year when compared to the 0 kg N ha^{-1} check. Even when N stress was severe, applying low N rates (34 kg N ha^{-1}) mid-season (V6–V8) had no effect on resultant by-row grain yields. However, at the higher N rates (>67 kg N ha^{-1}), yield increases were observed. For this study, there were obvious minimum amounts of N that were required by-row to affect maize grain yield changes. Higher N rates (100 and 134 kg N ha^{-1}) did produce significantly higher yields in those rows for all site years. The significance of the 67 kg N ha^{-1} application rate varied from site year to site year. In most cases, non-fertilized rows received little or no benefit from N applied to neighboring rows; however, there were instances where this benefit could be seen. Nonetheless, even if a benefit occurred, the resultant yield was depressed from that of the neighboring fertilized row(s), suggesting that the non-fertilized row's yield potential had been dampened by lack of adequate N. Row by row differences were seen due to no N and/or added N applied to each specific row, indicating that lateral movement of N was variable from year to year and from row to row. Results from this study showed that N needs to be applied to each row, since non-fertilized rows did not benefit from N applied to adjacent rows.

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