# Nitrogen Placement, Row Spacing, and Furrow Irrigation Water Positioning Effects on Corn Yield

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## ABSTRACT

**Furrow irrigation often leaches $NO_3$–N. We hypothesized that banding and sidedressing N fertilizer on a nonirrigated side of a corn (*Zea mays* L.) row would maintain yield and decrease $NO_3$–N leaching. In a 2-yr field study in southern Idaho on a Portneuf silt loam (coarse silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid), we evaluated the effects of (i) N placement (broadcast vs. banded), (ii) row spacing (0.76 m vs. a modified 0.56 m), and (iii) irrigation water positioning (applying water to the same side or alternating sides of a row with successive irrigations) on field corn yield and N uptake. We irrigated every second furrow nine times in 1988 and seven times in 1989. Compared with broadcasting, banding maintained grain yield in 1988 and increased it by 11% in 1989. Where N was banded in 0.56-m rows in 1989, silage yield when only the nonfertilized furrow was irrigated was 22.9 Mg $ha^{-1}$, which was 22% greater than when alternating furrows were irrigated. Compared with 0.56-m rows, the 0.76-m rows had no effect on 2-yr average grain yield but tended to increase 2-yr average silage N. Banding N on one side of a row, rather than broadcasting, and applying water all season to the furrow on the other side of the row maintained or increased grain yield, increased silage yield by up to 26%, and increased N uptake in silage by up to 21%, particularly from N-depleted profiles. Applying water to the same furrow, rather than alternating furrows, did not reduce yield or N uptake.**

NITRATE-NITROGEN LEACHED FROM FIELD SOILS is lost to plants and often contaminates groundwater, particularly beneath the irrigated, row-cropped areas of the western USA (Spalding and Exner, 1993). Nitrate-nitrogen concentrations $>10$ mg $L^{-1}$ in drinking water, usually drawn from groundwater, can be fatal to human infants (Comly, 1945). At greater concentrations, $NO_3$–N can be fatal to the young of other mammalian species (Shirley et al., 1974).

Nitrate contamination of groundwater can be minimized by management techniques such as avoiding excessive irrigation (Russelle et al., 1981), splitting N fertilizer applications (Martin et al., 1994; Ritter et al., 1993), adjusting sidedressed N application rates based on a presidedress $NO_3$–N test to account for mineralization, leaching, or both following planting (Ritter et al., 1993), applying no *insurance* N fertilizer (Robbins and Carter, 1980), and eliminating other nutrient deficiencies to encourage more efficient use of the $NO_3$–N present (Olsen et al., 1970). Management should strive to minimize postharvest soil $NO_3$–N because most $NO_3$–N is leached between the fall harvest and spring planting (Cambardella et al., 1999; Martin et al., 1994; Ritter et al., 1993).

Fertilizer placement in combination with furrow irrigation management can also lessen $NO_3$–N leaching (Robbins and Carter, 1980). Irrigation must be managed carefully to maximize N fertilizer use efficiency and minimize $NO_3$–N leaching, particularly where N fertilizer at nominal, economic rates is sidedressed near corn (Russelle et al., 1981). For irrigated corn production in eastern Nebraska, sidedressing N at the eight-leaf growth stage held mineral N ($NO_3$–N + $NH_4$–N) in the upper portion of an irrigated, fertile silty clay loam (Russelle et al., 1981). It may be possible to band and later sidedress N fertilizer on a nonirrigated, or dry furrow, side of a corn (or other crop) row and then irrigate the other side (Fig. 1) to reduce leaching by minimizing the contact between the applied N and the water that moves down from the irrigated furrow (Kemper et al., 1975; Parkin and Codling, 1990; Sojka et al., 1994; Timlin et al., 1992; Tracy and Hefner, 1993).

Applying split N applications to one side of a row and furrow-irrigating the other side has numerous potential benefits. First, applying a portion of the corn's N fertilizer in a band at planting and the remainder 5 to 6 wk later should increase both fertilizer use efficiency and N uptake by minimizing the leaching opportunity time and better timing the N application to N uptake (Westermann and Crothers, 1993). Second, splitting the N application also reduces the potential for $NH_3$ toxicity to seedlings when applying large quantities of urea $[(NH_2)_2CO]$ near the seed, as was observed in western Idaho (B.D. Brown, personal communication, 1999). Third, because roots grow and branch extensively around banded N fertilizer, likely due to much $NH_4$–N there initially (Kaspar et al., 1991; Passioura and Wetselaar, 1972), the roots concentrated near the fertilizer should minimize leaching. Fourth, positioning the fertilizer away from the irrigation water should also decrease leaching (Kemper et al., 1975; Parkin and Codling, 1990).

Banding and sidedressing N on the side of the corn row that is opposite the irrigated furrow, however, may have disadvantages (Sojka et al., 1994). The knives of the sidedress fertilizer applicator will prune roots. Seedlings may be injured by the $NH_3$ released as nearby banded urea hydrolyzes. Low soil water contents (low water potentials) near banded N in the dry furrow may limit the root extension toward the N. With little root growth into the dry soil or little water moving through it, passive N uptake via mass flow will be restricted, leading to crop N stress and reduced yields. Soil water supplied by the first furrow irrigation can transport banded N as $NO_3$–N away from the seedling's small root system, effectively eliminating the benefit of the starter

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**Abbreviations:** ANOVA, analysis of variance; LSD, least significant difference; NS, not significant.

N. Irrigation water can also transport $NO_3$–N from the band and sidedressing horizontally (Benjamin et al., 1998), and with evaporation (Boswell and Anderson, 1964), upward toward the surface into relatively dry soil where little uptake occurs (Keeney, 1982). In some areas of the western USA, efficient water management (to attain a low leaching fraction) may minimize the total $NO_3$–N lost from a soil profile, but it may also produce deep drainage with relatively large concentrations of $NO_3$–N (Devitt et al., 1976) and the salts that must necessarily be leached from the profile.

When every second furrow is irrigated, N placed midrow in the nonirrigated furrow may or may not be available for uptake. For 3 yr in southeast Missouri, corn grain yields from supplemental, every-second-furrow irrigated plots were maintained or increased when urea ammonium nitrate was knifed into the nonirrigated midrow, rather than every midrow (Hefner and Tracy, 1995). In contrast, N for corn grown with simulated every-second-furrow irrigation in Colorado was less available when it was placed in the nonirrigated midrow, rather than the irrigated midrow (Benjamin et al., 1997). In that study, N uptake was thought to be low from the relatively dry soil under the nonirrigated midrow. It may be necessary to irrigate the drying regions of the profile early in the season to stimulate adequate initial root growth there to enable plants to capture N from these regions (Skinner et al., 1998). In the Missouri study in 1991, corn ear leaf N concentrations were less with the irrigation of every furrow, rather than every second furrow. This suggests that the irrigation of every second furrow either (i) improved N fertilizer use efficiency or (ii) leached or denitrified less $NO_3$–N from the profile than the irrigation of every furrow.

Corn grain yield was similar whether irrigating every or every second furrow in small plots in Colorado (Benjamin et al., 1997). Fischbach and Mulliner (1974) grew corn for grain in a silt loam in Nebraska by irrigating every second furrow. Their yields were similar regardless of irrigation water positioning (i.e., positioning water in the same furrow or alternating furrows). Hefner and Tracy (1995) concluded that corn could be produced without a yield penalty by placing N fertilizer in every second furrow regardless of the irrigation system effectiveness.

In Idaho and elsewhere, interest has arisen recently in the effects of row spacing on corn grain and silage yields. Reducing row spacings to less than 1 m have, in whole or in part, increased grain yields (Cardwell, 1982; Karlen and Camp, 1985). Others (Westgate et al., 1997; Giesbrecht, 1969), however, have reported similar grain yields for row spacings of 0.38 and 0.76 m. Corn row spacings of 0.56 m would fit well into local rotations with sugar beet (*Beta vulgaris* L.) and field bean (*Phaseolus vulgaris* L.), also planted in 0.56-m rows. Sowing corn at row spacings that are less than 0.76 m may increase the corn's water use efficiency (Karlen and Camp, 1985) and better control weeds as well (Forcella et al., 1992). Not known, however, are the yield responses to the possible interacting effects of N placement, row spacing, and irrigation water positioning.

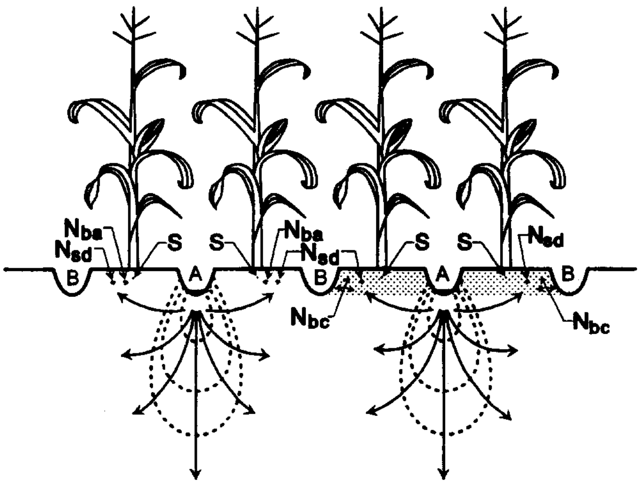

**Fig. 1. Positioning of seed (S), banded N ($N_{ba}$), sidedressed N ($N_{sd}$), and broadcast N ($N_{bc}$) where we irrigated the same furrow (A). Where we irrigated alternating furrows, we irrigated Furrow A first, then Furrow B, and then A, etc. Equipotential and flow lines are conceptually shown for 0.76-m rows (after Sojka et al., 1994).**

In west-central and southern Idaho, corn is often produced by furrow-irrigating silt loam soils. Most often, all fertilizer is broadcast onto the soil surface and then incorporated with a roller harrow to a depth of about 70 mm before planting in late April and May. Depending on the seedbed water content, the corn is first irrigated 2 to 4 wk after it emerges. Many producers irrigate every second furrow. If those producers planted corn with four-row equipment, they often irrigate the wheel-tracked furrows because those furrows' lower infiltration rates help the water stream reach the outlet (or tail) of the furrow more quickly. Later in the season, farmers commonly apply water to furrows that are not wheel tracked to increase infiltration when the crop water demand peaks. With the longer growing season in western Idaho, the corn is irrigated 8 to 10 times. In southern Idaho, seven to nine irrigations are made, with the last occurring in late August or early September for silage and in late September for grain.

Fertilizing in or near one furrow but irrigating another may decrease the $NO_3$–N that is leached from the root zone to the groundwater. Placing N midway between corn rows in the nonirrigated furrow of a supplemental, every-second-furrow irrigation system can potentially reduce leaching but not productivity (Benjamin et al., 1998). Simulations have projected less $NO_3$–N leaching beneath irrigated corn with N placed in the row rather than the furrow (Benjamin et al., 1994). Even less $NO_3$–N movement was projected with N placed in the nonirrigated furrow of plots that are irrigated using every second furrow.

One would expect to reduce $NO_3$–N leaching and increase N use efficiency (or N uptake) through the appropriate placement of N fertilizer, split fertilizer applications, and judicious water application. Field research using production-sized equipment and large plots is needed to examine these factors, including the relationships and interactions among them (Hefner and Tracy, 1995; Robbins and Carter, 1980; Strebel et al.,

**Table 1. Characteristics of Portneuf silt loam, sampled about 290 m southeast of the study site (McDole and Maxwell, 1987).**

| Horizon | Depth | Particle size distribution: Sand | Silt | Clay | Bulk density | Org. C | CEC† | pH (1:1 water) | EC‡ | $CaCO_3$ equiv. |
|---|---|---|---|---|---|---|---|---|---|---|
| | cm | % | % | % | g $cm^{-3}$ | g $kg^{-1}$ | $cmol_c$ $kg^{-1}$ | | S $m^{-1}$ | % |
| Ap | 0-28 | 14 | 66 | 20 | 1.48 | 10 | 18.6 | 8.0 | 0.07 | 2 |
| Bk | 28-58 | 8 | 71 | 21 | 1.45 | 6 | 13.7 | 8.4 | 0.05 | 24 |
| Bkq1 | 58-102 | 16 | 80 | 4 | 1.43 | 4 | 11.7 | 8.5 | 0.05 | 21 |
| Bkq2 | 102-137 | 18 | 81 | 1 | 1.42 | 2 | 12.7 | 8.5 | 0.05 | 16 |

† CEC, cation exchange capacity.
‡ EC, electrical conductivity.

1989). This 2-yr field study evaluated the effects of urea placement, row spacings, and irrigation water positioning on corn yield and N uptake.

## METHODS AND MATERIALS

### Overview and Statistical Analyses

The experiment was conducted on Portneuf silt loam at 42°33′ N and 114°21′ W, approximately 1.2 km northeast of Kimberly, ID. The site's slope was 0.94% from north to south, and its elevation was 1210 m. The Portneuf soil (Table 1) is well-drained and very deep, having formed in loess overlaying a fractured basalt plain. It has a B horizon enriched with calcium carbonate ($CaCO_3$) and silica ($SiO_2$), is weakly stable, and quite susceptible to furrow erosion. The site, which has a continental and semiarid climate, receives about 285 mm of precipitation annually but only about 90 mm from 1 May through 30 September (McDole and Maxwell, 1987). In 1987, the year before this study was established, the west half of the site (Blocks 1 and 2) was cropped to corn for grain (with cobs and stover returned unchopped), and the east half (Blocks 3 and 4) was cropped to sugar beet. Recognizing that previous crops could potentially cause differences in soil N (both residual and net mineralized) and in disease or insect incidence, we intentionally situated our blocks to statistically account for these differences, if they occurred.

A management system in which corn is grown continuously, or repeatedly in a multiyear rotation, may use applied N efficiently and reduce residual soil N by extracting mineralized N from the site's entire soil profile. To study both the short- and long-term effects of multiyear management systems on yield and soil N, each treatment should be applied to the same plot year after year. Consequently, this study was conducted on the same field site in 1988 and 1989, with no rerandomization of treatments among plots in the second year.

The experiment was a split-split plot with four replications and main plots in randomized complete blocks. The main-plot treatment was irrigation water positioning: Water was positioned in either the same furrow or alternating furrows. Where water was placed all season in the same furrow, it was a wheel-tracked, nonfertilized furrow (Furrow A in Fig. 1) on the side of the row that was away from the banded and sidedressed N fertilizer. When we irrigated alternating furrows, Furrow A was irrigated at the first irrigation, then Furrow B on the opposite side of the row at the second irrigation, then back to Furrow A, etc. When alternating furrows were irrigated, the nonfertilized furrow (Furrow A, being wheel-tracked or hard) was irrigated first because the first irrigation of the season often leaches the most solute from the profile (Tracy and Hefner, 1993; Silvertooth et al., 1992). Also, where alternating furrows were irrigated, the fertilized furrow (Furrow B, being nonwheel-tracked or soft) was irrigated at every second irrigation throughout the season to stimulate root growth and N uptake in that portion of the profile (Hefner and Tracy, 1995; Skinner et al., 1998).

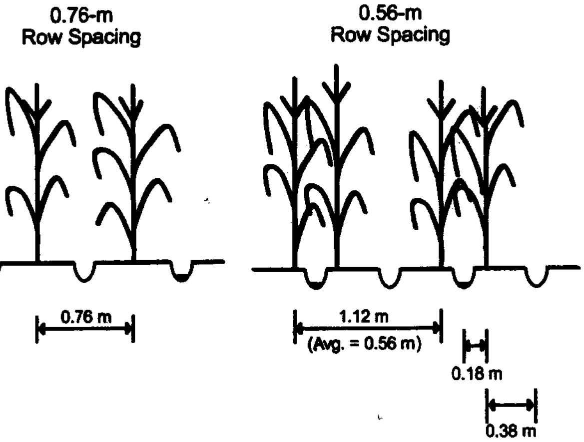

**Fig. 2. Row spacings were 0.76 m or a modified 0.56 m.**

The subplot treatments were row spacings: either 0.76 m or a modified 0.56 m (Fig. 2) (Sojka et al., 1992). Each 0.56-m row covered an equivalent of 0.56 m of plot width but was not equidistant from the row on either side of it. The rows in adjacent beds were close to one another; each in the bed shoulder and 0.18 m from an intervening furrow to increase water availability and decrease furrow erosion (Sojka et al., 1992). The use of a modified 0.56-m spacing can also increase corn yield and provide other benefits (Karlen and Camp, 1985). The sub-subplot treatments (N fertilizer placements, Fig. 1) were (i) half of the N rate was preplant-broadcast and then half was sidedressed at the eight-leaf growth stage, (ii) half the N was banded at planting and then half was sidedressed, or (iii) no N fertilizer was applied. To the plots fertilized with N [as urea, 0.45 kg N $kg^{-1}$], the application was split to apply the N when it could be best used by the growing corn (Silvertooth et al., 1992). The N applied as a sidedressing was arbitrarily chosen to be half of the total application. Each plot was four rows wide, 102 m long, and no smaller than 228 $m^2$. Due to space constraints, border plots were between each main plot within each block as well as between each complete block. Each border plot was planted to 0.56-m rows and irrigated with the method that was used on the monitored plot adjacent to it.

As preliminary statistical analyses, we used mixed-model procedures in SAS (SAS Inst., 1989)[1] to perform an analysis of variance (ANOVA) of the final plant populations each year. Other preliminary statistical tests included Bartlett's analyses to insure homogeneous variances for each response variable (grain and silage yield and N uptake in silage), with common log or rank transformations employed as needed. We then performed a mixed-model ANOVA using SAS. For multiyear analyses, the only factor that was modeled as ran-

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[1] Mention of trade names is for the reader's benefit and does not imply endorsement of the product by the USDA.

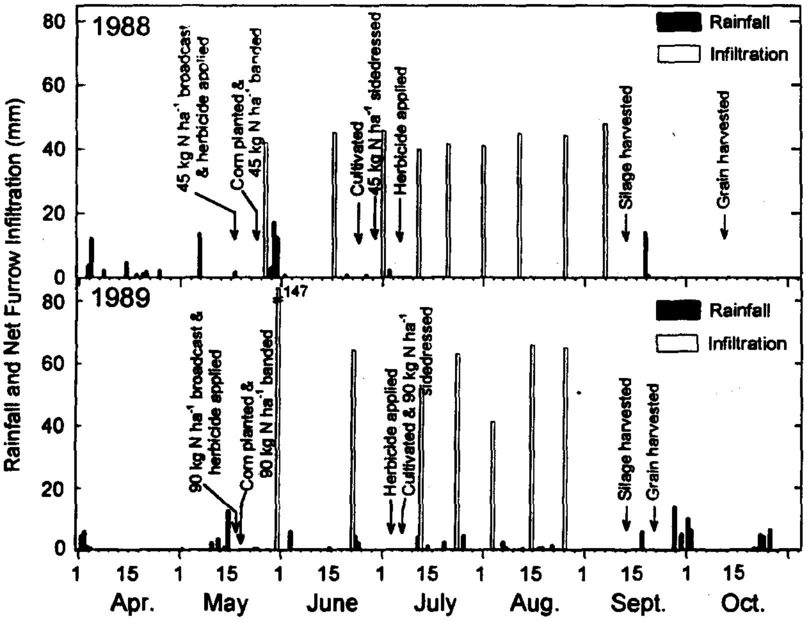

**Fig. 3. Timing of cultural practices, rainfall, and irrigations in 1988 and 1989.**

dom was replication. Year was modeled as a fixed effect because of the yield differences from one year to the next, particularly in the nonfertilized plots. We separated least-squares means using either Fisher's protected least significant difference (LSD) or *t*-tests of pairwise differences. Where needed, the means were back-transformed into original units for presentation.

## Cultural Details

In the fall of 1987 and 1988, all plots were moldboard-plowed to a depth of about 0.2 m and then roller-harrowed. Each spring before planting, soil samples were taken from depths of 0 to 0.3 m and 0.3 to 0.45 m and analyzed for macronutrients. The site was then fertilized according to University of Idaho soil test recommendations for irrigated field corn (Brown and Westermann, 1988). The N rate in 1988 was chosen to achieve the yield goals of 8150 kg ha$^{-1}$ grain (at 0.155 kg kg$^{-1}$ water content) and 63 Mg ha$^{-1}$ silage (at 0.65 kg kg$^{-1}$ water content). The N rate in 1989 was chosen to achieve the same yield goals from plots that were fertilized the year before. Each year's N rate was conservative to avoid overfertilization. The preplant residual soil $NO_3$-N concentrations, as averages to 0.45 m, were 17.7 mg kg$^{-1}$ in 1988, and in 1989, 9.8 mg kg$^{-1}$ from plots that were fertilized the year before and 4.6 mg kg$^{-1}$ from plots that were not fertilized the year before. On 10 May 1988, 20 kg P ha$^{-1}$ (as monocalcium phosphate) was broadcast on all plots and then incorporated with a roller harrow. On 16 May, 45 kg N ha$^{-1}$ was broadcast onto the broadcast/sidedressed plots and immediately incorporated with a roller harrow. On 23 May, 45 kg N ha$^{-1}$ was banded into the banded/sidedressed plots as a starter at planting (Fig. 3). The banded N was placed 50 mm to the side and 25 mm below the seed, being there about 50 mm above the water surface when the plots were later irrigated. All border plots received a broadcast application of 90 kg N ha$^{-1}$ in late May 1988. In 1989, 29 kg P ha$^{-1}$ was preplant-broadcast. On 17 May, 90 kg N ha$^{-1}$ was preplant-broadcast and incorporated. On 18 May, 90 kg N ha$^{-1}$ was banded into the appropriate plots at planting. In 1989, the border plots received a broadcast application of 90 kg N ha$^{-1}$ a few days after planting.

We planted 'Pioneer[1] 3901' corn, a 98-d relative maturity cultivar that is grown primarily for grain though at times for silage. The corn was planted at the 50-mm depth in 0.76-m rows on 23 May 1988 and in 0.56-m rows on 24 May. As an integral part of the planting operation, we formed triangular-shaped irrigation furrows that were 0.18 m wide at the top and 0.1 m deep using weighted 80° shaping tools every 0.56 or 0.76 m across all plots. In 1989, corn was planted on 18 May. The final populations were conservative, averaging 61 100 plants ha$^{-1}$ in 1988 and 68 200 in 1989. Despite efforts to achieve similar plant populations, the populations were 9% greater [not significant (NS)] in plots with 0.76-m rows than in plots with 0.56-m rows in 1988 but 15% greater (significant, described below) in 1989. After planting, the only other tillage performed was a cultivation at or a few days before sidedressing (Fig. 3).

To selectively control grasses, Eradicane[1] (*S*-ethyl-*N*, *N*, dipropylthiocarbamate + *N*, *N*-diallyl-1, 1-dichloroacetamide) was preplant applied at 3.75 kg a.i. ha$^{-1}$ on 16 May 1988 and 17 May 1989 and then incorporated with a roller harrow within 2 h. Each year after the corn emerged, a directed spray of 2,4-D [(2, 4-dichlorophenoxy) acetic acid] was applied at 1.05 kg a.i. ha$^{-1}$ in early July to control redroot pigweed (*Amaranthus retroflexus* L.). On or before 10 May 1989, glyphosate [isopropylamine salt of *N*-(phosphono-methyl) glycine] was applied at 1.12 kg a.i. ha$^{-1}$ to control green foxtail [*Setaria viridis* (L.) P. Beauv.] in the northwest corner of the site.

The irrigations were scheduled considering the crop water demand, as constrained by water availability. In south-central Idaho, strict scheduling according to, say, an evapotranspiration-based method for estimating crop water use is impossible where a single canal supplies water to several fields that are planted to different crops, each requiring different amounts of water at different times. At each irrigation, water was applied to every second furrow. To apply equal volumes of inflow per unit area to all plots, the irrigations were, in general, 12 h for the 0.76-m rows and 8.8 h for the 0.56-m rows. At each irrigation, our gross water application was commonly 70 mm in 1988 and 88 mm in 1989. The inflows were, in general, 0.91 m$^3$ h$^{-1}$ in 1988 and 1.14 m$^3$ h$^{-1}$ in 1989. The runoff rates from representative furrows of numerous treatments were measured several times each irrigation using small, longthroated trapezoidal furrow flumes (Brown and Kemper, 1987). The total outflow was the sum of each interval's runoff volume. Each plot's net infiltration, as volume per unit area, was calculated as total inflow minus the total outflow. Each irrigation's net infiltration was averaged across all monitored plots (Fig. 3).

We sidedressed 45 kg N ha$^{-1}$ into all fertilized plots using four-row equipment on 27 June 1988. The sidedressed N was knifed into the bed shoulder as a band 76 mm beneath the soil surface and 0.13 m to the dry furrow side of the corn (Fig. 1). The corn was then 0.3 m tall, at about the eight-leaf or four-whorl growth stage. The sidedressed N was placed closer to the plant row than the furrow to make the N more available to the corn (Hefner and Tracy, 1995) and less susceptible to leaching if that furrow was irrigated (Benjamin et al., 1994; Saffigna et al., 1976). The urea was always 0.13 m to the side of the corn row, regardless of the row spacing. We deemed like spacing from the row to be more important than like spacing from the furrow although this constraint had the following consequence. Where the same furrow was irrigated all season, the sidedressed N was 0.31 m from that irrigated furrow in 0.56-m rows and 0.51 m from it in 0.76-m rows because of different row spacings and plant positions on the bed (Fig. 2). Where alternating furrows were irrigated, the sidedressed N was 0.25 m from the irrigated furrow at every other irrigation, regardless of the row spacing. Additional cultural practices and irrigations are indicated in Fig. 3. On 6 July 1989, 90 kg N ha$^{-1}$ was sidedressed in the same position relative to the row as in 1988. In both 1988 and 1989, the border plots were sidedressed with 90 kg N ha$^{-1}$. In each growing season, the knives of the sidedress applicator were also passed through the plots that received no N fertilizer so that root pruning would be similar among the plots.

Three portions of each plot were harvested for silage, and another three were later harvested for grain. We harvested two adjacent interior rows, each 3.05 m long, at distances of 30.5, 61, and 91.4 m from the furrow inlet. The yields and uptake at these locations were averaged before statistical analyses. This sampling protocol provided a valid measure of the overall plot yield because it accounted for the yield variation that was caused by differences in infiltration with distance from the furrow inlet. After grain samples were taken, the remaining grain was harvested and the unchopped cobs and stover were returned to the respective plot. The corn was sampled for silage on 12 Sept. 1988 and 12 Sept. 1989 and for grain on 13 Oct. 1988 and 21 Sept. 1989. Subsamples of the harvested plant material were dried at 60°C and weighed. Dry silage was ground in a Wiley[1] mill to pass through a 635-μm stainless steel screen. After Kjeldahl digestion of the ground silage, its N concentration was determined colorimetrically using a salicylate–hypochlorite method in an automated flow injection analysis (Method 13-107-06-2-A, Lachat Instrument, Milwaukee, WI).[1]

## RESULTS

### Statistical Findings

As noted above, the final plant populations in 1988 were 63 800 plants ha$^{-1}$ in 0.76-m rows, not significantly different ($P > 0.105$) from the 58 400 plants ha$^{-1}$ in 0.56-m rows. In contrast, the populations in 1989 were 73 200 plants ha$^{-1}$ in 0.76-m rows, more than 15% greater ($P < 0.001$) than the 63 300 plants ha$^{-1}$ in 0.56-m rows. However, when plant population was used as a covariate in a preliminary analysis of the 1989 data, the covariate term in each of the models was never significant ($P > 0.27$ for grain yield, $P > 0.57$ for silage yield, and $P > 0.12$ for N uptake in silage). In addition, the *F* ratios from the ANOVAs differed little whether plant population as a covariate was present or absent in the model (*F* ratios not shown). The other modeled sources of variation seemed to account for most of the structure in the data, eliminating any possible significance of the covariate. Consequently, plant populations were not included in any of the final ANOVA models.

**Table 2. Analysis of variance (ANOVA) for corn grain yield, silage yield, and N uptake in silage for 1988 and 1989.**

| Source of variation | df | Significance of *F* ratio | | | |
|---|---|---|---|---|---|
| | | Grain yield | Silage yield† | | N uptake in silage‡ |
| | | | 1988 | 1989 | |
| Year (Y) | 1 | *** | NA§ | NA | ** |
| Irrigation water positioning (I) | 1 | NS | NS | NS | NS |
| Y × I | 1 | NS | NA | NA | NS |
| Row spacing (R) | 1 | NS | NS | *** | *** |
| Y × R | 1 | ** | NA | NA | ** |
| I × R | 1 | NS | NS | * | ** |
| Y × I × R | 1 | NS | NA | NA | NS |
| Placement (P) | 2 | *** | * | *** | *** |
| Y × P | 2 | *** | NA | NA | *** |
| I × P | 2 | NS | * | *** | NS |
| Y × I × P | 2 | NS | NA | NA | * |
| R × P | 2 | * | * | NS | *¶ |
| Y × R × P | 2 | NS | NA | NA | NS |
| I × R × P | 2 | NS | NS | *** | NS |
| Y × I × R × P | 2 | NS | NA | NA | NS |

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† Data were analyzed by year owing to heterogeneous variances. To stabilize the variance within each year, the yields were ranked and an ANOVA performed on the data's ranks.

‡ ANOVA was performed on log-transformed data.

§ NA, not applicable.

¶ $P = 0.0510$.

Row spacing and N placement were often significant as main effects in the final ANOVAs (Table 2). Irrigation water positioning was not significant as a main effect, but it often interacted with row spacing and N placement. When the data for both years could be analyzed together, two-way interactions of year with row spacing and with placement were always significant at probability levels of 0.01 or smaller. The only other two-way interaction that was often detected was with row spacing and N placement, significant at the 0.05 level.

### Grain Yield

The overall grain yield in 1988 averaged 7770 kg ha$^{-1}$, which was 95% of our yield goal of 8150 kg ha$^{-1}$. From the plots fertilized with N in 1989, the grain yield was 5710 kg ha$^{-1}$, which was only 70% of our goal. The smaller yields in 1989 were due in large measure to nonuniform water application. In 1989, for reasons we could neither identify nor fully overcome, we were unable to irrigate our plots as uniformly from the furrow inlet to the outlet as in 1988.

Irrigation water positioning as a main effect did not affect the grain yield when averaged across years, row spacings, and N placements (Table 2). Moreover, irriga-

**Table 3. Nitrogen placement effects on corn grain yield, averaged across years and irrigation water positioning, at each row spacing.**

| N placement | Corn grain yield† Row spacing (m) 0.56 | 0.76 |
|---|---|---|
| | kg ha$^{-1}$ | |
| Banded & sidedressed | 7050 | 6690 |
| Broadcast & sidedressed | 6690 | 6730 |
| Nonfertilized | 4810 | 5100 |
| LSD (0.05) | 370 | 370 |

† Yields adjusted to 0.155 kg kg$^{-1}$ water content. Row spacing effects were not significant at $P = 0.05$.

tion water positioning never interacted with years, row spacings, or N placements to affect the grain yield in our study (Table 2). Repeatedly irrigating the same furrow yielded 6210 kg ha$^{-1}$ vs. 6140 kg ha$^{-1}$ (NS) when irrigating alternating furrows. Fischbach and Mulliner (1974) also reported similar corn yields when either the same furrow or alternating furrows were irrigated.

The 2-yr average grain yield from 0.56-m rows was greatest where we banded N (Table 3). From 0.56-m rows, the grain yield was more than 5% greater ($P = 0.051$) from banded than broadcast N. From 0.76-m rows, however, the yield was similar from banded and broadcast N (Table 3). Kaspar et al. (1991) reported similar corn grain yields when N fertilizer was placed in the row or in the interrow zone at planting. In our study, when grain yield was averaged across years and irrigation water positioning, grain yield did not differ from one row spacing to another at any N placement (Table 3).

When grain yield was averaged across irrigation water positioning and N placement, it did differ from one row spacing to another (Table 4). In 1988, the yield was nearly 6% greater ($P < 0.029$) from 0.56-m rows than from 0.76-m rows. In 1989, the trend reversed, with the yield nearly 10% greater ($P < 0.033$) from 0.76-m rows than from 0.56-m rows. As noted above, in the spring of 1988, residual soil N concentrations were relatively large in the uppermost 0.45 m of the profile, so they were not likely growth limiting. In the spring of 1989, however, there was nearly 45% less $NO_3$–N in the uppermost 0.45 m of the fertilized plots of our study than in 1988. From these N-depleted profiles in 1989, soil N may not have been scavenged efficiently in 0.56-m plots because the roots were likely concentrated under each pair of 0.56-m rows, and thus were relatively sparse between each pair of 0.56-m rows (Fig. 2). Alternatively, the closer proximity of the irrigation furrows to the N fertilizer in 0.56-m rows may have led to more leaching of both the fertilizer and limited residual soil N in the 1989 profiles (Lehrsch et al., 2001). The generally 35% larger irrigations in 1989 than in 1988 (Fig. 3) may have sufficiently increased $NO_3$–N leaching under the 0.56-m rows to reduce the yield in 1989 but not in 1988 (Table 4).

The N placement effects on grain yield depended on the year (Fig. 4). Compared with broadcasting, banding maintained the grain yield in 1988 and increased it by 11% ($P < 0.002$) in 1989. The overall yields were less the second year despite the two-fold greater N rate in 1989. The grain yield in 1989 may have been reduced because, as noted above, there was much less residual soil N in the spring of 1989 than in 1988. There were 119 kg ha$^{-1}$ $NO_3$–N in the upper 0.45 m shortly before planting in 1988, but in 1989, there were 66 kg ha$^{-1}$ $NO_3$–N in the plots that were fertilized the year before and only 31 kg ha$^{-1}$ $NO_3$–N in those that were not fertilized the year before. Also, fertilizer and soil N was leached from the developing corn's root system (Lehrsch et al., 2001) by the two relatively large, early season irrigations in 1989 (Fig. 3). The soil N data will soon be reported in more detail (Lehrsch et al., 2001).

**Table 4. Row spacing effects on corn grain yield in 1988 and 1989.**

| Row spacing | Grain yield† 1988 | 1989 |
|---|---|---|
| m | kg ha$^{-1}$ | |
| 0.56 | 7990 | 4370 |
| 0.76 | 7550 | 4800 |
| LSD (0.05) | 390 | 390 |

† Yields adjusted to 0.155 kg kg$^{-1}$ water content.

## Silage Yield

For the study as a whole in 1988, the silage yield was 20.1 Mg ha$^{-1}$, which was only 32% of our yield goal. Yield less than the target was a consequence of (i) the cultivar being better adapted to produce grain than silage and (ii) the plant populations being smaller than recommended for silage production (Brown and Westermann, 1988; D. Sass, personal communication, 1999). From N-fertilized plots in 1989, the silage yield averaged 20.3 Mg ha$^{-1}$, which was still far short of the goal even though the plant populations were nearly 12% greater than the year before. The silage yield in 1989 was less than the target because, in addition to the reasons noted for 1988, furrow water application was less uniform than we desired.

Irrigation water positioning interacted with N place-

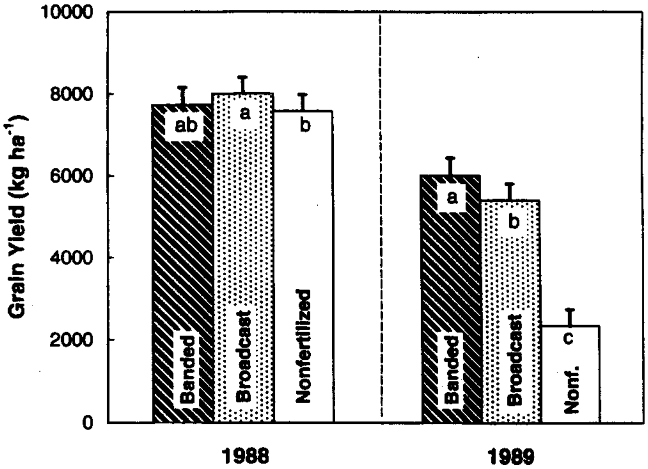

Fig. 4. Nitrogen placement effects on grain yield in 1988 and 1989. Within years, the means with the same letter are not significantly different according to *t*-tests of pairwise differences at $P = 0.05$. Each mean's error bar is its upper 95% confidence limit.

**Table 5. Irrigation water positioning and N placement effects on 1988 silage yield, averaged across row spacings.**

| | Silage yield† | |
|---|---|---|
| | Irrigation water positioning | |
| N placement | Alternating furrow | Same furrow |
| | Mg ha$^{-1}$ | |
| Banded & sidedressed | 20.7 | 20.2 |
| Broadcast & sidedressed | 20.4 | 20.4 |
| Nonfertilized | 18.6‡ | 20.3 |

† Yields adjusted to 0.65 kg kg$^{-1}$ water content. To stabilize the variance, silage yields were first ranked. The ANOVA was performed on the data's ranks. Yield means shown are in original units.

‡ This mean is significantly less ($P < 0.05$) than the other means in its column and significantly less ($P < 0.016$) than the other mean in its row, according to $t$-tests of pairwise differences.

ment to affect the silage yield in 1988 (Table 5). When no N was applied, irrigating the alternating furrow, rather than the same furrow, reduced the silage yield (significant at $P < 0.016$), likely due to the leaching of residual $NO_3$–N from a larger portion of the corn's root zone. The yield was also less from nonfertilized plots than from fertilized plots when alternating furrows were irrigated but not when the same furrow was irrigated (Table 5).

An advantage of banding instead of broadcasting for silage production using 0.56-m rows was suggested in 1988 and confirmed in 1989. In 1988, where water was applied to the same furrow, yields from banding and broadcasting were similar—about 20.3 Mg ha$^{-1}$ when averaged across row spacings (Table 5). When one considers only the 0.56-m rows in 1988, the silage yield was 5% greater for banding than broadcasting ($P = 0.054$, data not shown). In 1989, banding's superiority not only continued but increased. The yield from banding was 26% greater than from broadcasting in 0.56-m rows, and it was 7% greater in 0.76-m rows when the same furrow was irrigated (Table 6).

Irrigation water positioning affected the silage yield in 1989 only where N was banded in 0.56-m rows (Table 6). In that instance, irrigating the alternating furrow, rather than same furrow, decreased the silage yield more than 18% (significant at $P < 0.001$). Water stress may have decreased the silage yield when we irrigated alternating furrows. For 0.56-m rows at every second irrigation, the irrigated furrow was 0.2 m farther from the row than for the same-irrigated-furrow plots (Fig. 2). Thus, periodic water stress may have reduced the silage yield where water was applied to alternating furrows. Moreover, irrigation water was not applied as uniformly from the furrow inlet to the outlet in 1989 as it was in 1988. Alternatively, the 35% larger irrigations in 1989 may have leached $NO_3$–N deeper under the 0.56-m rows or transported $NO_3$–N farther horizontally toward the adjacent furrow. When that furrow was subsequently irrigated, much of that $NO_3$–N may have been leached below the root zone.

**Table 6. Irrigation water positioning and N placement effects on 1989 silage yield at each row spacing.**

| | Silage yield† | | |
|---|---|---|---|
| | N placement | | |
| Irrigation water positioning | Banded & sidedressed | Broadcast & sidedressed | Nonfertilized |
| | Mg ha$^{-1}$ | | |
| | | 0.56-m row spacing | |
| Alternating furrow | 18.7*b*‡*x*§ | 19.3*ax* | 9.6*ay* |
| Same furrow | 22.9*ax* | 18.2*ay* | 9.7*az* |
| | | 0.76-m row spacing | |
| Alternating furrow | 21.6*ax* | 20.7*ax* | 13.1*ay* |
| Same furrow | 21.0*ax* | 19.6*ay* | 12.5*az* |

† Yields adjusted to 0.65 kg kg$^{-1}$ water content. To stabilize the variance, silage yields were first ranked. The ANOVA was performed on the data's ranks. Yield means shown are in original units.

‡ Within a column for each row spacing, means followed by the same letter (*a* or *b*) are not significantly different according to a $t$-test of pairwise differences at $P = 0.05$.

§ Within a row for each row spacing, means followed by the same letter (*x*, *y*, or *z*) are not significantly different according to $t$-tests of pairwise differences at $P = 0.05$.

**Table 7. Row spacing and N placement effects on silage N, averaged across years and irrigation water positioning.**

| | N uptake in corn silage | | |
|---|---|---|---|
| | N placement | | |
| Row spacing | Banded & sidedressed | Broadcast & sidedressed | Nonfertilized |
| m | kg ha$^{-1}$ | | |
| 0.56 | 142*a*†*x*‡ | 133*ax* | 85*by* |
| 0.76 | 148*ax* | 140*ax* | 100*ay* |

† Within a column, means followed by the same letter (*a* or *b*) are not significantly different according to a $t$-test of pairwise differences at $P = 0.05$.

‡ Within a row, means followed by the same letter (*x* or *y*) are not significantly different according to $t$-tests of pairwise differences at $P = 0.05$.

## Nitrogen Uptake in Silage

Row spacing often interacted with other factors to affect the N uptake in silage. When averaged across furrow positioning and N placement, uptake from 0.76-m rows only exceeded that from 0.56-m rows in 1989 (data not shown). In that year, the N uptake from 0.76-m rows was 108 kg ha$^{-1}$, which was 16% greater ($P < 0.001$) than the 93 kg ha$^{-1}$ from the 0.56-m rows. In 1988, the N uptake from 0.56- and 0.76-m rows averaged 149 kg ha$^{-1}$.

When averaged across years and irrigation water positioning, the N uptake was consistently greater from 0.76-m rows than from 0.56-m rows at every placement (Table 7). In fertilized plots, silage N was about 5% greater (NS) from wider rows than from narrower rows. In nonfertilized plots, silage N was nearly 18% greater ($P < 0.001$) from wider rows than from narrower rows. The N uptake from banding tended to exceed that from broadcasting by about 6% ($P < 0.105$ for 0.56-m rows and $P < 0.151$ for 0.76-m rows). Thus, N uptake tended to be greater from banding near the row than from broadcasting, regardless of the row spacing. Nitrogen that is broadcast and then incorporated, or applied midway between crop rows, is particularly susceptible to leaching under the furrow (Benjamin et al., 1994; Jaynes and Swan, 1999; Saffigna et al., 1976).

When N uptake was averaged across years and N placements, irrigation water positioning did not affect the N uptake at either row spacing (data not shown). Row spacing did affect uptake, however, when alternating furrows were irrigated. When water was applied to alternating furrows, the average N uptake from 0.76-m rows was 131 kg ha$^{-1}$, which was 15% greater ($P < 0.001$) than the 114 kg ha$^{-1}$ from the 0.56-m rows. Row spacing did not affect N uptake when the same furrow was irrigated. In that case, uptake from 0.56- and 0.76-m rows was similar—about 122 kg ha$^{-1}$.

**Table 8. Irrigation water positioning and N placement effects on N uptake in silage in 1988 and 1989. Data have been averaged across row spacings.**

| | N uptake in corn silage | | |
|---|---|---|---|
| | N placement | | |
| Irrigation water positioning† | Banded & sidedressed | Broadcast & sidedressed | Nonfertilized |
| | kg ha$^{-1}$ | | |
| | | 1988 | |
| Alternating furrow | 161*a*‡ | 151*ab* | 136*b* |
| Same furrow | 149*a* | 153*a* | 146*a* |
| | | 1989 | |
| Alternating furrow | 131*a* | 128*a* | 60*b* |
| Same furrow | 140*a* | 116*b* | 60*c* |

† Irrigation water positioning did not affect N uptake at any placement in either year.

‡ Within a row for each year, means followed by the same letter are not significantly different according to *t*-tests of pairwise differences at $P = 0.05$.

Irrigation water positioning did not affect silage N at any placement in either 1988 or 1989 (Table 8). However, where water was applied all season to the same furrow, the N uptake from banding was similar to that from broadcasting in the first year, but it was 21% greater ($P < 0.001$) in the second year. In 1988, a year with much residual N in all plots of the study, the N uptake was 15% less from nonfertilized than from banded placement when irrigating alternating furrows (Table 8). In contrast, when irrigating the same furrow that year, the N uptake from those two placements was similar. Alternating-furrow irrigation likely leached residual N from the nonfertilized plots, reducing N uptake in the silage grown in those plots.

## DISCUSSION

In every instance where irrigation water positioning significantly affected the silage yield, irrigating the alternating furrow, rather than the same furrow, decreased the yield. Irrigating alternating furrows significantly reduced the 1988 yield in nonfertilized plots (Table 5) and the 1989 yield in banded, 0.56-m rows (Table 6). These smaller yields suggest that the irrigation of alternating furrows leached $NO_3$–N from the root zone and thereby reduced the silage yield. When we irrigated alternating furrows, more leaching may have been a consequence of irrigating, at every second irrigation, the furrows that were not wheel tracked. Infiltration into our soils is greater through furrows that are not wheel tracked than through those that are wheel tracked, especially early in the season. The $NO_3$–N concentrations in the soil samples that were collected from monitored treatments (mostly those with 0.76-m rows) a few days after each irrigation support the $NO_3$–N leaching hypothesis. The soil $NO_3$–N concentrations that were measured at the 0.6- to 0.9-m depth under 0.76-m rows in 1988 (data not shown) were 45% greater ($P < 0.05$) when alternating furrows were irrigated, rather than when the same furrow was irrigated.

The relatively small silage yield from banded, 0.56-m rows when irrigating alternating furrows in 1989 (Table 6) may have been caused by $NO_3$–N leached at every second irrigation. During every second irrigation, water infiltrated through the wetted perimeter of the furrow on the fertilized side of the row. That furrow was not wheel tracked and consequently allowed more water to infiltrate than a wheel-tracked furrow, particularly at the second irrigation of the season. As some of the water initially moved laterally to the fertilizer band and then downward due to gravity, that water likely transported fertilizer N (as $NO_3$–N) from the nearby band farther down in the profile every time the water infiltrated from that furrow. Also, water moving laterally from the nonfertilized furrow may have transported $NO_3$–N from the band to or possibly under the furrow near the fertilizer band. Subsequent irrigation of that furrow could have leached $NO_3$–N below it (Benjamin et al., 1994; Jaynes and Swan, 1999). Broadcast N, like banded N, could also be leached horizontally, downward, or both. The data in Table 6 show that the yield from the broadcast, 0.56-m-row treatment that was irrigated using alternating furrows was similar to the smallest yield (18.2 Mg ha$^{-1}$) of any fertilized treatment.

Silage N from 1988 (Table 8) also suggests that alternating-furrow irrigation may have leached $NO_3$–N from the root zones of both the broadcast and nonfertilized plots, reducing the N uptake compared with the banded plots. The soil $NO_3$–N concentrations were 21% greater ($P < 0.07$), on average, with broadcasting than with banding through the 1988 irrigation season at the 0.6- to 0.9-m depth under 0.76-m rows (data not shown).

Where water was repeatedly applied to the same furrow in 1989, the N uptake was 21% greater ($P < 0.001$) from banding than from broadcasting (Table 8). From these profiles with little residual spring N, the soil N was used more efficiently when urea was banded on one side of a row, rather than broadcast, and water was always applied to the furrow on the other side of the corn row. This finding was consistent across both row spacings because row spacing did not significantly alter this interaction (Table 2). Lehrsch et al. (2001) found that $NO_3$–N in soil profiles to a depth of 0.9 m under corn rows was least in 1989 where N was banded, rather than broadcast, and where the nonfertilized furrow was irrigated, also suggesting a greater N use efficiency under these conditions. Where N was broadcast into the N-depleted profile in 1989 and the same furrow was irrigated, the root development (and to a limited degree, the N uptake via mass flow) may have been inhibited in relatively dry soil under the nonirrigated furrow. To enable plants to capture N from the fertilized regions of the profile that are likely to later dry, one might need to apply sufficient water to those regions early in the season to ensure adequate initial root growth there (Skinner et al., 1998). However, in our study, when we banded N near a nonirrigated furrow, rather than broadcasting N evenly across the plot surface, we did not need to irrigate the furrow near the banded N to maintain both the yield and N uptake (Tables 5, 6, and 8).

In our experiment, we applied only half of each fertilized treatment's N differently, with the remainder sidedressed identically into all fertilized plots. Nonetheless, we still detected placement effects with only half of our applied N placed differently. We identified statistically significant differences between banding and broadcasting in the 2-yr average grain yield (Table 3, at $P = 0.051$), 1989 grain yield (Fig. 4), 1989 silage yield (Table 6), and 1989 silage N (Table 8). For furrow-irrigated corn production, N placement is obviously very important in determining both the yield and N uptake in silage.

Some producers contend that irrigation water should be applied to the same side of the corn row as banded N, sidedressed N, or both to transport $NO_3$–N horizontally to the plant's root system. A relatively young corn seedling would have a small root system and could benefit from $NO_3$–N transported to its roots by mass flow. On the other hand, if too much water flows either horizontally or vertically through its modest rooting volume, $NO_3$–N may be flushed from the rhizosphere, which would reduce N uptake. Our second-year findings show that alternating-furrow irrigation (i.e., irrigation management that applies water close to banded N will decrease silage yield in narrow rows (Table 6), may decrease N uptake (Table 8), and will likely leach $NO_3$–N downward in or even through corn root zones. A detailed characterization of water flow, mobile nutrient transport, and crop N uptake from alternate-furrow irrigation management studies should help answer these questions and provide useful data to model these complicated, spatially and temporally varying processes (Benjamin et al., 1994).

As noted above, our objective should be to use both residual N and applied fertilizer N as efficiently as possible to decrease production costs, maximize crop N uptake, and minimize the $NO_3$–N remaining in the soil at harvest. With less $NO_3$–N present at season's end, less should be leached (Cambardella et al., 1999; Martin et al., 1994) and groundwater should be less affected (Ritter et al., 1993). One means toward attaining this objective may be to physically separate N fertilizer from furrow irrigation water to minimize $NO_3$–N movement downward through or entirely from crop root zones. Wider row spacings permit fertilizer N to be banded, sidedressed, or both farther from irrigation water. Indeed, we found that the 2-yr average N uptake in corn silage was consistently greater (though not always significantly so) from 0.76-m rows than from 0.56-m rows (Table 7). Considering only when alternating furrows were irrigated, the average silage N was 15% greater ($P < 0.001$) from 0.76-m rows than from 0.56-m rows, as noted above. In 1989, when averaged across furrow positioning and N placement, silage N was 16% greater from wider rows than from narrower rows, as noted above.

To minimize leaching of $NO_3$–N from furrow-irrigated soil profiles, one should consider irrigating the same furrow throughout the season. When irrigating the same furrow, one should band N on the nonirrigated side of the row, rather than broadcast N before planting, to increase both the silage yield and N uptake in silage. Banding is particularly advantageous when producing corn for either grain or silage in N depleted profiles, as occurred in 1989 (Fig. 4 and Table 6). If corn is planted into soil with sufficient residual N to serve as a starter, the application of 100% of the fertilizer N as a sidedressing may increase N use efficiency and yield even more.

Additional, follow-up field studies should be conducted. Greater plant populations should be studied with, ideally, statistically equal populations in all plots. Early in the corn's growing season, investigators should measure the root systems and N uptake. They should also study water flow as well as nutrient transport and deposition in two dimensions: Horizontally from one row to an adjacent row and beyond to the next row and vertically from the soil surface to at least the 0.6-m depth. One might also compare (i) a single preplant N application vs. split N applications at either one or two row spacings and (ii) initially irrigating the fertilized furrow vs. initially irrigating the nonfertilized furrow.

In conclusion, grain yield, silage yield, and N uptake in silage were maintained in this study by applying water to the same furrow, rather than to alternating furrows. In some cases, irrigating the same furrow, rather than alternating furrows, increased the silage yield. In contrast, irrigating alternating furrows, rather than the same furrow, significantly reduced the silage yield from nonfertilized plots in 1988, possibly by leaching residual $NO_3$–N from the root zone. Where alternating furrows were irrigated, the 2-yr average N uptake was less from 0.56-m rows than from 0.76-m rows. Where water was applied all season to the same furrow, banding N, rather than broadcasting N, either maintained or increased the grain yield, silage yield, and N uptake in silage, particularly from N depleted profiles.

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