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FURROW IRRIGATION AND N MANAGEMENT STRATEGIES TO PROTECT WATER QUALITY

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ABSTRACT

N management under furrow irrigation is difficult because nitrate-nitrogen (NO_3-N) is frequently leached to groundwater. Banding and sidedressing N fertilizer on a non-irrigated side of a row of corn (*Zea mays* L.) might increase N uptake and minimize nitrate leaching potential by reducing the NO_3-N in soil profiles at harvest, thereby protecting water quality. For two years in the field, we evaluated two N placements (broadcast vs. banded), two row spacings (0.76-m vs. a modified 0.56-m), and two ways of positioning irrigation water (applying water to the same side or alternating sides of the row with successive irrigations) for their effects on N uptake in corn silage and soil profile NO_3-N (to the 0.9-m depth). In southern Idaho, we grew field corn in Portneuf silt loam (coarse silty, mixed superactive, mesic *Durinodic Xeric Haplocalcid*) by irrigating every second furrow nine times in 1988 and seven times in 1989. We measured N uptake by harvesting whole plants at physiological maturity and NO_3-N in soil samples taken

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at two in-row locations in selected plots after each irrigation. Where irrigating alternating sides of the row, two-year average N uptake from 0.76-m rows was 131 kg ha^{-1}, 15% greater ($P<0.001$) than from 0.56-m rows. Where irrigating the same furrow all season, N uptake from banding equaled that from broadcasting the first year but was 21% greater ($P<0.001$) the second. Applying water to the same furrow decreased profile N by about 170 kg ha^{-1} under 0.76-m rows by season's end in 1988. In 1989, irrigating the same furrow and banding N into an adjacent, never-irrigated furrow produced season-average profile N of *a*) 303 kg ha^{-1}, the least under all fertilized 0.76-m rows, and *b*) 152 kg ha^{-1} under 0.56-m rows, half that under similarly treated 0.76-m rows. Our findings suggest that corn in 0.76-m rows should be fertilized by banding N into every second furrow and irrigated season-long using the remaining, non-fertilized furrows because those practices maintained or increased N uptake in silage and minimized residual NO_3-N in 0.9-m soil profiles at season's end.

INTRODUCTION

NO_3-N concentrations >10 mg L^{-1} in drinking water can be fatal to human infants (Comly, 1945). NO_3-N is also toxic to young of other mammals, though at greater concentrations (Shirley et al., 1974). Consequently, increasing NO_3-N concentrations in groundwater used for drinking are of concern in the Pacific Northwest (Bonn et al., 1995; Jones and Wagner, 1994; Neely and Crockett, 1999; Rupert, 1997), the Nation (Mueller et al., 1995; Ritter et al., 1993), and around the globe (Spalding and Exner, 1993; Strebel et al., 1989).

In the western U.S., NO_3-N is the constituent that most affects groundwater quality beneath irrigated row-cropped areas (Spalding and Exner, 1993). Furrow irrigation was used on nearly a fourth of the irrigated area in the seven western states in 1998 (National Agricultural Statistics Service, 1998). One difficulty with furrow irrigation, however, is the substantial difference in infiltration (or intake) opportunity time between furrow inlet and outlet. Since there is more time for infiltration to occur near the inlet than outlet, the potential for deep percolation or leaching is greater near the inlet. Where furrow irrigation is practiced, NO_3-N is often leached through soil profiles to groundwater.

In semi-arid areas, nitrate leaching is usually greatest from heavily irrigated profiles that *a*) have been fertilized excessively (Ayars and Tanji, 1999; Robbins and Carter, 1980) or *b*) contain much residual N from previous cropping (Robbins and Carter, 1980). From 50 to 150 kg NO_3-N ha^{-1} can be lost from southern Idaho silt loams during the non-growing season, even with relatively little winter drainage (Wright et al., 1998). In Idaho and elsewhere, residual and recently mineralized NO_3-N can be leached by late-season irrigations (Wright et al., 1998) or an early-season irrigation just before planting (Meek et al., 1995; Robbins and Carter, 1980).

Irrigation must be well managed to efficiently use N fertilizer applied at nominal, economic rates (Keeney, 1982; Robbins and Carter, 1980; Russelle et al., 1981). In western Idaho, many producers apply large amounts of N to onion (*Allium cepa*) to compensate for leaching and denitrification losses from excessive irrigation (B.D. Brown, personal communication, 1999). Irrigating excessively decreases nitrate availability, crop quality, and producer profit (Stark et al., 1993).

Both N uptake and N fertilizer use efficiency (NUE) should increase as N is retained in the upper profile. With greater N uptake, less N will remain in soil at harvest. To reduce NO_3-N leaching and increase NUE, corn producers should end the growing season with as little N as possible in the soil profile (Karlen et al., 1998). If irrigated corn producers could achieve this goal of minimizing end-of-season profile N, groundwater quality in many areas could improve since corn is grown on more than one-fifth of all irrigated land nationwide (National Agricultural Statistics Service, 1998). Where much water percolates during the non-growing season, nitrate leaching is greatest from profiles with the greatest amount of N at harvest (Liang et al., 1991; Zhou et al., 1997). Minimizing NO_3-N in soil profiles at season's end is desirable because most nitrate leaching in relatively humid areas occurs between harvest and next year's planting (Cambardella et al., 1999; Kengni et al., 1994; Martin et al., 1994; Ritter et al., 1993).

If N fertilizer is banded, and later sidedressed on a corn row's non-irrigated side and the other side irrigated (Fig. 1), nitrate leaching should be reduced by minimizing the nitrate's contact with water that moves down from the irrigated furrow (Kemper et al., 1975; Martin et al., 1995; Sojka et al., 1994; Tracy and Hefner, 1993). N placed there, however, may be positionally unavailable if low soil water contents (low water potentials) near banded N in the dry furrow limit root extension toward the N (Taylor and Ashcroft, 1972). Low hydraulic conductivities in dry soil also restrict passive N uptake via mass flow. Dry soil can also reduce crop N uptake and yield (Benjamin et al., 1997; Keeney, 1982). Placing N fertilizer in or near a non-irrigated furrow, though, does not always reduce corn yield (Hefner and Tracy, 1995; Lehrsch et al., 2000). If one irrigates near the fertilizer to increase N availability (Skinner et al., 1998), N may be leached from the root zone. As water redistributes in a profile during and after an irrigation, banded or sidedressed N as nitrate can also be transported horizontally (Benjamin et al., 1998) and upward with evaporation (Boswell and Anderson, 1964) into drier soil where less uptake occurs (Keeney, 1982).

In addition to separating N from irrigation water, splitting the N fertilizer application should reduce nitrate leaching (Martin et al., 1994; Power et al., 2000; Ritter et al., 1993). Applying a portion of the corn's N in a band at planting and

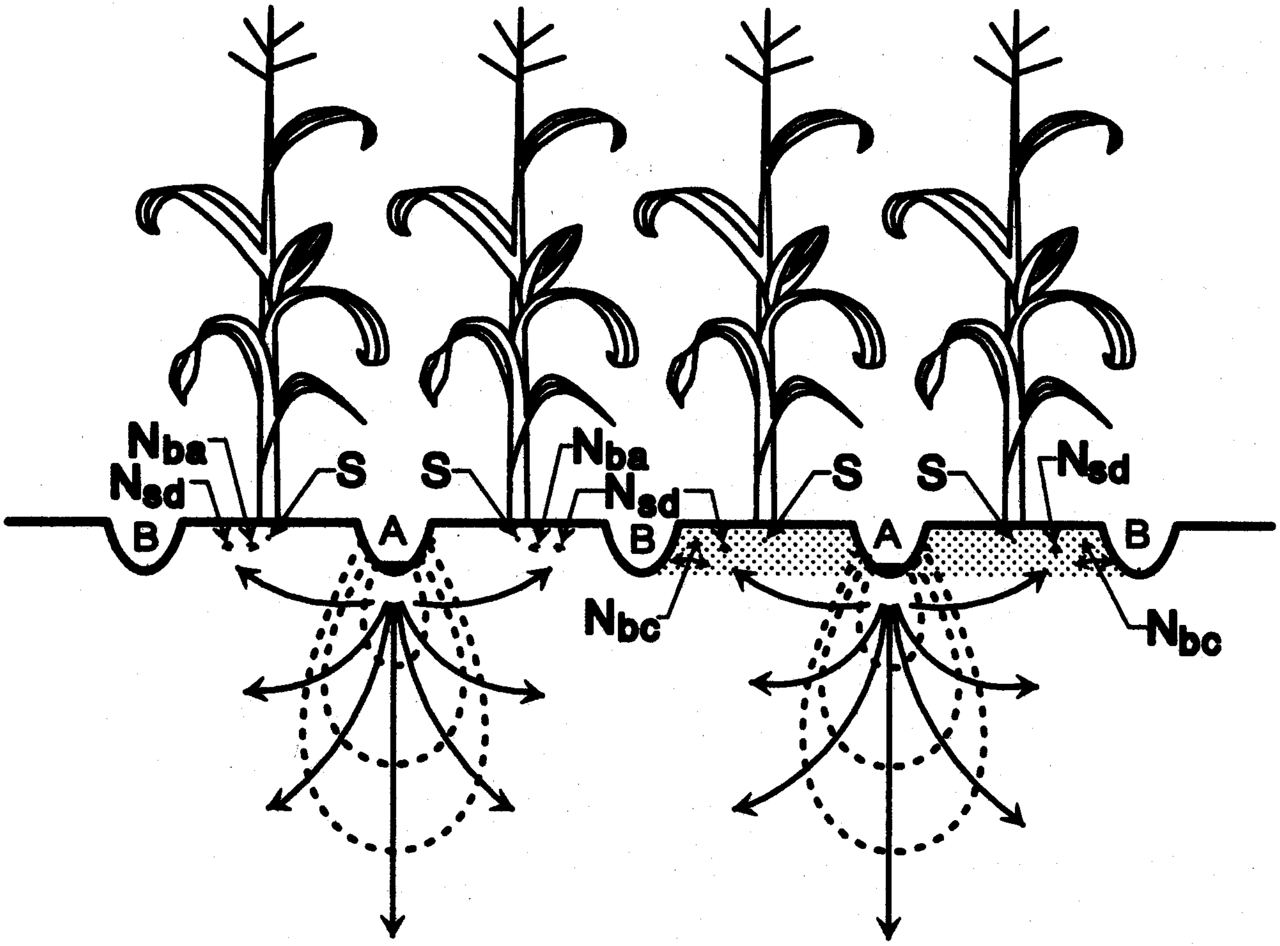

Figure 1. Positioning of seed (S), banded N (N_{ba}), sidedressed N (N_{sd}), and broadcast N (N_{bc}) where we irrigated the same furrow (A). Where we irrigated alternating furrows, we irrigated Furrow A first, then B, then A, etc. Equipotential and flow lines are conceptually shown for 0.76-m rows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

the remainder five to six weeks later should increase both N fertilizer use efficiency (NUE) and N uptake by minimizing leaching opportunity time and better timing the N application to N uptake (Westermann and Crothers, 1993).

The goal of this research was to minimize downward flux of NO_3-N through soil under furrow-irrigated row crops in order to increase N fertilizer use efficiency. To achieve our goal, we are investigating furrow irrigation and N fertilizer management strategies that should increase N uptake and protect water quality. This two-year field study evaluated the effects of N placement, row spacings, and irrigation water positioning on N uptake in corn silage and nitrate−N accumulation in 0.9-m soil profiles.

MATERIALS AND METHODS

The experiment was conducted on Portneuf silt loam at 42° 33′ N latitude and 114° 21′ W longitude, 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. The site, with a continental and semi-arid climate, receives about 285 mm of precipitation annually but only about 90 mm from 1 May through 30 September (McDole and Maxwell, 1987). Additional background and other experimental details were given by Lehrsch et al. (2000).

The experiment was a split-split plot with four replications and main plots arranged in randomized complete blocks. The main plot treatment was irrigation water positioning: either the same furrow or alternating furrows were irrigated. Where the same furrow was irrigated season-long, it was a wheel-tracked, nonfertilized furrow (Furrow A in Fig. 1) on the side of the row away from the banded and sidedressed N fertilizer. Where we irrigated alternating furrows, we irrigated Furrow A at the first irrigation, then Furrow B on the opposite side of the row at the second irrigation, then A, etc. Where alternating furrows were irrigated, the nonfertilized furrow 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). The subplot treatments (row spacings, Fig. 2, after Sojka et al., 1992) were either single rows spaced 0.76 m apart or paired rows, spaced on average 0.56 m apart. Every pair of 0.56-m rows was centered on an intervening irrigated furrow to increase water availability and decrease furrow erosion (Sojka et al., 1992). The sub-subplot treatments (N placements, Fig. 1) were *a*) 50% of the N (always as urea, 0.45 kg N kg^{-1}) broadcast pre-plant then 50% sidedressed at the eight-leaf stage 6 wks after planting, *b*) 50% banded at planting then 50% sidedressed at the eight-leaf stage, or *c*) no N fertilizer applied. The N application was split to apply the N when it could be best utilized by the growing corn (Silvertooth et al., 1992). Each plot was four rows wide and 102 m long. The study was conducted on the same field site in 1988 and 1989 with no re-randomization of treatments among plots the second year. Treatments were applied to the same plots the second year to study effects of multi-year fertility and irrigation management systems on N uptake by silage and soil profile N.

Each spring prior to seedbed preparation, soil samples were taken from depths of 0–0.3 and 0.3–0.45 m and analyzed for macronutrients. Shortly thereafter, we applied P at rates recommended by University of Idaho for irrigated field corn (Brown and Westermann, 1988). Pre-plant 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 fertilized the year before and 4.6 from plots not fertilized the year before. About a week before planting, 45 kg N ha^{-1} (90 kg ha^{-1} in 1989) was broadcast onto the broadcast/sidedressed plots and immediately incorporated with a roller harrow (Fig. 3). At planting, 45 kg N ha^{-1} (90 kg ha^{-1} in 1989) was banded into the banded/sidedressed plots as a starter at planting. This band of N was 50 mm to the side and 25 mm below the seed, being about 50 mm above the water surface when irrigating. About six weeks after planting, a sidedressing of 45 kg N ha^{-1} (90 kg ha^{-1} in 1989) was knifed into bed shoulders as a band 76 mm

Table 1. Characteristics of Portneuf Silt Loam Sampled About 290 m Southeast of the Study Site (McDole and Maxwell, 1987)

Horizon	Depth cm	Particle Size Distribution Sand %	 Silt %	 Clay %	Bulk Density† g cm^{-1}	Org. C g kg^{-1}	CEC $cmol_c$ kg^{-1}	pH (1:1 water)	EC S m^{-1}	$CaCO_3$ Equiv. %
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

† Measured using the clod technique.

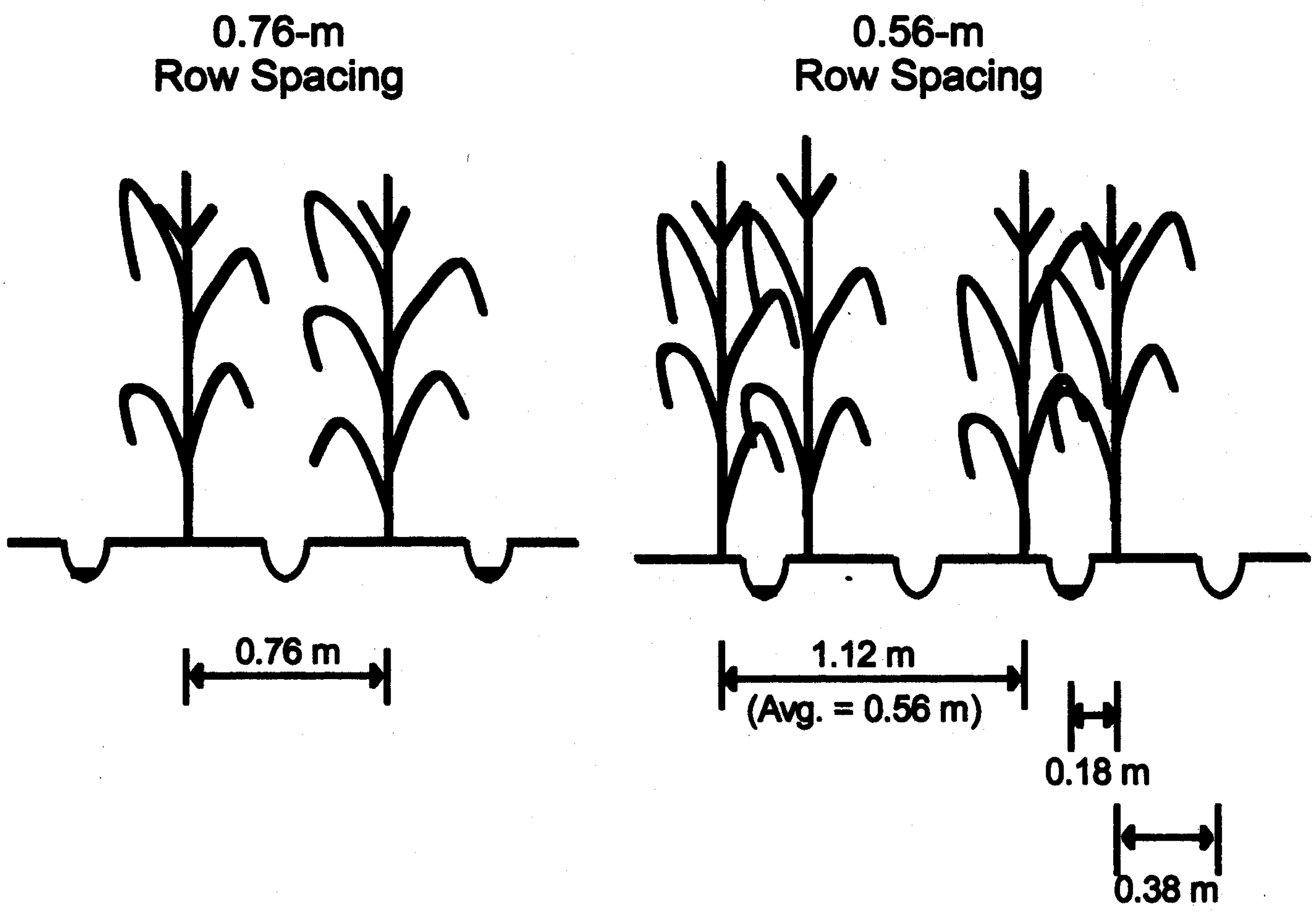

Figure 2. Row spacings were 0.76 m or a modified 0.56 m.

beneath the soil surface and 0.13 m to the dry furrow side of the corn in both the preplant broadcast and banded plots (Fig. 1). The sidedressed N was placed nearer the plant row than furrow so that the N would be 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). In both years, 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. Additional cultural practices are given in Figure 3.

We planted "Pioneer[1] 3901" corn, a 98-d relative maturity cultivar grown for grain and, sometimes, for silage. The corn was planted both years at the 50-mm depth. As an integral part of the planting operation, we formed triangular-shaped irrigation furrows 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. The corn was 0.3 m tall, at about the eight-leaf growth stage, when later sidedressed. Final populations averaged 61,100 plants ha^{-1} in 1988 and 68,200 in 1989.

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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.

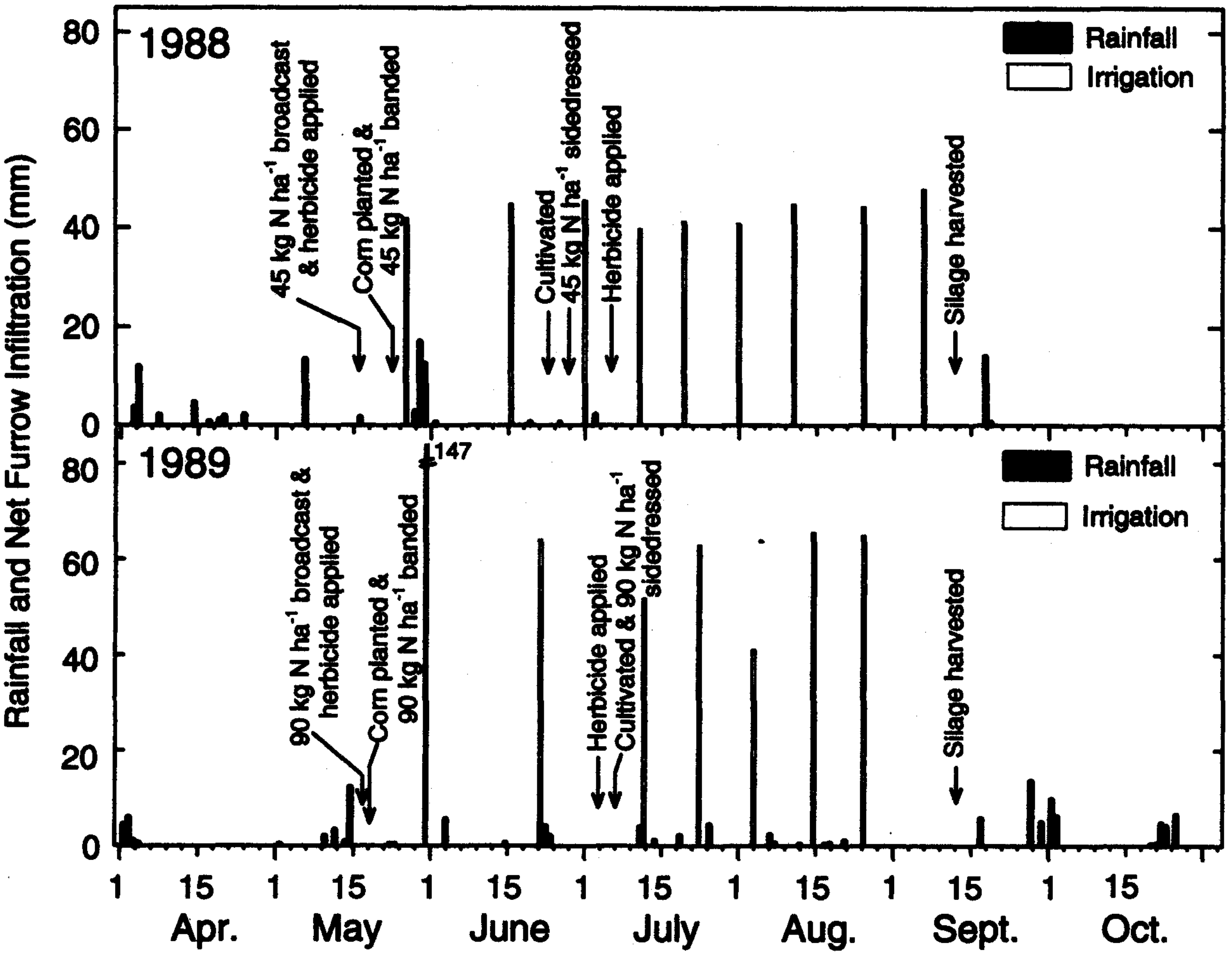

Figure 3. Timing of cultural practices, rainfall, and irrigations in 1988 and 1989. Net infiltration has been plotted for each irrigation.

Irrigations were scheduled considering crop water demand, as constrained by water availability. In southcentral Idaho, irrigation water is not always available when desired because a single canal supplies water to several fields planted to different crops, each requiring water in different amounts at different times. Thus, strict scheduling using evapotranspiration-based estimates of crop water use is impossible. Water was applied to every second furrow at each irrigation (Fig. 3). Irrigations were, in general, 12 h for the 0.76-m rows and 8.8 h for the 0.56-m rows to apply equal volumes of inflow per unit area to all plots. Our gross water application at each irrigation was commonly 70 mm of water in 1988 and 88 mm in 1989. Inflows were commonly 0.91 $m^3\ h^{-1}$ in 1988 and 1.14 $m^3\ h^{-1}$ in 1989. Several times each irrigation, runoff rates from representative furrows of numerous treatments were measured using small, long-throated trapezoidal furrow flumes (Brown and Kemper, 1987). Total outflow was the sum of each measurement interval's runoff volume. Each plot's spatially averaged net infiltration, as volume per unit area, was calculated as total inflow less total outflow. Each irrigation's net infiltration was averaged across all monitored plots and reported (Fig. 3).

Soil samples were taken about six days after each irrigation to allow soil water to redistribute and the nitrate in the profile to reach a quasi-equilibrium. Bucket augers with diameters of 51 mm, per Baker et al. (1989), were used to take soil samples in the row in 0.15-m depth increments to a depth of 0.3 m, then in 0.3-m increments to a depth of 0.9 m at two locations, one each near a furrow inlet and outlet, in an interior row of selected treatments. Sampling locations were 34 and 69 m from the upper (northernmost) end of each plot.

We chose to sample our soil profiles directly beneath the row due primarily to our irrigation management treatments. Our irrigation water positioning would introduce significant variation in the NO_3!N concentrations in soil samples taken below furrows. For example, in those plots where the same furrow was irrigated, one furrow was irrigated season-long while the furrow adjacent to it was never irrigated (Fig. 1). In other plots, one furrow was irrigated at one irrigation while the furrow adjacent to it was irrigated the following irrigation. In light of such irrigation water effects, there was no logistically feasible way to sample soil from beneath the furrows of every monitored treatment after each irrigation in two entire seasons. Our only recourse was to sample soil beneath the corn rows. However, sampling beneath the corn row involved tradeoffs as well. For samples taken after the first one or two irrigations of the season, some of the N that was banded 50 mm to the side of the row at planting would likely be sampled with the the 51-mm-diameter bucket auger used to take soil samples directly beneath the row (Clay et al., 1995). The possibility of this occurring, however, would decrease with time, due to plant uptake of N from the nearby band. Sampling in the row also would likely underestimate the amount of N in a plot since much of the N taken up by the plant's root system would have been from beneath the row.

Within 3 h of collection, the soil samples were transported to the laboratory. After a 25- to 50-g subsample was removed to determine gravimetric water content, the remainder was air-dried at about 30°C in a forced-air drying cabinet, ground, and sieved. The fraction passing a 2-mm sieve was stored for less than 120 days at room temperature until analyzed. Each sample's NO_3-N concentration was determined colorimetrically after cadmium reduction of a KCl extract in an automated flow injection analysis (Lachat Instrument, Milwaukee, WI, Method 12-107-04-1-B)[1]. Thereafter, we calculated the NO_3-N in each depth increment, assuming a bulk density of 1.33 g cm^{-3} (as measured on a core), and totaled the N to 0.9 m.

Three portions of each plot were harvested for silage. 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 N uptake at these locations was averaged, then statistically analyzed. This sampling protocol provided a valid measure of the plot's average N uptake due to varying dry matter yield caused by differences in infiltration with distance from the furrow inlet. About 3 wks after silage sampling, the remaining grain was harvested, with the cobs and stover returned, unchopped, to the respective plot. Silage was sampled on 12 Sept. 1988 and 12 Sept. 1989. Subsamples of the harvested silage 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 (Lachat Instrument, Milwaukee, WI, Method 13-107-06-2-A)[1]. N uptake in silage was calculated by multiplying oven-dry silage yield (that included grain) by the silage N concentration.

Preliminary statistical tests included Bartlett's analyses to insure homogeneous variances for each response variable (N uptake in silage and profile N totals), with a common log transformation employed as needed. We then used mixed model procedures (SAS Institute Inc., 1997)[1] to perform an analysis of variance (AOV). Replication was the only factor modeled as random for multi-year analyses. Year was modeled as a fixed effect because N uptake differed from year to year, particularly by corn not fertilized with N. We separated least-squares means using either Fisher's protected LSD or *t* tests of pairwise differences (SAS Institute Inc., 1997)[1]. Where needed, means and upper 95% confidence limits on the mean were back-transformed into original units for presentation.

RESULTS AND DISCUSSION

N Uptake in Silage

Interactions Involving Row Spacing

Nitrogen uptake in silage, averaged across years and water positioning, was affected by an interaction (significant at $P=0.051$) of row spacing with placement (Fig. 4). In fertilized plots, silage N tended to be about 5% greater from 0.76-m than 0.56-m rows. In nonfertilized plots, silage N was nearly 18% greater ($P<0.001$) from 0.76-m than 0.56-m rows. Uptake was less from 0.56-m than 0.76-m rows likely because of NO_3-N leached by water that moved downward through a greater portion of the root zone under narrower than wider rows. Such loss of NO_3-N would have most affected uptake from nonfertilized plots, as the data in Figure 4 suggest. More leaching under 0.56-m than 0.76-m rows was confirmed by profile N under narrower rows being about half ($P<0.001$) that under wider rows in 1989 (discussed below). At every placement, N uptake in silage was greater, or tended to be greater, from 0.76-m than 0.56-m rows ($P<0.330$ for banded, $P<0.244$ for broadcast, and $P<0.001$ for nonfertilized) (Fig. 4).

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) (Fig. 4). Thus, if N uptake was positively correlated with N use efficiency from plots equally fertilized, N tended to be used more efficiently from banding near the row than broad-

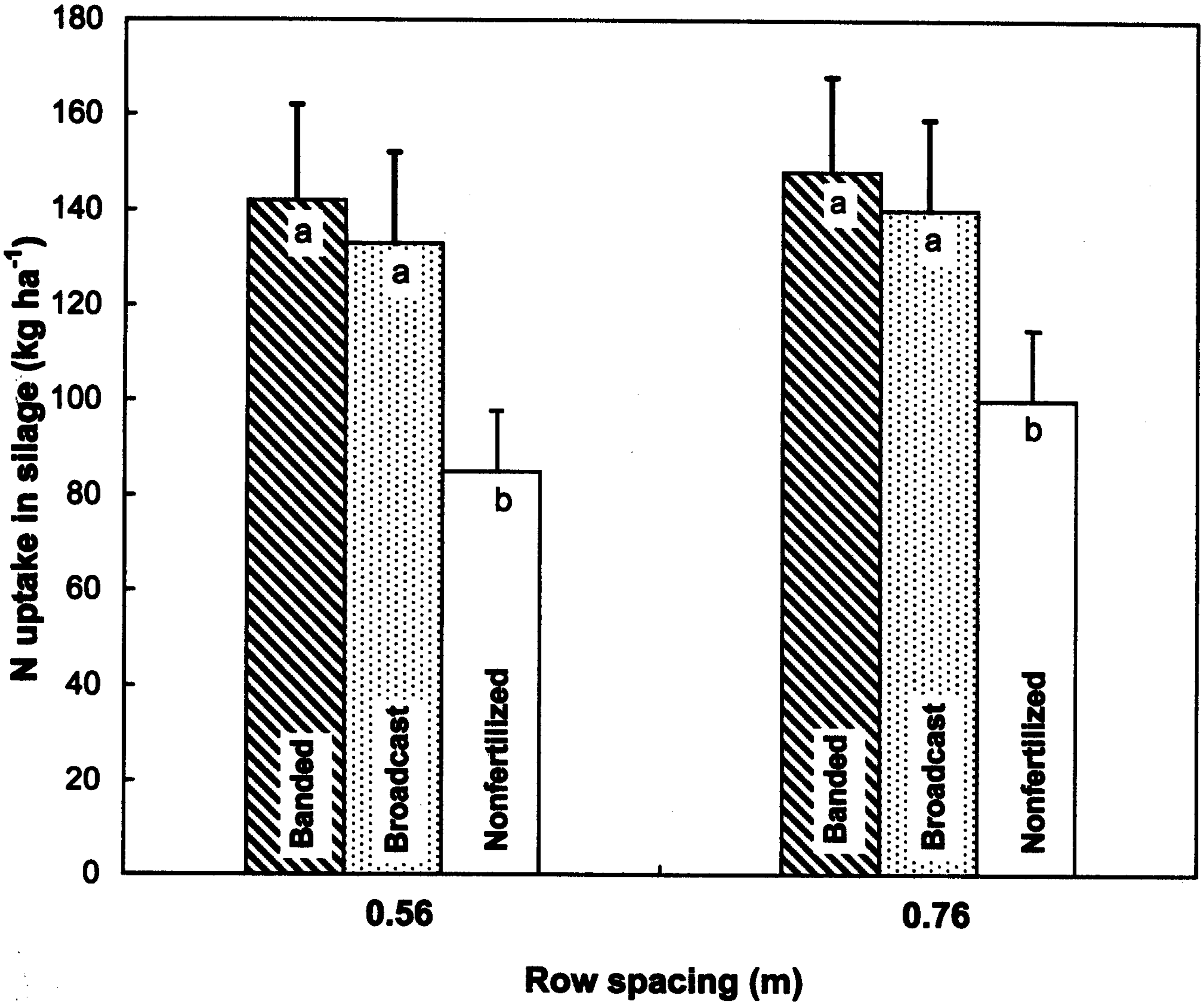

Figure 4. N placement and row spacing effects on two-year average N uptake in silage, averaged across irrigation water positioning. Within row spacings, means with the same letter are not significantly different according to *t* tests of pairwise differences at $P=0.05$. The row spacing effect was significant, according to a *t* test of pairwise differences, only for nonfertilized placement (at $P=0.001$). Each mean=s error bar is its upper 95% confidence limit.

casting. Broadcast-incorporated N is particularly susceptible to leaching under the furrow (Saffigna et al., 1976). The potential for nitrate leaching is greater with broadcast than banded N (Power et al., 2000).

Row spacing interacted (at $P<0.007$) with irrigation water positioning to affect N uptake, averaged across years and placements (data not shown). Average N uptake from 0.76-m rows was 131 kg ha^{-1}, 15% greater ($P<0.001$) than the 114 kg ha^{-1} from 0.56-m rows where water was applied to alternating furrows. Less uptake from 0.56-m rows and alternating furrow irrigation was likely a consequence of greater leaching of fertilizer N that was closer to irrigation furrows in 0.56-m than 0.76-m rows. Wider row spacings permit fertilizer N to be banded and/or sidedressed farther from irrigation water. Where the same furrow was irrigated, uptake was 122 kg ha^{-1}, statistically similar from both 0.56-m and 0.76-m rows.

When N uptake was averaged across water positioning and N placement, in only one case did uptake from 0.76-m rows exceed that from 0.56-m rows (data not shown). In 1989, N uptake in silage from 0.76-m rows was 108 kg ha^{-1}, 16% greater ($P<0.001$) than the 93 kg ha^{-1} from 0.56-m rows. In 1988, in contrast, uptake from 0.76-m rows was 150 kg ha^{-1}, statistically similar to the 148 kg ha^{-1} from 0.56-m rows. A fixed 0.76-m spacing from one row to the rows on either side (Fig. 2) likely led to more uniform inter-row root distribution and more efficient N removal from 1989's N-depleted profiles.

Interaction of Water Positioning with N Placement in 1988 and 1989

When averaged across row spacings, irrigation water positioning did not affect silage N uptake at any placement in either 1988 or 1989 (Fig. 5). However, where water was applied season-long to the same furrow, N uptake from banding was equal to that from broadcasting the first year but was 21% greater ($P<0.001$) the second. As noted above, in the spring of 1988 pre-plant residual soil N concentrations were relatively large, not likely growth-limiting, in the uppermost 0.45 m of the profile. In the spring of 1989, however, residual soil N concentrations in plots fertilized the year before were only 55% of what they were the previous spring. From these 1989 profiles with much less residual spring N, soil N was used more efficiently where urea was banded on one side of a row and water always applied to the furrow on the other side of the row. This finding was consistent across both row spacings we studied. Where N was broadcast onto N-depleted plots in 1989 and the same furrow irrigated, root development (and to a limited degree, passive N uptake via mass flow) may have been inhibited in relatively dry soil under the non-irrigated furrow. To enable plants to absorb N from fertilized regions of the profile likely to later dry, one might need to wet those regions via irrigation early in the season to stimulate rooting in those areas (Skinner et al., 1998). Where we banded N into a non-irrigated furrow, however, we did not need to irrigate that furrow to maintain both yield (Lehrsch et al., 2000) and N uptake (Figs. 4–5).

On average, less N was taken up in silage from Portneuf profiles in 1989 than 1988 (Fig. 5), due in large part to poor silage yield from nonfertilized plots in 1989 (Lehrsch et al., 2000). Fertilizer and soil N may have been leached below the developing corn's root system by the two relatively large, early season irrigations in 1989 (Fig. 3). Infiltration was high for the first irrigation because its duration was twice that of the other 1989 irrigations, owing to slow and erratic advance of furrow streams from inlet to outlet. Where we irrigated alternating

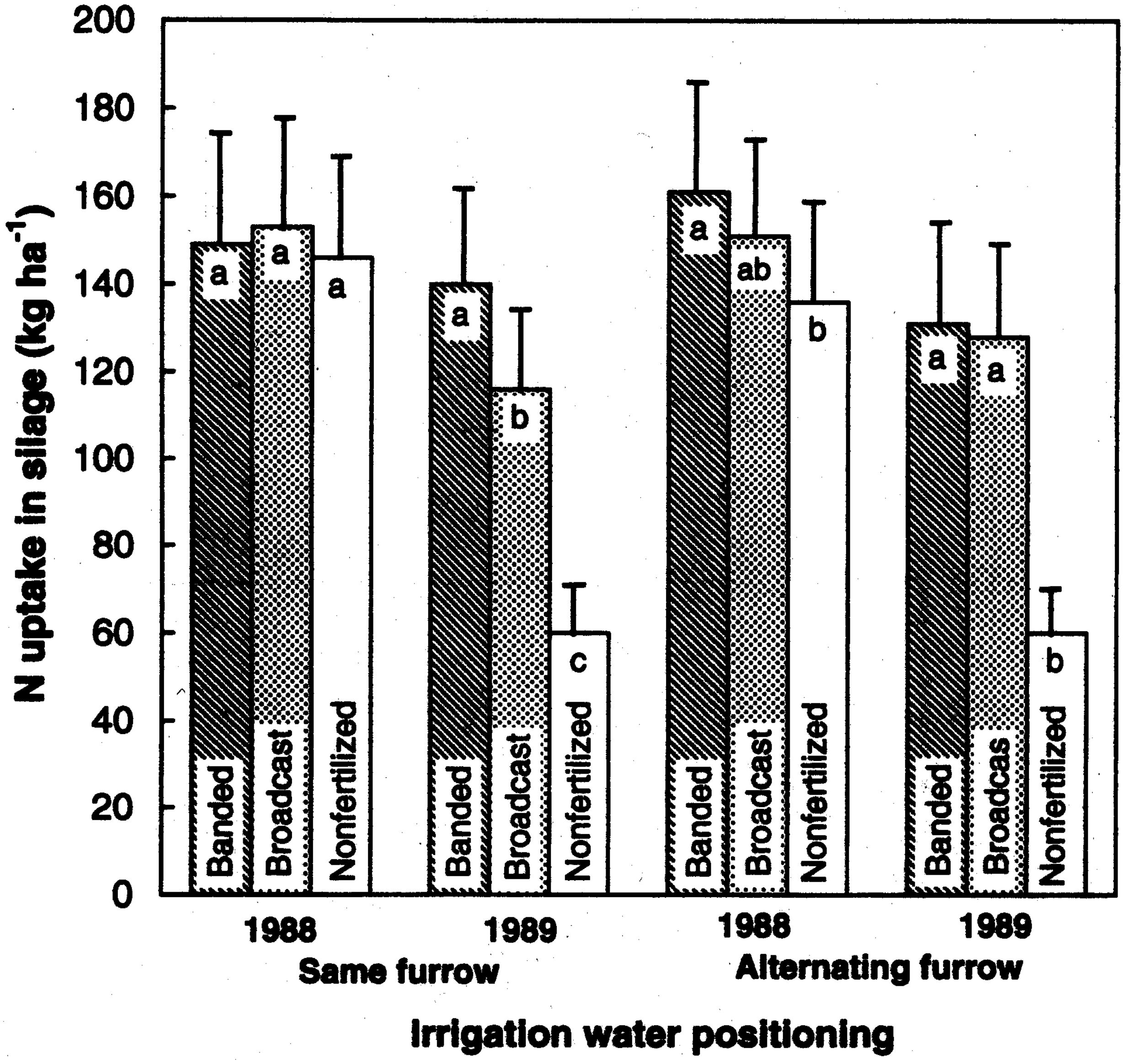

Figure 5. Irrigation water positioning and N placement effects on N uptake in silage in 1988 and 1989. Data have been averaged across row spacings. Within water positioning each year, means with the same letter are not significantly different according to *t* tests of pairwise differences at $P=0.05$. Water positioning did not affect N uptake at any placement in either year. Each mean=s error bar is its upper 95% confidence limit.

furrows in 1988, uptake decreased in the order banding > broadcasting > nonfertilized (Fig. 5). In 1988 with near adequate spring N, nitrogen uptake was 15% less from nonfertilized than banded plots where irrigating alternating furrows (Fig. 5). Alternating-furrow irrigation appears to have leached residual N from the corn root zones in nonfertilized plots and, to a lesser degree, both fertilizer and residual N from the root zones in broadcast plots. Soil NO_3-N concentrations in the lower profile (at the 0.6- to 0.9-m depth) were 21% greater ($P<0.07$) with broadcasting than banding, on average through the 1988 irrigation season under

0.76-m rows (data not shown). Soil N data will be reported in more detail in another paper in preparation.

Profile NO_3-N

Interactions Involving Water Positioning

Irrigating the same furrow at every irrigation in 1988 minimized NO_3-N in 0.9-m profiles by mid-July onward (Fig. 6). Irrigating the same furrow, however, did not reduce 1988 N uptake in silage, averaged across row spacings (Fig. 5).

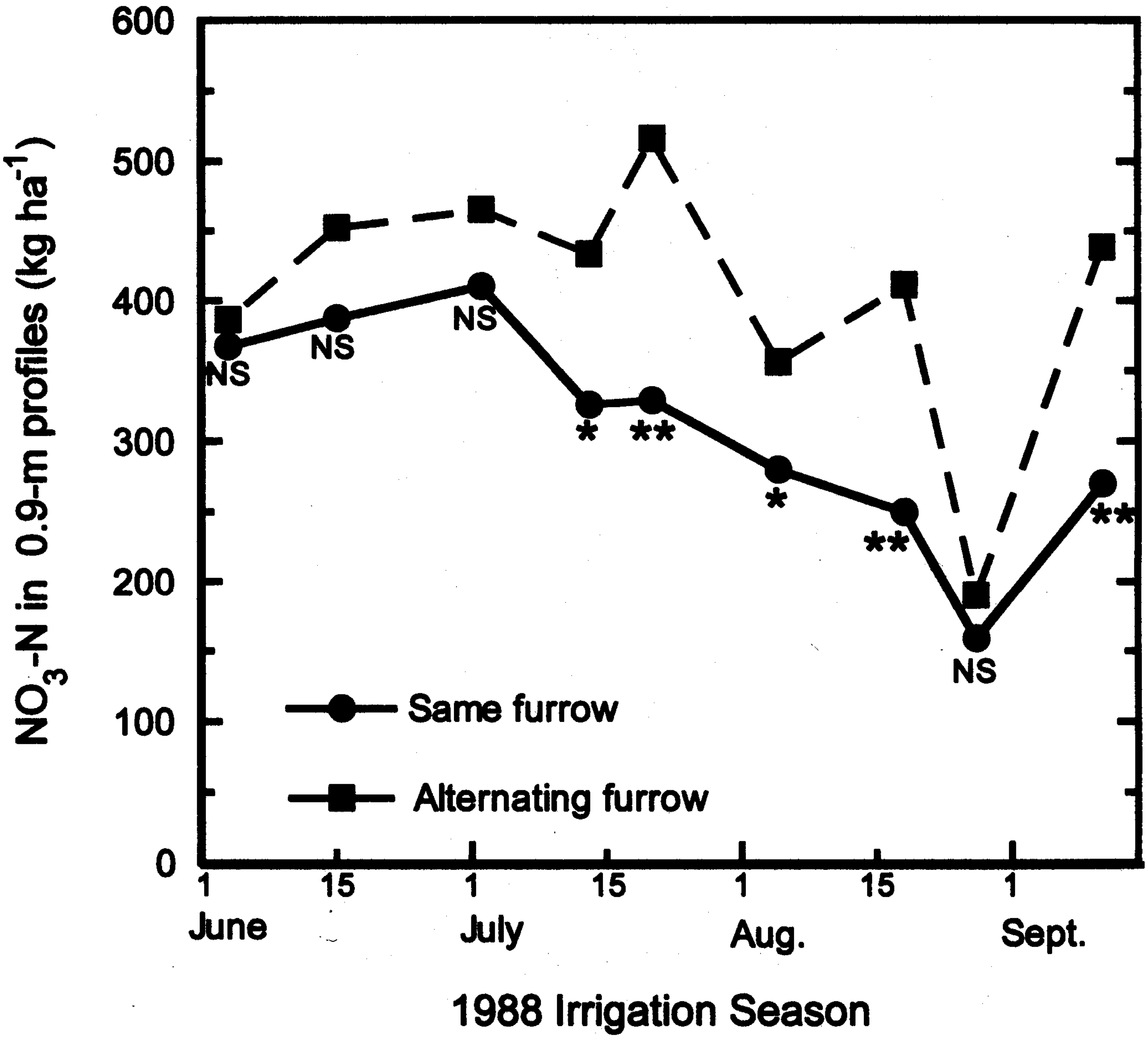

Figure 6. NO_3-N in 0.9-m profiles under 0.76-m rows in 1988. Data have been averaged across N placements. Within dates, means with NS are not significantly different at $P=0.05$ while those with * and ** are significantly different according to a *t* test of pairwise differences at $P=0.05$ and 0.01, respectively.

Thus, irrigating the same furrow resulted in similar N uptake (Fig. 5) yet reduced end-of-season profile N under the row (Fig. 6). The NO_3-N remaining in soil profiles at season's end has been found proportional to the nitrate leached from those profiles the following winter (Liang et al., 1991; Zhou et al., 1997). Our findings suggest that post-harvest nitrate leaching is decreased where the same furrow is used to irrigate silage corn grown in 0.76-m rows. The data shown in Figure 6 could be viewed as suggesting greater in-season nitrate leaching where the same furrow was irrigated. The smaller profile N for same-furrow irrigation is most likely due to water transporting NO_3-N horizontally from beneath the sampled row, possibly toward the never-irrigated furrow (Benjamin et al., 1998). This horizontal movement of NO_3-N is discussed in more detail below.

Similar to the findings for 1988, season-average profile N was least among fertilized treatments in 1989 where we irrigated the same furrow at every irrigation and banded N on the other side of the row (Fig. 7). Where N was banded at planting, profile N where the adjacent furrow was always irrigated was 54% of that where alternating furrows were irrigated. In this second study year, profile N was significantly less where we irrigated the same furrow at each N placement (Fig. 7). As found in 1988, N uptake in 1989 was similar (Fig. 5) yet 1989 profile N was less (Fig. 7) where the same furrow was irrigated. Producers should consider banding N on one side of the row and irrigating the other side throughout the season to maintain N uptake in silage and lessen the potential for over-winter leaching of NO_3-N remaining in soil profiles at harvest.

In both 1988 and 1989, more N was present in the sampled profile under the row where the alternating rather than the same furrow was irrigated (Figs. 6 and 7). Water infiltrating from each furrow in turn was apparently transporting NO_3-N not only downward but also horizontally, positioning it below the row where it accumulated and was sampled. In 1989, alternating, rather than same furrow irrigation significantly increased profile N under the row at each N placement (Fig. 7). Where we irrigated using the same furrow season-long, the water likely transported NO_3-N from beneath the row, possibly downward but more likely into the soil beneath the never-irrigated furrow. Where irrigation water positioning is studied, NO_3-N contents should be measured in soil samples taken under the furrows as well as under the rows.

In 1989, water from alternating-furrow irrigation positioned much more N under the row where N was banded rather than broadcast (Fig. 7). Water infiltrating from the furrow on the banded side of the row likely transported NO_3-N from the fertilizer band laterally to the row or, possibly, slightly beyond it. During the subsequent irrigation, water infiltrating from the furrow on the opposite side of the row probably helped to move the NO_3-N downward in the profile, ultimately positioning it below the row, where we sampled it. NO_3-N from the broadcast urea application was likely transported in a similar manner but, since less of it was initially placed between the furrow and row, less of it was positioned below the row (Fig. 7).

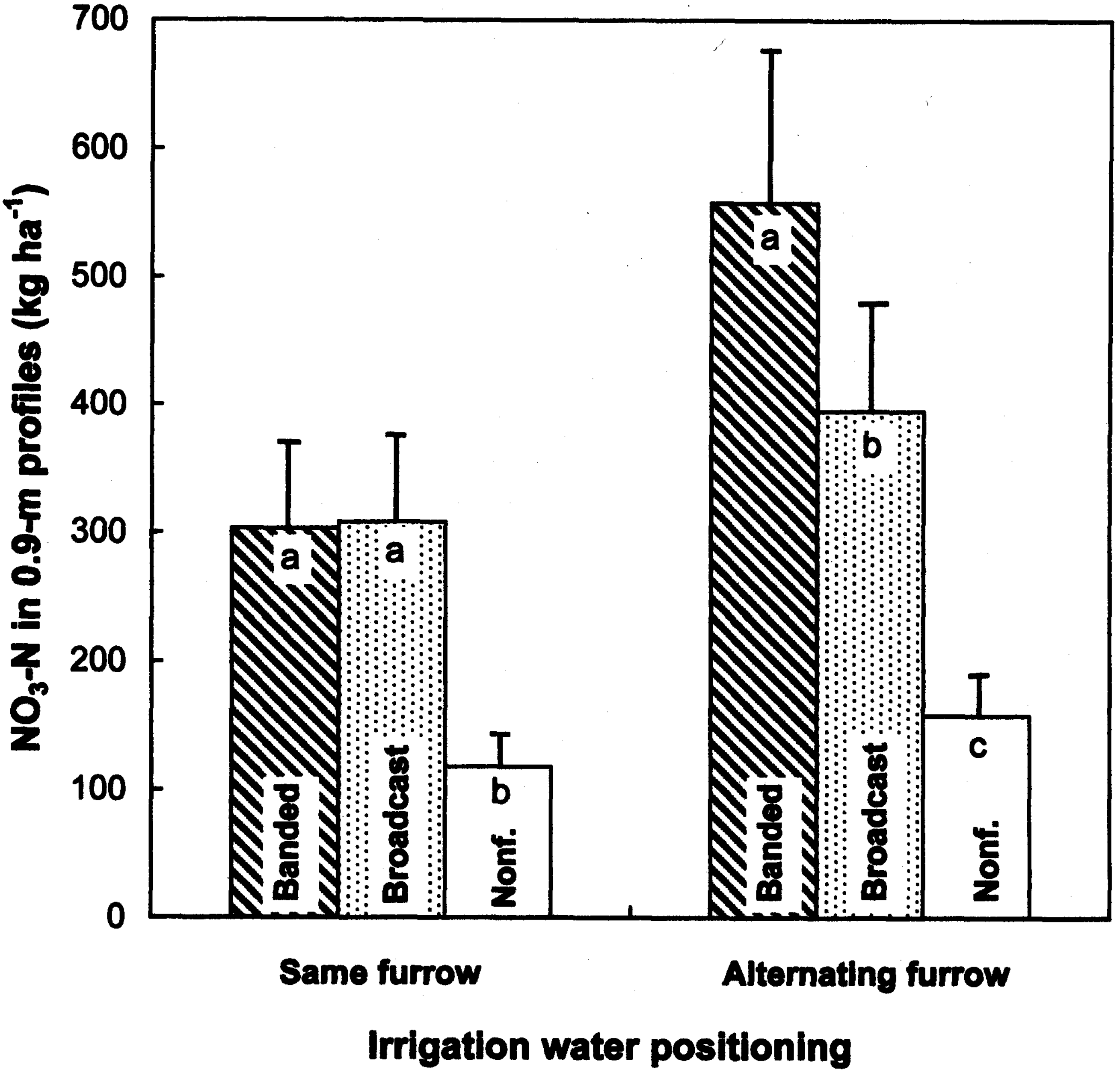

Figure 7. Irrigation water positioning and N placement effects on season-average NO_3-N in 0.9-m profiles under 0.76-m rows in 1989. Data have been averaged across furrow inlet and outlet. For each mean, $n=56$; interaction was significant at $P<0.07$. Within water positioning, means with the same letter are not significantly different according to *t* tests of pairwise differences at $P=0.05$. The water positioning effect was significant, according to a *t* test of pairwise differences, at $P=0.001$ for banded placement and at $P=0.05$ for both broadcast and nonfertilized placement. Each mean=s error bar is its upper 95% confidence limit.

Row Spacing Effects in 1989

Season average profile N with band placement and same-furrow irrigation in 1989 was 152 kg ha^{-1} under 0.56-m rows, about half ($P<0.001$) that under 0.76-m rows (data not shown). Water from irrigation probably leached more NO_3-N from below 0.56-m rows since the irrigated furrow was 0.2 m closer to the banded N in 0.56-m than 0.76-m rows (Fig. 2).

N Placement Effects During 1989

Profile NO_3-N under 0.76-m rows was less near furrow inlets than outlets for the first three irrigations in 1989 (Fig. 8). Near the inlet, infiltration opportunity time was longer, increasing infiltration and leaching, particularly early in the season when root systems and uptake were small. It is also likely that NO_3-N near the inlet was leached from beneath the row by the two relatively large early season irrigations in 1989 (Fig. 3). Profile N was greater with banded than broadcast N near both the furrow inlet and outlet for those same first three irrigations. While this difference may suggest that more broadcast than banded N had already been leached from beneath the row, it is more likely related to our soil sampling. Bucket auger samples taken in the banded rows likely sampled some NO_3-N from the fertilizer band centered only 50 mm to the side of the row. Clay et al. (1995) found, as might be expected, that soil cores taken downward through banded N fertilizer overestimated that soil profile's residual inorganic N while, in contrast, cores collected 8 cm from the band properly estimated profile N. Clay et al. (1995) recommended that soil cores be collected between 8 and 22 cm from banded N fertilizer to adequately estimate soil profile residual N. The axial center of our soil

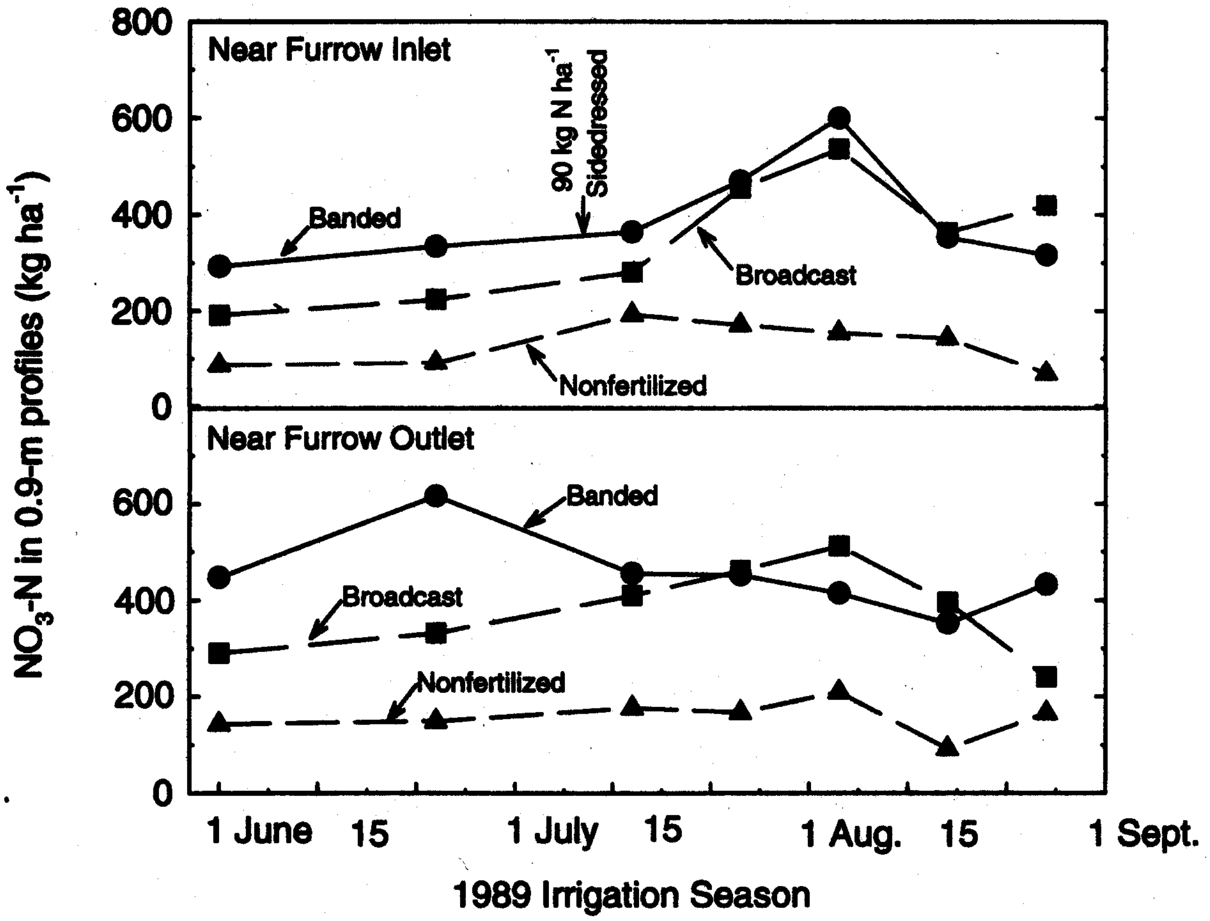

Figure 8. NO_3-N in 0.9-m profiles under 0.76-m rows near furrow inlet and outlet in 1989. Data have been averaged across irrigation water positioning.

cores was 2 cm from banded urea (50% of the N we applied) and 13 cm from sidedressed urea (the remaining 50%). Profile N differences between banding and broadcasting decreased following sidedressing, in general (Fig. 8).

Profile N doubled ($P<0.012$) by season's end near the furrow inlet of broadcast plots (Fig. 8). This doubling suggests that corn did not use fertilizer N efficiently from this broadcast/sidedress treatment. This treatment's additional 230 kg N ha^{-1} at season's end was susceptible to leaching that could occur in the winter (Wright et al., 1998) or the following spring (Robbins and Carter, 1980). Profile N totals were not different ($P>0.43$) from season start to end for any other N placement near either the furrow inlet or outlet in 1989 (Fig. 8).

CONCLUSIONS

Two-year average N uptake was 15% greater ($P<0.001$) from 0.76-m than 0.56-m rows where we irrigated alternating sides of the row with successive irrigations. Where irrigating the same furrow all season, N uptake in silage from banded plots was equal to that from broadcast plots the first year but was 21% greater the second. In 1988, profile NO_3-N under 0.76-m rows was less at season's end where irrigating the same rather than alternating furrow. Season average profile N in 1989 was least (303 kg ha^{-1}) under fertilized 0.76-m rows where we irrigated the same furrow all season and banded N next to the non-irrigated furrow. In both 1988 and 1989, NO_3-N was positioned beneath the row where alternating furrows were used to irrigate corn planted in 0.76-m rows. Banding N on one side of a row and irrigating the furrow on the other side of the row all season maintained or increased N uptake in silage, particularly from soil with low residual spring N, while minimizing residual nitrate-N under the row in 0.9-m soil profiles at growing season's end. To improve N management under furrow irrigation and protect groundwater quality, we conclude that N fertilizer should be placed separate from irrigation water to allow the applied N to be used efficiently by the growing corn, reduce the NO_3-N remaining in soil profiles at season's end, and minimize the potential for NO_3-N contamination of groundwater.

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