Irrigation and Nitrogen Management for Sprinkler-irrigated Cabbage on Sand

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Abstract. Six field studies were conducted from 1980–88 to evaluate the response of cabbage (*Brassica oleracea* L., *Capitata* group) to sprinkler irrigation and sprinkler-applied N fertilizer on a coarse-textured soil. The plots were irrigated using a modified self-moving lateral sprinkler irrigation system that applied five levels of water and five levels of N (liquid NH_4NO_3) in specified combinations of central composite rotatable design. Cabbage yields were significantly increased by water and N applications in all experiments. The N rates predicted for maximum yield exceeded typical cabbage N fertilizer recommendations. However, the above-average plant populations used in these studies resulted in above-average yields and plant N accumulation. Deficit and excess irrigation produced negative results. Generally, cabbage production was optimized and N losses to the environment were minimized when crops were irrigated for evapotranspiration (ET) replacement. However, even when irrigated for ET replacement, these data demonstrate the potential for N leaching at high N rates, presumably as a result of rainfall.

Cabbage produced during the fall and winter in the southwestern United States almost totally depends on irrigation for its water requirement. Nitrogen is the nutrient most limiting to crop production in this region. Like many vegetables, cabbage is often heavily fertilized as a result of quality standards enforced by the market. However, large amounts of N are often lost to leaching below the root zone of vegetable crops (Pionke et al., 1990). The potential for N leaching is especially large on coarse-textured soils because of their low cation-exchange capacity and high water permeability.

The importance of water management on N availability to crops has been recognized for some time (Middleton et al., 1975; Smika and Watts, 1978; Smika et al., 1977). Where either excess or deficient moisture limits crop yields, response to N is often limited. Furthermore, when a crop receives excess moisture through rainfall and irrigation, appreciable N is often leached from the crop root zone and becomes unavailable for crop uptake. Hence, an understanding of the interaction between N fertilization and irrigation is needed for selecting management practices that optimize crop yield and quality and minimize N losses to the environment.

Nitrogen application timing is another important management practice critical for achieving efficient N fertilization on coarse-textured soils (Smika and Watts, 1978).

Applying N with irrigation water expands opportunities for timed applications (Gardner and Roth, 1984). Studies have shown improved N fertilizer use efficiency for some vegetable crops with frequent applications of N in irrigation water (Smittle and Threadgill, 1982; Stark et al., 1983b). The objective of our studies was to evaluate the response of cabbage to sprinkler-applied water and N fertilizer on a coarse-textured soil.

Materials and Methods

Six field studies were conducted from 1980–88 to evaluate the response of cabbage to sprinkler irrigation and sprinkler-applied N fertilizer at the Univ. of Arizona, Yuma, Agricultural Research Center. These studies were conducted on a soil mapped as a

Superstition sand (Typic calciorthid, sandy, mixed, hyperthermic 95% sand). Preliminary soil samples collected at each site showed a uniformly low inorganic N (NH_4 and NO_3) content. Soil and water tests indicated adequate levels of all nutrients except N and P. Phosphorus as triple superphosphate was applied at the rate of 224 kg P/ha and disked into the soil before each planting.

The plots were irrigated using a modified self-moving lateral sprinkler irrigation system (Roth and Gardner, 1989) that applied five levels of water and five levels of N (liquid NH_4NO_3) in specified combinations (Table 1). The treatments were arranged in a central composite rotatable design (Cochran and Cox, 1960). Briefly, nine treatments are defined by this statistical design (Table 1), with the standard treatment replicated five times; this gave a total of 13 plots randomized down the crop row. Each plot was 12 m long and four rows wide. Two replications of the design were

Table 1. Water and N treatment combinations of the central composite design used in cabbage field experiments.

Treatment ^x	Water applied ^z (%)	N applied ^y (%)
1	50	100
2	65	53
3	65	147
4	100	33
5	100	100
6	100	167
7	135	53
8	135	147
9	150	100

^zWater applied at 100% each week was based on published consumptive use estimates (Erie et al., 1965) in the 1980–82 seasons and actual measurement of soil water depletion in 1983–88. Other treatments were applied in the proportional amounts indicated.

^yNitrogen applied at 100% each week was based on existing fertilizer recommendations for the first growing season and then modified during the following seasons based on plant tissue analysis (Gardner and Roth, 1989) and additional experience gained. Other treatments were applied in the proportional amounts indicated.

^xThe central composite design called for treatment 5 to be replicated five times down the row to give a total of 13 plots per line. The whole treatment structure was replicated and rerandomized down two lines to give a total of 26 plots.

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planted, with the treatments randomized differently for each replication to give a total of 26 plots. This design was accomplished because the lateral contained three spray lines that ran along the 13 plots. One spray line was used for each of the two replications and one was used for uniform irrigation during germination and stand establishment.

Colorado River water, with an average electrical conductivity of $1.4 \text{ dS} \cdot \text{m}^{-1}$, was used for all irrigations. Water was applied twice weekly during the crop growing period. The amount of water applied for the 100% level was based on previously published data for consumptive use (CU) in 1980–82 (Erie et al., 1965). After the 1982–83 season, the amount of water applied for the 100% level in each irrigation was calculated from soil water depletion in the profile, as determined by a neutron moisture meter. Adjustments in irrigations were made after rainfall and the total amount of water applied each season was tracked (Table 2). Nitrogen applied at the 100% level each week was based on existing fertilizer recommendations for the first growing season and then modified during subsequent seasons based on tissue analysis (Gardner and Roth, 1989) and additional experience gained.

The amount of water applied during each irrigation was calculated from the flow rate and the time required for the irrigation system to move a known distance. The amount of water applied was controlled by the use of various-sized nozzles. Stainless-steel orifice plates were used to meter the required amount of liquid NH_4NO_3 fertilizer into the irrigation water in each plot.

The four cultivars were planted in September or October, and first and final harvest dates were between mid-January and mid-March (Table 3). ‘Moran 109’ and ‘Headstart’ are generally used as fresh-market cultivars, whereas ‘Condor’ is generally used for processing. Cabbage was planted with a between-row spacing of 0.36 m. A flat-bed culture was used to facilitate the use of the overhead sprinkler system. Plants were thinned at the four- to six-leaf stage to a spacing of 0.3 m along the row to give an approximate population of 92,600 plants/ha. Mature cabbage

heads were harvested from the center two rows of each plot and marketable yields were determined after grading. The cabbage was harvested from one to four times depending on uniformity of maturity.

Whole plant samples were taken from the optimal water and N treatment (treatment 5) beginning at the four- to six-leaf stage of growth and thereafter at ≈ 14 -day intervals until just before harvest to calculate N uptake in Expts. 1 through 4 (1980–84). Midribs for nitrate analysis (Baker and Smith, 1969) were collected at 14-day intervals for all treatments in Expts. 1 through 4 (1980–84). Critical levels derived from midrib analysis have been reported (Doerge et al., 1991; Gardner and Roth, 1989). In 1987, marketable head tissue samples were obtained from all treatments to estimate apparent crop N recovery. All plant tissues were dried at 65°C for 48 h and ground to pass a 0.417-mm (40-mesh) screen. Total N was determined using a micro-Kjeldahl method modified for nitrate-N (Bremner and Mulvaney, 1980). Soil samples were also collected in 1987 and 1988 to a depth of 120 cm (individual samples representing 0 to 3, 3 to 30, 30 to 60, 60 to 90, and 90 to 120 cm) to determine residual nitrate remaining in the soil. Six cores were collected from each plot, composited, and air-dried. Soil nitrate-N

Table 3. Cultivar, planting dates, and harvest periods for each cabbage field experiment.

Expt.	Cultivar	Planting date	First harvest date	Last harvest date
1) 1980–81	Moran 109	23 Sept.	19 Jan.	16 Feb.
2) 1981–82	Moran 109	23 Sept.	19 Jan.	12 Feb.
3) 1982–83	Condor	30 Sept.	24 Feb.	13 Mar.
4) 1983–84	Condor			
	Headstart	26 Sept.	2 Feb.	8 Mar.
5) 1986–87	Condor	16 Sept.	18 Feb.	26 Feb.
6) 1987–88	Headstart	5 Oct.	29 Feb.	29 Feb.

Table 2. Bimonthly irrigation² (I), rainfall (R), and N³ application for the 100% water and N treatments in all cabbage field experiments.

Date	Expt. 1 (1980–81)			Expt. 2 (1981–82)			Expt. 3 (1982–83)			Expt. 4 (1983–84)			Expt. 5 (1986–87)			Expt. 6 (1987–88)		
	I	R	N	I	R	N	I	R	N	I	R	N	I	R	N	I	R	N
Sept.																		
1–15	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	---	---	0
16–30	9.1	0	0	2.5	0	0	2.6	0	0	6.7	0.6	0	7.0	1.0	19.1	---	---	43.6
Oct.																		
1–15	4.8	0	7.6	8.8	0.1	0	9.8	0	22.2	9.5	1.1	19.0	4.6	0.2	17.2	9.9	0.2	22.5
16–31	5.5	0	21.4	3.3	0	32.7	9.7	0	22.6	5.1	0	21.3	5.5	0	35.7	4.0	0.9	19.0
Nov.																		
1–15	5.6	0	21.8	4.0	0	22.6	3.6	0.1	21.8	6.1	0	55.8	4.9	0	37.1	1.3	2.5	32.6
16–30	5.6	0	38.2	3.3	0.3	22.4	5.8	0.6	42.8	5.5	0.2	37.2	5.7	0.3	38.0	1.8	0.2	35.6
Dec.																		
1–15	4.5	0.4	41.3	3.6	0	40.4	1.3	4.2	43.1	3.7	1.4	27.5	7.0	0.5	36.6	4.4	0	36.8
16–31	5.9	0	42.3	3.6	0	32.7	5.5	0	48.6	5.3	1.1	40.7	8.0	0.1	36.9	2.1	1.7	21.3
Jan.																		
1–15	2.8	0.7	0	4.7	0.5	37.3	3.4	0	56.3	4.9	0.7	43.0	6.3	0.2	19.4	3.8	0	21.3
16–31	5.6	0	0	4.2	0.3	20.6	3.8	1.0	62.3	6.5	0	20.9	8.8	0	0	4.1	0.6	21.2
Feb. 1–15	4.0	0.3	0	2.9	0.4	0	4.2	1.9	69.4	6.0	0	0	7.4	0	25.8	6.1	0.1	56.3
16–28(29)	0	0	0	0	2.0	0	5.2	0	31.8	6.9	0	0	7.9	0.1	0	6.3	0	0
Mar.																		
1–15	---	---	---	---	---	---	8.8	0.8	0	2.9	0	---	1.5	0.9	0	7.2	0.1	0
Total	53.5	1.4	172.7	40.9	3.6	208.8	63.7	9.3	421.0	69.2	5.1	265.4	74.6	3.3	265.8	51.3	6.3	310.3

²Irrigation treatments were 50%, 65%, 100%, 135%, and 150% these levels.

³Nitrogen fertilizer treatments were 33%, 53%, 100%, 147%, and 167% these levels.

was determined by steam distillation after extraction with 2N KCl.

Crop production functions were fit to quadratic equations using SAS-REG and SAS-RSREG. Marketable yield and crop N recovery were regressed to total water received (irrigation plus rainfall) and N fertilizer applied. Marketable cabbage yields for each season are presented as yield isoquants calculated from the response surface model. Marketable yield, N accumulation, and N not accounted for in the above-ground cabbage during the 1986–87 season are presented by N rate for each irrigation level. This procedure involved calculating the predicted response to a single variable (N rate) at each level of the other variable (irrigation level) as described by Heady et al. (1955). This presentation was used because of the difficulty associated with the visual interpretation of N recovery data in isoquant form.

Results and Discussion

All plots received uniform irrigation during the first 2 weeks after seeding. After plant stands were established, the irrigation treatments imposed were proportional to the 100% CU treatment (Table 1). Although attempts were made to adjust irrigations after rainfall, deviations occurred when considerable rain fell, as in Expt. 3 (1982–83) and to a lesser extent in Expt. 6 (1987–88). Cumulative N fertilization rates were proportional to the 100% level in each experiment (Table 1).

Marketable cabbage yields ranged from 0 to 90 Mg·ha⁻¹ for the

fresh-market cultivars Moran 109 and Headstart and from 0 to 120 Mg·ha⁻¹ for the processing cultivar Condor. Cabbage yields responded positively and significantly to increased water and N in all experiments (Fig. 1). In 1983–84, during which 'Headstart' and 'Condor' were compared under identical growing conditions, these cabbage types showed a similar response to water and N (Fig. 1).

In most experiments, yields were maximized within the range of water and N treatments applied as predicted from the response surface models. The exception was Expt. 3 (1982–83), in which the quadratic response surface model did not appear to fit the data in a typical manner (Table 4). Instead of yields increasing with water and N as in most experiments, marketable yield decreased with increasing water at low N rates. Cabbage produced during 1982–83 received abnormally high amounts of rainfall (Table 2), which made it difficult to impose irrigation treatments and manage N efficiently. This unseasonably high rainfall may partially explain the seemingly absurd results obtained during this particular experiment. Because results obtained during 1982–83 would be atypical relative to those of a normal fall–winter growing period in the low desert region of the southwestern United States, our discussion will focus on the results from the other seasons.

In Expt. 1 (1980–81), the amount of water required for optimal yield was near the upper end of our treatment range (Table 4 and Fig. 1). However, in Expts. 2, 4, 5, and 6, the amount of water required for maximum yield was at or near the 100% CU water

Fig. 1. Predicted marketable yield (Mg·ha⁻¹) contours of cabbage from six field experiments.

Table 4. Equation constants for yield response of cabbage and N recovered by cabbage to N and water in field experiments.

									Required for maximum yield	
									Water	N
									(cm)	(kg·ha ⁻¹)
Expt.	Cultivar	Equation constants						<i>R</i> ²		
		C ₀	C ₁	C ₂	C ₃	C ₄	C ₅			
<i>Marketable yield</i>										
1) 1980–81	Moran 109	−139.0	7.263	0.0598	−0.0821	−0.0010	0.00922	0.70	61	300
2) 1981–82	Moran 109	−129.9	8.437	0.1246	−0.0861	−0.003	−0.00001	0.93	49	230
3) 1982–83	Condor	156.8	−1.29	−0.255	−0.0135	−0.00019	0.0084	0.82	---	---
4) 1983–84	Condor	−386.9	10.69	0.4917	−0.0777	−0.0013	0.0054	0.84	81	356
	Headstart	−179.9	5.93	0.1378	−0.0416	−0.0005	0.0028	0.67	84	389
5) 1986–87	Condor	−107.1	2.72	0.5299	−0.0169	−0.0006	−0.00022	0.90	77	458
6) 1987–88	Headstart	−132.2	4.13	0.3430	−0.0349	−0.0004	0.00082	0.84	64	439
<i>N recovered in marketable crop</i>										
5) 1986–87	Condor	−352.9	6.91	1.52	−0.0446	−0.0028	0.000295	0.94		
<i>N not recovered in marketable crop</i>										
5) 1986–87	Condor	352.9	−6.91	−0.523	0.0446	0.00208	0.000295	0.97		

^zAll equations follow the form $\text{yield (cabbage, Mg·ha}^{-1}\text{)} = C_0 + C_1W + C_2N + C_3W^2 + C_4N^2 + C_5WN$, where C_0 through C_5 are constants and W = water (cm) and N = nitrogen (kg·ha⁻¹).

treatment. This observation is especially relevant from the standpoint of crop production in experiments 4, 5, and 6, for which the 100% CU treatment was equivalent to evapotranspiration (ET) as determined by soil water depletion.

The amounts of N predicted for maximum yield were near the upper end of the treatment range in most experiments. These rates exceeded typical cabbage N fertilizer recommendations (Doerge et al., 1991). However, we used above-average plant populations, resulting in above-average cabbage yields (Fig. 1). Cabbage yields are often 35 to 50 Mg·ha⁻¹ (Knave and Herron, 1981; Thomas et al., 1970), ≈50% of those obtained in these studies. These higher yields also resulted in an accompanying increase in plant N accumulation per unit area (Fig. 2). At irrigation and N fertilization for maximum yield, the predicted N recovered as a portion of that applied was 36% in 1987, a result that compares favorably to recoveries of N by crops reported elsewhere (Legg and Meisinger, 1982). Nevertheless, caution should be used in trying to extrapolate the results of these experiments to systems in which lower planting densities are used, such as with the standard bed culture.

The N accumulation data collected in 1987 show that the predicted amount of N recovered in the marketable crop was maximum and the predicted unaccounted-for N was minimum at 100% CU across N rates (Fig. 2). These data are similar to those for marketable yield data in that deficit and excess irrigation produced negative results. Apparently, under conditions of deficit irrigation, moisture stress restricted crop growth, resulting in reduced N uptake and lower N fertilization efficiencies. Excess irrigation is known to affect crop growth in several ways. However, on this coarse-textured soil, the major effect was probably leaching of N below the crop root zone, resulting in positional unavailability of N to the crop. This conclusion is supported by midrib analysis, which showed that N concentrations declined below published critical levels (Doerge et al., 1991) when irrigations exceeded ET replacement (Fig. 3). Further, soil samples collected after harvest in 1987–88 show that soil NO₃-N concentrations at the lowest soil depths sampled were higher when irrigations exceeded ET (Fig. 4). Overall, our results indicate that cabbage production is optimized and N losses to the environment are minimized when cabbage is irrigated for ET replacement, except perhaps where additional leaching for salinity control is needed. Under the conditions of

Fig. 2. Predicted yield (Mg·ha⁻¹) (A), N accumulation in the marketable harvest (kg·ha⁻¹) (B), and N that was applied but not recovered in the marketable harvest (kg·ha⁻¹) (C) during the 1986–87 growing season.

Fig. 3. Midrib nitrate-N concentrations at three irrigation levels during the 1983–84 growing season relative to the critical level.

Fig. 4. Residual soil nitrate-N at three irrigation levels in the 1986–87 and 1987–88 growing seasons.

Fig. 5. Residual soil nitrate-N at three N rates in the 1986-87 and 1987-88 growing seasons.

Fig. 6. Seasonal N accumulation by cabbage in the 1980-81 growing season (t = days after planting).

these studies, the slight excess irrigation during germination and the occasional rainfall event were apparently sufficient to avert detrimental salt accumulation.

Results from this study are similar to those reported by Stark et al. (1983a) for sprinkler-irrigated celery (*Apium graveolens* L.) and those reported by Letey et al. (1983) for furrow-irrigated broccoli (*Brassica oleracea* L., Botrytis group) and underscore the importance of irrigation practices on crop N use efficiency. Additional work is needed to develop practical strategies for efficient irrigation management for vegetables produced in the low desert region of the southwestern United States. Recent work has shown that climate-based irrigation scheduling models are a practical means of improving water-use efficiency for some vegetable crops (Smittle and Dickens, 1992; Smittle et al., 1990).

Results of soil samples collected after harvest show the potential for N leaching at high N rates, even where crops are irrigated for ET replacement (Fig. 5). Such leaching occurred during Expt. 6 (1987–1988) and probably resulted from two intense rainfalls that occurred during this season. While rainfall cannot be controlled, it may be possible to minimize its impact by further refining N application timing. In these experiments, N was applied once a week at similar rates. Nitrogen fertilization efficiency may be improved even further by timing application to precede the typical N uptake curve shown in Fig. 6. Additional work is needed to explore N timing strategies that minimize the impact of N leaching resulting from rainfall.

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