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Localized Soil Management in Fertilizer Injection Zone to Reduce Nitrate Leaching

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Abstract

Nitrogen fertilization of row crops in humid regions can result in leaching of NO_3, which represents an inefficient use of resources and may result in environmental degradation. A localized compaction and doming (LCD) fertilizer injector was developed to alter the physical properties of soil surrounding knife-injected N. Injection by LCD includes smearing macropores below the injection slot, formation of a localized compacted soil layer over the injected N, and formation of a surface dome to cover the compacted soil layer and the fertilizer band. The LCD injector was tested, along with a conventional knife injector (without a covering disk), to evaluate its effect on leaching by determining NO_3 and Br tracer redistribution after NO_3 fertilizer injection. Chemical distributions were determined by intensive soil sampling to 0.8 m below the soil surface. In a second experiment, corn (*Zea mays* L.) yield response to both N injectors was evaluated. Four fertilization rates (67, 112, 157, and 202 kg N ha^{-1} of UAN [urea-ammonium nitrate]) were used to define yield response. During seasons when rainfall was below average, neither NO_3 redistribution nor crop yield showed a response to fertilizer injection technique. During a growing season with above-average rainfall, 26 kg ha^{-1} more NO_3 and 25 kg ha^{-1} more Br remained in the top 0.8 m of soil when LCD.injected. LCD injection increased crop yield approximately 0.48 Mg ha^{-1} over injection by the conventional knife method during an above-average rainfall season, indicating that one-fifth of the conventional knife-applied N was lost prior to crop uptake during the wet year. These findings suggest that the LCD injector may be effective at reducing leaching losses during growing seasons when rainfall is abundant.

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Localized Soil Management in Fertilizer Injection Zone to Reduce Nitrate Leaching

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ABSTRACT

Nitrogen fertilization of row crops in humid regions can result in leaching of NO_3, which represents an inefficient use of resources and may result in environmental degradation. A localized compaction and doming (LCD) fertilizer injector was developed to alter the physical properties of soil surrounding knife-injected N. Injection by LCD includes smearing macropores below the injection slot, formation of a localized compacted soil layer over the injected N, and formation of a surface dome to cover the compacted soil layer and the fertilizer band. The LCD injector was tested, along with a conventional knife injector (without a covering disk), to evaluate its effect on leaching by determining NO_3 and Br tracer redistribution after NO_3 fertilizer injection. Chemical distributions were determined by intensive soil sampling to 0.8 m below the soil surface. In a second experiment, corn (*Zea mays* L.) yield response to both N injectors was evaluated. Four fertilization rates (67, 112, 157, and 202 kg N ha^{-1} of UAN [urea–ammonium nitrate]) were used to define yield response. During seasons when rainfall was below average, neither NO_3 redistribution nor crop yield showed a response to fertilizer injection technique. During a growing season with above-average rainfall, 26 kg ha^{-1} more NO_3 and 25 kg ha^{-1} more Br remained in the top 0.8 m of soil when LCD-injected. LCD injection increased crop yield approximately 0.48 Mg ha^{-1} over injection by the conventional knife method during an above-average rainfall season, indicating that one-fifth of the conventional knife-applied N was lost prior to crop uptake during the wet year. These findings suggest that the LCD injector may be effective at reducing leaching losses during growing seasons when rainfall is abundant.

NITROGEN FERTILIZERS are widely used in corn (*Zea mays* L.) production in the north-central region of the USA. Because rainfall and irrigation amounts typically exceed the annual evaporative demand in this region, drainage to ground water or surface water (via tile drainage) can result in N movement out of the root zone. Kolpin et al. (1991) reported that 6% of 599 samples collected from 303 shallow wells in the midwestern USA had NO_3–N concentrations that exceeded the 10 mg L^{-1} drinking water standard. Groundwater provides a significant component of the total flow in many Midwestern rivers and streams, and, where they exist, subsurface tile drains can transport NO_3 from agricultural soils to waterways (Keeney and DeLuca, 1993; Johnson and Baker, 1982, 1984).

Knife injection of N fertilizers is a common application technique in the north-central region. This technique leaves a porous knife slit above the injected fertilizer. This knife slit results in a soil zone more favorable to water movement than is the surrounding soil (Ressler et al., 1997). Two soil zones are created: (i) undisturbed soil with a background N concentration and (ii) loose, porous, disturbed soil with an increased N concentration. The disturbed soil above the injected fertilizer commonly settles into the knife slit, leaving a depression that may channel nearby rain water through the fertilizer band.

Several management strategies have been proposed to reduce N leaching from agricultural lands. One recent strategy is to divert the flow of infiltrating water away from or around the N fertilizer. Placing soluble fertilizer in elevated ridges has been shown to reduce leaching (Clay et al., 1992; Hamlett et al., 1990; Kemper et al., 1975). Compacting the soil above applied fertilizers is another approach that can reduce leaching (Baker et al., 1997; Kiuchi et al., 1994, 1996; Hira and Singh, 1979). Compacted soil can be used as a barrier to water flow, limiting water and chemical movement in the fertilizer band. Lastly, chemical incorporation associated with tillage results in reduced leaching compared with no-till because macropores are disrupted and there is less bypass water flow (Kanwar et al., 1985, 1988; Tyler and Thomas, 1977). To date, no attempts have been made to combine macropore disruption, compacted soil layers, and ridges at the field scale during fertilizer injection. On Iowa farms, only 2% of cropland was in ridge-till in 1994, slightly higher than the national average of 1.2% (National Crop Residue Management Survey, Conservation Technology Information Center {CTIC}, West Lafayette, IN), and there were no reported field-scale attempts to use subsurface barriers to limit N movement in production agriculture.

A N fertilizer injector has been designed and built that forms a locally compacted soil layer and a surface ridge or dome (localized compaction and doming: LCD) over the injected fertilizer band (Ressler et al., 1997). The injector includes a knife with a triangular, horizontal shoe at the base that smears the soil at the bottom of the knife slit to close any existing macropores. A cone disk guide wheel follows the knife, to close the knife slit and compress a soil layer over the fertilizer band. Another following disk completes the closure of the slit and mounds soil above the fertilizer band. These soil manipulations are performed in between crop rows at the time of fertilizer injection, and no additional soil management was conducted during the growing season.

Physical properties of the soil within the dome and subsurface barrier (described by Ressler et al., 1997) indicated that the soil manipulations with the LCD injector reduced water flow through the injected fertilizer

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Abbreviations: LCD, localized compaction and doming; UAN, urea–ammonium nitrate.

band compared with the conventional knife injector. Ressler et al. (1998) showed that LCD-injected anions were less susceptible to leaching to subsurface drains in lysimeters than conventional knife-injected or broadcast anions. Our objective was to evaluate the effectiveness of the LCD injector to reduce NO_3 leaching and improve N-use efficiency in a continuous corn field. More specifically, we wanted (i) to determine leaching by measuring chemical redistribution of NO_3 and Br following LCD fertilizer injection (a solution containing NO_3 and Br) and comparing the results with redistribution of conventional knife-injected fertilizer NO_3 and Br and (ii) to assess fertilizer N-use efficiency by measuring N uptake in corn grain and stover along with corn yield.

MATERIALS AND METHODS

Leaching (1993–1994) and yield (1995–1996) investigations were conducted on a Nicollet silt loam (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) located at the Agronomy and Agricultural Engineering Research Center about 13 km west of Ames, IA. The experiment used a randomized complete block design. Treatments were application of N via LCD injection or conventional knife injection. Treatments were replicated four times in 1993 and six times in 1994, a total of 8 and 12 plots, respectively. A plot consisted of a 3.8- by 18.3-m area in a continuous-corn field ('Pioneer 3517 IR' hybrid, planted at 73 100 plants ha^{-1}). The field, which was not tile drained, was chisel plowed each fall and disked or field cultivated in the spring prior to planting. Subsequent weed control relied on commercially available herbicides. The plots received no additional tillage during the growing season. Injection treatments were (i) injection of a liquid solution containing calcium nitrate ($CaNO_3$) and potassium bromide (KBr) using a conventional knife injector and (ii) injection of the

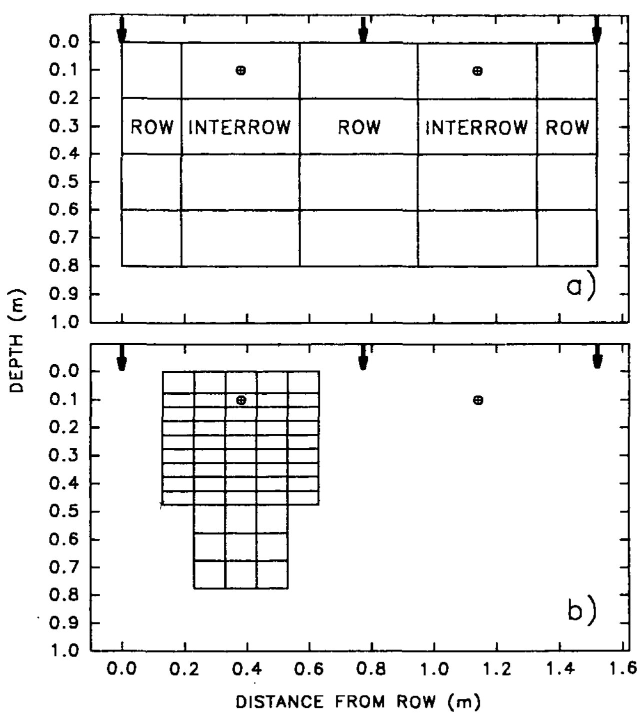

Fig. 1. Soil sampling grids: (a) large grid samples, (b) small grid samples. Circled plus indicates a fertilizer band; arrows denote corn rows.

same liquid solution using the LCD injector (Ressler et al., 1997).

A $CaNO_3$ fertilizer solution was applied to maintain constant and reproducible NO_3 injection rates for the plots. Additionally, the solution contained Br as a tracer of NO_3 movement. Bromide moves similarly to NO_3 in this soil, but is not subject to the microbial processes and gaseous losses that may affect soil NO_3 concentrations (Kessavalou et al., 1996; Simmons et al., 1992). Because Br is not native to these soils, distributions determined during soil sampling gave a clear representation of soluble chemical movement in the soil. The fertilizer solution was injected by both injectors at 0.10 m below the soil surface in the center of the interrow area. In 1993, the chemical solution consisted of 91.0 g L^{-1} NO_3-N and 100 g L^{-1} Br, and was injected at 1420 L ha^{-1}, resulting in injection rates of 129 kg ha^{-1} NO_3-N and 141 kg ha^{-1} Br. The 1994 chemical solution consisted of 91.5 g L^{-1} NO_3-N and 100 g L^{-1} Br and was injected at 1260 L ha^{-1}, resulting in slightly lower injection rates of 115 kg ha^{-1} NO_3-N and 126 kg ha^{-1} Br.

To reduce interference of background soil NO_3-N levels on N concentrations, this field was cropped to corn and received no fertilizer N for three years prior to the experiments. Background soil NO_3 levels were determined from four 0.08-m-deep soil cores collected within the plot area on 29 Apr. 1994, 13 d before the chemical injections were made. Corn is capable of significant Br uptake (Jemison and Fox, 1991; Kessavalou et al., 1996), so (to prevent Br and NO_3 cycling via crop residue) plots were used for only one growing season.

The chemical solution was applied between corn rows at 45 d after planting in the 1993 growing season. Wet soil conditions prevented earlier injection. Drier weather in 1994 allowed chemical injection at 15 d after planting. During injection, monofilament plastic fishing line was released at the depth of chemical injection from both injectors, so that the original position of the chemical band could be accurately determined at any time during the experiment.

Solute redistribution and leaching were determined by measuring soil NO_3 and Br concentrations at selected times after injection. Soil samples were obtained from a vertical pit wall perpendicular to the corn rows and spanning three corn rows and the two interrow areas (1.52 m). Soil blocks, each 0.38 m wide, 0.20 m deep, and 0.10 m thick, were collected from the two interrow positions (centered around the fertilizer band) at each 0.20-m depth interval (Fig. 1a), and were mixed by hand in the field and then subsampled. The soil in row positions (centered around the corn stalk and roots) was sampled by excavating a 0.38- by 0.20- by 0.10-m block centered on the middle corn row, then adding two half-blocks, 0.19 by 0.20 by 0.10 m, from each edge of the pit face. The resulting subsamples represented two complete interrow areas and two complete row areas. Samples were collected to a total depth of 0.8 m. In 1993, soil sampling was conducted at 38 and 83 d after fertilizer injection; in 1994, it was conducted at 33, 68, and 131 d after fertilizer injection.

Concurrent with the large block grid sampling, smaller soil samples (0.10 m wide, 0.05 m deep, and 0.10 m thick) from another sampling grid (Fig. 1b) were collected from four of the plots (two LCD and two conventional knife). These samples were used to provide a more detailed image of the chemical redistribution than the larger samples provided. These smaller soil samples were excluded from the statistical analysis described in the next section because only two plots in each treatment were sampled.

Due to the number of soil samples collected at each event, only four replications of each treatment were used the first year of the study. Soil has sources of NO_3 other than fertilizer, which contributed to experimental error; for this reason, along with the small degrees of freedom, we decided to accept significance at the 0.10 probability level.

Nitrate and Br were extracted from moist soil samples using a 4:1 distilled water:soil ratio procedure. Filtrates were analyzed for NO_3–N using an automated Cd reduction method (USEPA, 1979), which also includes NO_2–N, with a Technicon Autoanalyzer II system. Bromide concentrations were determined using high performance liquid chromatography, with a 10-μL aliquot from each sample injected into a stream of 3 mM potassium hydrogen phthalate, buffered to pH 3.8. The stream passed through a 0.10-m IC A1 anion column, maintained at 40°C. A Spectroflow 783 (Kratos Analytical Instruments, Ramsey, NJ) equipped with a conductivity sensor was used in combination with Axxiom Chromatography software (Model 727; Moorpark, CA) to digitally integrate the conductivity response. Sample concentration was determined by comparing the peak area of a sample chromatogram with the associated response of a series of calibration solutions. The NO_3 and Br masses resident at each depth were calculated by adding the fraction present in the interrow and the row samples. An ANOVA model was used to determine statistical differences between the mass fraction recovered at each layer from the LCD and conventional knife injection treatments.

In 1995 and 1996, experiments were designed to evaluate corn yield response to LCD and conventional knife-injected fertilizer N. Plots measuring 3.8 by 18.3 m were planted with 'Pioneer 3514' hybrid at 111 000 plants ha^{-1}, then manually thinned to 78 000 plants ha^{-1} to provide accurate population control. Weeds were controlled using labeled rates of acetochlor (2-chloro-*N*-(ethoxymethyl)-6′-ethyl-*o*-acetotoluidide). Four N rates (67, 112, 157, and 202 kg N ha^{-1}) were applied, by injecting a 28% UAN solution using the LCD and conventional knife injectors. A ninth treatment was a no-fertilizer control. A randomized complete block experimental design was used with six replications of the nine treatments, a total of 54 plots. Lower N rates were chosen to maintain N as the limiting nutrient, so that differences in N sufficiency would be expressed in cornstalk NO_3 concentrations and crop yield. Soil tests indicated that the levels of P and K in the soil were in the optimum range for each nutrient, so P and K were not added.

Blackmer (1986) discussed situations where corn yield may show significant responses to treatments that prevented losses of fertilizer N. Numerical calculations from Blackmer (1986) suggest that treatments that conserve a considerable amount of fertilizer N may not result in a statistically significant yield response. For this reason, we decided to accept significance at the 0.10 probability level in this experiment.

Corn stalks were collected from plots that received either the 157 or 202 kg N ha^{-1} treatments after physiological maturity to determine N sufficiency of the plants using the end-of-season cornstalk test (Binford et al., 1992; Blackmer and Mallarino, 1995). Nitrate was extracted from a 0.5-g subsample of dried and ground stalks with a 50-mL solution containing 20 mM aluminum sulfate [$Al_2(SO_4)_3$)], 20 mM boric acid [H_3BO_3], 6.4 mM silver sulfate [Ag_2SO_4], and 20 mM sulfamic acid [NH_2HSO_4]. Filtrate was analyzed using a NO_3–specific electrode.

Corn yields were measured during mechanical harvest and adjusted to reflect a 15.5% (w/w) moisture content. Yield difference between injection treatments imply that there was a difference in the amount of N available to the crop, attributed to differences in leaching of fertilizer N. It was assumed that the LCD injector changes only the physical properties of the soils in the injection zone (Ressler et al., 1997) and not chemical or biological interactions between the fertilizer and the corn plants, so only a single zero-fertilizer plot was used. An analysis similar to Blackmer (1986) was used to determine the effectiveness of the LCD injector to reduce leaching compared with conventional knife injection. We assume that in the absence of leaching, yield can be described by a quadratic relation:

$$Y_{LCD} = aN^2 + bN + c \quad [1]$$

where a, b, and c are site- or climate-specific parameters whose values were determined by a least-squares fit of LCD yield data (Y_{LCD}) and N application rate (N).

Using the coefficients a, b, and c determined from the LCD yield data, conventional knife yields (Y_{knife}) are assumed to be altered only by the fraction of N lost (L) compared with the LCD yield data:

$$Y_{knife} = a[N(1 - L)]^2 + b[N(1 - L)] + c \quad [2]$$

For simplicity, the value of L is assumed to be a constant fraction of the total N applied. Thus, if $L = 0$ during a dry year, Eq. [2] is identical to Eq. [1], and $Y_{knife} = Y_{LCD}$. Note that both Y_{LCD} and Y_{knife} are a function of the parameters a, b, and c, so Eq. [1] and [2] have identical maximum yield, though the maximums occur at different fertilization rates. The fertilizer rates for maximum yields can be loosely compared with the results from the cornstalk tests to assess the validity of Eq. [1] and [2].

RESULTS AND DISCUSSION

Leaching Study

Weather and soil conditions strongly influence fertilizer N movement in Iowa fields. In a relatively dry season, little water and therefore little N moves below the root zone, whereas water and N movement may be significant in a wet year (Schuman et al., 1975). The first study year (1993) was unusually wet, with 429 mm of rain during the first 38 d of the study (after fertilizer N injection), followed by 308 mm during the next 45 d. Long-term average precipitation values for these periods were 109 mm and 130 mm, respectively, based on weather records from 1948 through 1986 (Perrich, 1992). The second study year (1994) had a more typical Iowa summer. Rainfall totals were 104 mm during the first 33 d following fertilizer N injection, 113 mm during the next 34 d, and 175 mm during the final 63 d of the experiment. The long-term average rainfall values for these periods were 130 mm, 128 mm, and 184 mm, respectively. Thus, 1993 conditions were much wetter than average, while 1994 conditions were slightly drier than average.

Leaching and solute redistribution of NO_3 measured by the small (0.10 by 0.05 by 0.10 m) grid samples during 1993 are shown sequentially in Fig. 2 and 3. Thirty-eight days after N injection, NO_3 had moved deeper in the soil and dispersed more extensively in the conventional knife plot than in the LCD plot (Fig. 2). These distributions were still evident at the end of the growing season (Fig. 3). The pattern of solute redistribution in the knife plot suggests that transport was dominated by downward movement with water (i.e., advective transport or mass flow). The LCD plot instead suggests a more diffusive redistribution, which suggests water flow through the injected chemicals was reduced compared

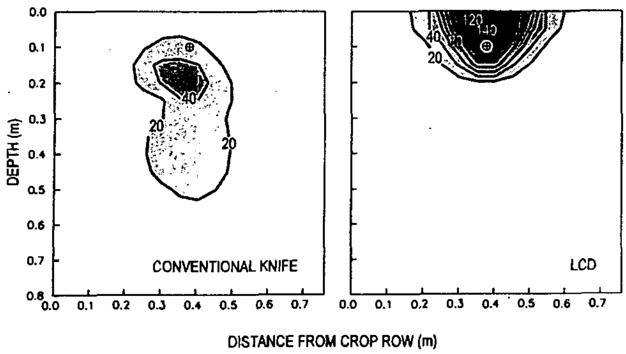

Fig. 2. Soil NO_3 distribution at 38 d after injection, as affected by conventional knife or localized compaction and doming (LCD) fertilizer injection, 1993. Contour interval is 20 mg NO_3 kg^{-1} soil. Fertilizer band is indicated by a circled plus.

with the conventional knife treatment. Bromide redistribution patterns were nearly identical with respect to depth and lateral distribution (data not shown), suggesting that the redistribution patterns were not a function of gaseous movement or biological processes. These data indicate that chemical injection using the LCD injector reduced NO_3 movement during the 1993 growing season compared with the conventional knife injector.

Measurements of solute concentration in large grid samples (0.38 by 0.20 by 0.10 m) confirmed the downward movement of NO_3 and Br when injected by the conventional knife injector, and the relative retention of chemicals when injected by the LCD injector. The 1993 leaching data are presented in Fig. 4. Surface layer mass of NO_3 and Br was greater for the LCD plots than those of the conventional knife plots at both 38 and 83 d after fertilizer injection. At 83 d, Br mass in the upper two layers was greater in LCD plots than those of conventional knife plots. These data are consistent with the chemical distributions shown in Fig. 2 and 3. This suggests that, during a year when precipitation is abundant, the LCD method limits the movement of N out of the injection zone near the soil surface, and thus reduces leaching.

In 1994, the second year of the study, prefertilization soil NO_3 was measured at 13 d prior to chemical injection. Data are superimposed on Fig. 5. Total prefertilization soil NO_3 in the profile to 0.8 m deep was 27.5 kg ha^{-1}, which was less than 25% of the NO_3 injected as fertilizer.

Precipitation totals were slightly lower than historical averages in 1994. Thus, the potential for leaching losses was reduced compared with 1993. Bromide applied by LCD injection showed higher mass at the surface than knife-injected mass after 33 d (Fig. 5). Nitrate distributions at 33 d showed similar trends, although the difference was not statistically significant. Samples collected in the middle of the growing season (68 d; data not shown) and at the end of the growing season (131 d; Fig. 5) showed little downward movement of the injected chemicals and sharp reductions of the surface layer

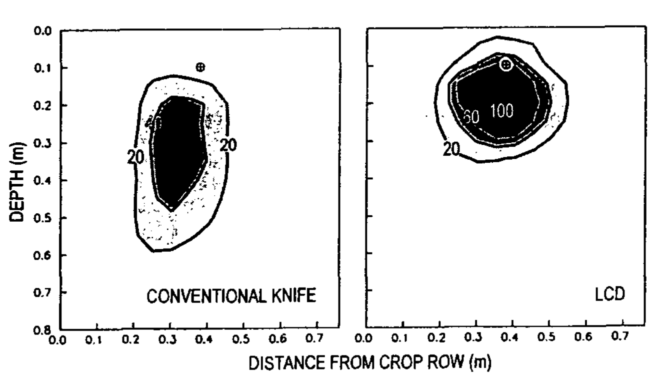

Fig. 3. Soil NO_3 distribution at 83 d after injection, as affected by conventional knife or localized compaction and doming (LCD) fertilizer injection, 1993. Contour interval is 20 mg NO_3 kg^{-1} soil. Fertilizer band is indicated by a circled plus.

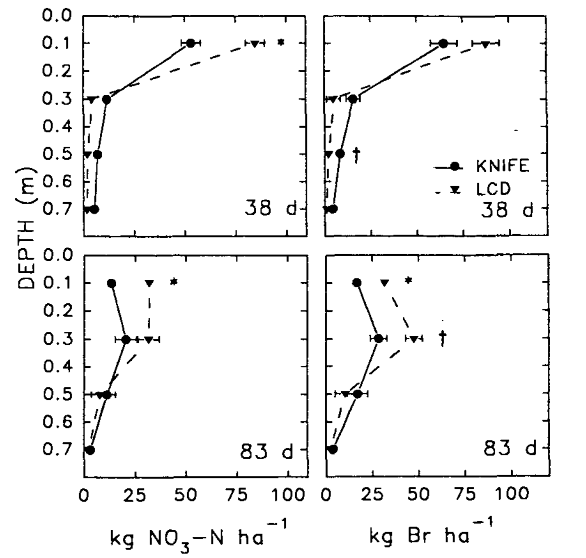

Fig. 4. Distribution of NO_3 and Br as affected by conventional knife or localized compaction and doming (LCD) fertilizer injection, at 38 and 83 d after injection, 1993. Error bars indicate ±1 SE. †,* Significant at the 0.10 and 0.05 probability levels, respectively.

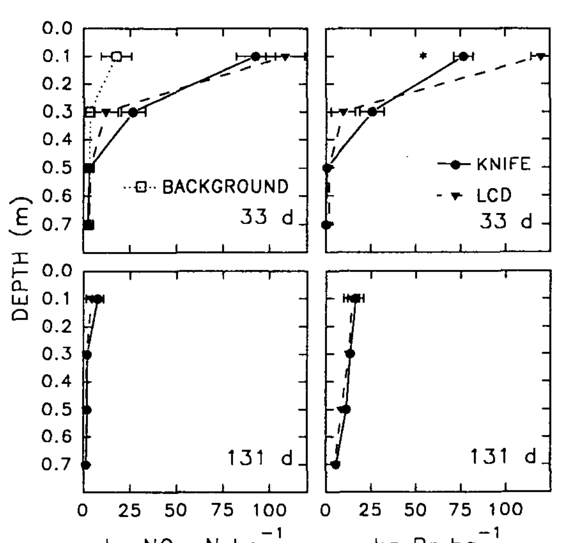

Fig. 5. Distribution of NO_3 and Br as affected by conventional knife or localized compaction and doming (LCD) fertilizer injection, at 33 and 131 d after injection, 1994. Background mass was determined at 13 d prior to N injection. * Significant at the 0.05 probability level.

mass, regardless of injection method. These reductions suggest loss by plant uptake rather than leaching. Data from the smaller (0.10 by 0.05 by 0.10 m) samples showed the same trends: NO_3 and Br were retained near the soil surface at 33 d, and were removed from the profile as the season progressed (data not shown). Considering the rainfall differences between 1993 and 1994, along with the distributions of NO_3 and Br in the soil profile, leaching was not likely to be a significant problem in 1994.

Distributions of NO_3 and Br in the soil profile are summarized in Fig. 6 by showing the total mass stored in the upper 0.8 m of the root zone at each time samples were collected. The LCD injector treatment retained 26 kg ha^{-1} more NO_3 and 25 kg ha^{-1} more Br in the upper part of the root zone than the conventional knife injector during the above-average precipitation year in 1993. During 1994, when precipitation was lower, a difference was measured in Br mass, but only at the first sample date.

Yield Study

During 1995, the first year of the yield study, 317 mm of rainfall fell between fertilizer injection (17 May) and harvest (24 October), which is 76 mm below the long-term average for the period. Conditions in spring 1996 were wet, which delayed fertilizer injection until 1 July. After fertilizer injection, 422 mm of rainfall was observed through harvest (12 November), 79 mm greater than the average for the period. Thus, the 1995 season was drier than average, while the 1996 season was wetter than average.

There were no yield differences between injection methods at any N rate in 1995 (Fig. 7), probably because leaching was limited by reduced rainfall. In 1996, when rainfall was more plentiful, for similar fertilizer rates, plots that received LCD-applied N yielded an average 0.48 Mg ha^{-1} more than plots that received N via the conventional knife injector (Fig. 7). Although none of the individual yield values were significantly different between injector treatments at a single N rate, differences observed across all rates in 1996 were significant

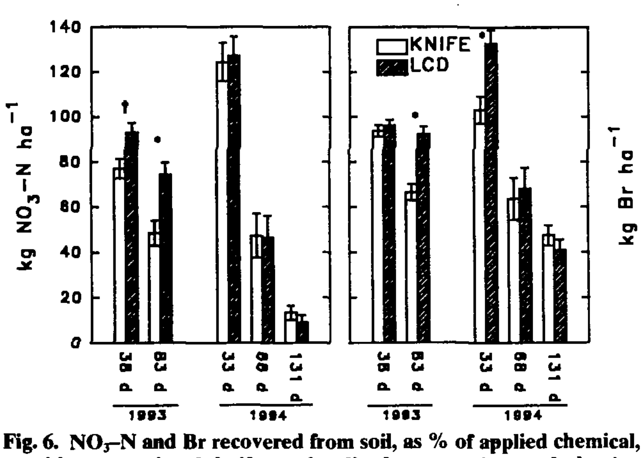

Fig. 6. NO_3–N and Br recovered from soil, as % of applied chemical, with conventional knife or localized compaction and doming (LCD) fertilizer injection. †,* Significant at the 0.10 and 0.05 probability levels, respectively.

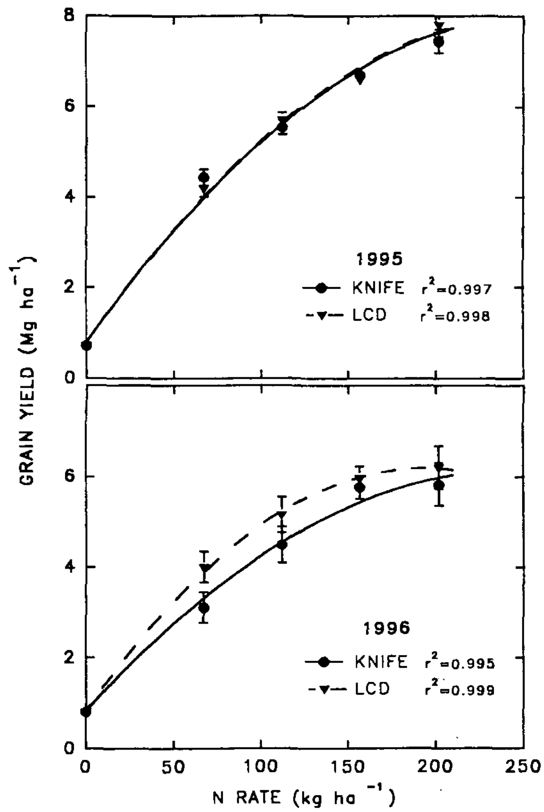

Fig. 7. Corn yield response to fertilizer rate and to conventional knife or localized compaction and doming (LCD) injection method, 1995 and 1996.

at the 0.10 probability level. There was no interaction between N rate and injection method.

Parameters determined from the regression analysis (Eq. [1] and [2]) are shown in Table 1. In 1995, a drier than average growing season, yield was not affected by injection method, and leaching loss by the conventional knife injection was estimated to be only 1% greater than with LCD injection, based on yield response (see Table 1). In 1996, a growing season with above-average precipitation, leaching loss via conventional knife injection was estimated to be nearly 23% greater than LCD injection.

Use of the end-of-season cornstalk test allows a rough check of the conclusion drawn from the regression equations. For example, the maximum yield for the 1996 LCD treatment was predicted to be 184 kg ha^{-1} (Table

Table 1. Values of regression parameters from corn yield data with localized compaction and doming (LCD) or conventional knife-injected fertilizer.

Parameter	1995	1996
a	-1.05×10^{-4}	-1.43×10^{-4}
b	0.0554	0.0526
c	0.781	0.831
r^2	0.998	0.999
L_{knife}	0.012	0.226
r^2	0.997	0.995
$N_{max(LCD)}$†	262	184
$N_{max(knife)}$	266	238

† N_{max} is the fertilization rate (kg ha^{-1}) at which the maximum yield is expected using Eq. [1] and [2].

Table 2. Tissue N status of corn plants at end of season.

	NO_3–N					
	1995			1996		
N rate	Knife	LCD	SE†	Knife	LCD	SE
kg ha^{-1}	mg kg^{-1}					
157	4.6‡	8.1	0.5	221	217	81
202	163	32	59	500	821§	144

† Standard error.
‡ Significant at the 0.1 probability level.
§ Value is within the optimal range (700–2000) according to Binford et al., 1992.

1). This suggests that the 157 kg N ha^{-1} LCD injection rate should have a stalk NO_3 concentration in the low range, while the 202 kg N ha^{-1} LCD injection stalk nitrate should be optimal. Cornstalk NO_3 data presented in Table 2 are in agreement with results of the regression analysis. Similarly, all other treatments had stalk NO_3 concentrations in the low range, suggesting that more than 202 kg N ha^{-1} was required for maximum yield. These stalk NO_3 data are consistent with the N_{max} values in Table 1, which show that the maximum yield should have been achieved at application rates greater than 200 kg ha^{-1}.

CONCLUSIONS

These data indicate that, when growing season precipitation was above average in Iowa, larger soil concentrations of NO_3^- were measured closer to the surface in plots where N was applied by the LCD injector than with the conventional knife injector. Data also indicate that yields during a wet year were larger for plots with N applied by the LCD injector than with the conventional knife injector, indicating greater amounts of available N. In a separate study, anion leaching from injected bands to subsurface drains was reduced for LCD-injected chemicals compared with conventional knife-injected chemicals (Ressler et al., 1998). Results of the present study indicate that localized compaction and doming may reduce NO_3 leaching and improve N-use efficiency in a rainfed Iowa corn field during years that have greater than average rainfall. Application of this technology to additional soil types and water management regimes may yield similar results. In a related study, Kiuchi et al. (1996) showed that a compacted layer formed in a sandy loam soil reduced anion leaching. Similarly, experimental measurements of leaching considering chemical placement with respect to surface shape (Kemper et al., 1975) and computer simulations of chemical placement and surface shape (Benjamin et al., 1994) suggest that the LCD injector could produce desirable results in sands and clay loam soils. Considering the quantity of N fertilizer applied in the U.S. Corn Belt, preventing even small amounts of N from leaching out of the root zone would tremendously benefit the environment.

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