DIVISION S-8—NUTRIENT MANAGEMENT & SOIL & PLANT ANALYSIS

Nitrogen and Water Interactions in Subsurface Drip-Irrigated Cauliflower: I. Plant Response

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ABSTRACT

Production of cauliflower (*Brassica olearacea* L. var. *botrytis* L.) in the southwestern U.S. is highly dependent on inputs of water and N fertilizer to achieve optimum yields and quality. Subsurface drip irrigation offers what is likely the ultimate in control of the plant root zone for crop production. However, the water and N-response characteristics of subsurface drip-irrigated cauliflower have not previously been reported. Three field experiments were conducted in southern Arizona in 1993–1996. The objectives were to determine: (i) an optimum range of soil water tension for subsurface drip-irrigated cauliflower, (ii) the effects and interactions of water and N fertilizer on crop yield and quality, and (iii) seasonal and daily N uptake for high-yielding cauliflower. The experiments were randomized complete block factorial with three irrigation regimes (low, medium, high), four N rates (60–600 kg N ha^{-1}), and four replications. Irrigation was applied daily to maintain target soil water tensions and all N was applied by fertigation. With respect to marketable yield, curd weight, and curd diameter, the optimum soil water tension was approximately 10 to 12 kPa in this sandy loam soil during the 3 years. Marketable yields across all treatments ranged from <5 to >30 Mg ha^{-1}. Yields and quality were generally more responsive to N rate than to irrigation and showed significant irrigation by N rate interactions during 2 of the 3 years. At equivalent N rates, excessive irrigation generally resulted in lower yields and quality. Cauliflower accumulated up to 250 kg N ha^{-1} in the aboveground biomass and N-uptake fluxes were as high as 5 kg N ha^{-1} d^{-1} at the 12-leaf to folding growth stage.

Cauliflower production is highly dependent on inputs of irrigation water and N fertilizer to achieve optimum yields and quality in the southwestern U.S. Pronounced water × N interactions have been documented for many crops, including asparagus (*Asparagus officinalis* L.) (Roth and Gardner, 1989), broccoli (*Brassica oleracea* L. var. *italica* Plenck) (Beverly et al., 1986; Gardner and Roth, 1989a), cabbage (*Brassica oleracea* L. var. *capitata* L.) (Gardner and Roth, 1989b), cauliflower (Gardner and Roth, 1990), celery (*Apium graveolens* L.) (Feigin et al., 1982), leaf lettuce (*Lactuca sativa* L.) (Thompson and Doerge, 1996), tomato (*Lycopersicon esculentum* Mill.) (Bar-Yosef and Sagiv, 1982a, 1982b) and watermelon (*Citrullus lanatus* [Thumb.] Matsu and Nakai) (Pier and Doerge, 1995). In arid regions of the U.S., high rates of water and N input are commonly used for cauliflower production. High rates of water and N input, and rapid rates of nitrification typical of thermic and hyperthermic soils, can contribute to increased production costs and losses of water and N. Therefore, accurate guidelines for water and N management for drip-irrigated cauliflower are needed. However, management practices that increase water and N-use efficiency must also be economically feasible.

Total N uptake by cauliflower ranges from 70 to 260 kg ha^{-1} in whole plants and 40 to 125 kg ha^{-1} in the harvested portion of plants (Stivers et al., 1993). In Arizona, growers generally apply 224 to 370 kg N ha^{-1} (U.S. Department of Agriculture, 1991), although recommended amounts are somewhat lower (Doerge et al., 1991). Cauliflower is an initially slow-growing crop that takes up little N in its first 60 d of growth; 90% or more of its total N accumulation may occur during the final 50 to 60 d preceding harvest (Welch et al., 1987). Cauliflower is highly responsive to N fertilizer inputs and is rarely negatively affected by excessive N applications (Stivers et al., 1993).

Cauliflower is an important vegetable crop grown on a combined 65 000 ha in California and Arizona. It is often heavily irrigated and fertilized to meet quality standards demanded by the fresh vegetable market. Subsurface drip irrigation, when combined with regular monitoring of plant water and N status, offers what is probably the ultimate in control of water and nutrient management for crop production. However, the water and N-response characteristics of subsurface drip-irrigated cauliflower have not previously been reported. Therefore, the objectives of this study were to determine: (i) an optimum range of soil water tension for subsurface drip-irrigated cauliflower, (ii) the effects and interactions of water and N fertilizer inputs on crop yield and quality, and (iii) the seasonal patterns of N uptake by high-yielding subsurface drip-irrigated cauliflower.

MATERIALS AND METHODS

Three field experiments using subsurface drip irrigation were conducted at the University of Arizona Maricopa Agricultural Center in southern Arizona during the 1993 through 1996 winter growing seasons. The experiments were random-

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Abbreviations: DCD, degree Celcius days; HUAP, heat units after planting.

ized complete block factorial designs with three irrigation regimes (low, medium, high), four N application rates ranging from deficient to excessive, and four replications. Additionally, four replicate control plots received 120 kg P ha^{-1}, the medium irrigation regime, and no N fertilizer. A commercially important cultivar ('Candid Charm' from Sakata Seed America) of cauliflower was planted. The field used each year is mapped as a Casa Grande sandy loam (reclaimed fine-loamy, mixed, hyperthermic, Typic Natriargid). The surface (0–0.3 m) soil has a pH of 8.5 and an organic C content of 1.7 g kg^{-1}. Soil NO_3–N in the top 0.6 m was 2 to 4 mg kg^{-1} before cauliflower planting each season. The experimental area was cropped with unfertilized, flood-irrigated sudangrass (*Sorghum sudanenses* L.) for 5 mo before planting cauliflower each season to lower concentrations of available N in the root zone and reduce field variability. The aboveground biomass of the sudangrass was removed from the experimental area at least three times during each season.

Before each growing season, drip tubing (Twin-wall IV, 0.36-mm wall thickness, 0.23-m emitter spacing delivering 1×10^{-3} L s^{-1} m^{-1} at 70 kPa, Chapin Watermatics, Watertown, NY) was buried 0.15 m deep directly under the midline of north–south oriented soil beds that were 1.02 m apart. In 1993–1994 four to five leaf cauliflower plants (30 000 ha^{-1}) were transplanted by hand into the soil beds on 2 Oct. 1993. During 1994–1995 and 1995–1996, seeds were planted into dry soil using a Stanhay precision planter. Planting dates were 20 Sept. 1994 and 2 Oct. 1995. One seedline was planted along the center of each bed. Plants were thinned at the 2 to 3 leaf stage to final plant populations of 30 000 plants ha^{-1}. Plots consisted of four beds 12.2 m long. Irrigation through the drip tubing commenced after planting and uniform irrigation was continued on all plots until the stand was established (1–2 leaf stage). Water amounts used for stand establishment were 217, 181, and 311 mm for 1993–1994, 1994–1995, and 1995–1996, respectively. After stand establishment, daily irrigations were initiated by an automatic controller (Irritrol MC-6, Garden America, Carson City, NV) connected to electronic valves (UltraFlow 700 series, Hardie Irrigation, El Cajon, CA). Volumes of water applied by irrigation were monitored by duplicate in-line, propeller-type flow meters.

Tensiometers were installed in all plots shortly after germination. Tensiometers were vertically inserted adjacent to the drip tubing midway between two plants, with the porous cups positioned at a depth of 0.3 m. Tensiometer placement was similar to that in earlier studies (e.g., Pier and Doerge, 1995; Thompson and Doerge, 1996) and was based on observations that the maximum density of cauliflower roots under subsurface drip irrigation is at a depth of 15 to 40 cm surrounding the tubing (T. Thompson, unpublished data, 1996). Soil water tensions were measured two or more times per week using a Tensicorder (Soil Measurement Systems, Tucson, AZ) as described by Marthaler et al. (1983).

Irrigation was applied daily to maintain target soil water tensions, except when rainfall or cool weather made irrigation unnecessary. Target and average seasonal soil water tensions, and total postestablishment irrigation and rainfall amounts, for the low, medium, and high irrigation treatments are shown in Table 1. The target soil water tensions were intended to supply moisture over the range from deficient to excessive. All N fertilizer was supplied as a solution of urea–ammonium nitrate (320 g N kg^{-1}), injected directly into the irrigation water using venturi-type injectors (Performance Products, Coolidge, AZ). The split N applications were scheduled to occur at approximately 3-wk intervals (Table 2). Phosphorus (120 kg P ha^{-1}) was broadcast-applied as granular triple superphosphate before planting each season and incorporated into soil beds.

Table 1. Target and actual soil water tension (SWT) and amounts of water applied to 'Candid Charm' cauliflower during the 1993–1996 winter growing seasons.

Season	Irrigation treatment	Target SWT	Average SWT†	Water applied‡
		kPa		mm
1993–94	Low	12	17.5	350
	Medium	7	7.8	400
	High	4	4.2	781
1994–95	Low	20	12.6	167
	Medium	12	9.4	199
	High	4	4.0	573
1995–96	Low	20	23.2	122
	Medium	10	10.0	211
	High	4	4.0	450

† Average soil water tension measured two or more times per week at 30-cm depth.
‡ Sum of precipitation and postestablishment irrigation.

All other plant nutrients were present in adequate amounts, as indicated by preplant soil tests. During each of the 3 yr, the insecticides acephate (O,S-dimethylacetylphosphoroamidothioate) and imidacloprid [1-((6-chloro-3-pyridinyl)-methyl)-4,5-dihydro-N-nitro-1H-imidazol-2-amine] were applied as needed at labeled rates during early season growth. Weed control was accomplished by hand hoeing.

During each growing season, aboveground portions of cauliflower plants were collected from 1-m^2 sections of one of the two center beds of plots receiving the medium irrigation treatment and the 300 to 340 kg N ha^{-1} treatment. Sampling dates, growth stages, and heat unit accumulations are shown in Table 3. Samples were dried at 65°C in a forced-air oven for determination of dry matter accumulation. Dried plant samples were then ground to pass a 40-mesh sieve and total N was determined by the micro-Kjeldahl method modified to recover NO_3^- (Bremner and Mulvaney, 1982). At the end of each growing season, cauliflower heads were harvested from 3-m^2 sections within each plot when plants were at harvestable size. Heads were trimmed to "U.S. No.1" specifications for cauliflower (USDA, 1968) and individually graded for diameter, weight, riciness, discoloration, hollow stem, and green stem. Harvest dates were 21 Jan. to 2 Feb. 1994, 25 Jan. to 2 Feb. 1995, and 9 Feb. to 19 Feb. 1996. Seasonal rainfall amounts for the three growing seasons were 87, 132, and 52

Table 2. Nitrogen fertilizer applications made to 'Candid Charm' cauliflower during the 1993–1996 winter growing seasons.

Season	DAT/DAP†	N1	N2	N3	N4
		kg ha^{-1}			
1993–94	5	0	55	70	85
	24	20	60	60	90
	47	20	80	80	160
	66	20	105	180	190
	82	0	40	60	75
	Total	60	340	450	600
1994–95	23	0	20	40	60
	49	20	40	60	100
	63	30	50	80	150
	88	40	60	70	120
	112	10	30	50	70
	Total	100	200	300	500
1995–96	22	0	20	40	60
	50	20	40	60	100
	72	30	50	80	150
	93	40	60	70	120
	115	10	30	50	70
	Total	100	200	300	500

† DAT = days after transplanting (1993–1994 season); DAP = days after planting (1994–1995 and 1995–1996 seasons).

Table 3. Sampling events for whole plant samples.

Season	Date	DAT/DAP†	HUAT/HUAP‡	Growth stage
1993–94	10/26/93	24	374	6–8 leaf
	11/2/93	31	448	10 leaf
	12/2/93	61	661	12 leaf
	12/20/93	79	749	2–3 cm buds
	1/28/94	118	950	Harvest
1994–95	11/4/94	45	629	5–6 leaf
	11/22/94	63	738	8.5 leaf
	12/13/94	84	848	12 leaf
	1/5/95	107	970	4–7 cm buds
	2/2/95	135	1104	Harvest
1995–96	11/21/95	50	616	5–6 leaf
	12/7/95	66	750	9 leaf
	12/23/95	82	829	12 leaf
	1/25/96	115	993	2.5–5 cm buds
	2/14/96	135	1161	Harvest

† DAT = days after transplanting (1993–1994); DAP = days after planting (1994–1995 and 1995–1996).
‡ HUAT = heat units (degree Celcius days) after transplanting (1993–1994); HUAP = heat units after planting (1994–1995 and 1995–1996).

mm, respectively; seasonal reference crop evapotranspiration amounts were 348, 371, and 434 mm, respectively.

Seasonal crop N-uptake patterns were derived from the whole-plant sample data obtained during each season. Nitrogen uptake was calculated as the product of the crop biomass (dry wt.) and the N concentrations in plant material for each of the whole-plant sampling dates throughout the season. Smoothed cumulative N-uptake curves were constructed using cubic splines (Burden et al., 1981). The cubic spline functions were then differentiated and plotted to define trends in daily N uptake (flux) (Crawford et al., 1982; Karlen et al., 1988). By definition, the cubic spline function passes through each data point. Analysis of variance procedures was accomplished using the SAS statistical procedure PROC GLM. The response surfaces were derived using the SAS regression procedure PROC RSREG (SAS Inst., 1988).

RESULTS AND DISCUSSION

The seasonal average soil water tensions were generally close to the target tensions (Table 1). However, the low irrigation treatment in 1993–1994 was drier than the target tension because of the dry weather conditions during this season. Similarly, low treatment during the 1994–1995 season was wetter than expected because of unusually wet conditions. Amounts of applied water were greatest during the 1993–1994 season, mostly because warm and windy conditions at the time of cauliflower transplanting necessitated more irrigation than normal (cauliflower is particularly sensitive to moisture stress soon after transplanting [Stivers et al., 1993]).

To estimate an optimum range for soil water tension, data for marketable yield, curd weight, and curd diameter were normalized for each season. Normalization was accomplished by expressing each plot response as a percentage relative to the highest average treatment response for that variable in that year. The 3 yr of normalized data were then fitted to response surfaces (Fig. 1). The predicted maximum response for each normalized variable is indicated by the intersections of the arrows on Fig. 1. All three measurements were responsive to N rate, but marketable yield was more responsive to

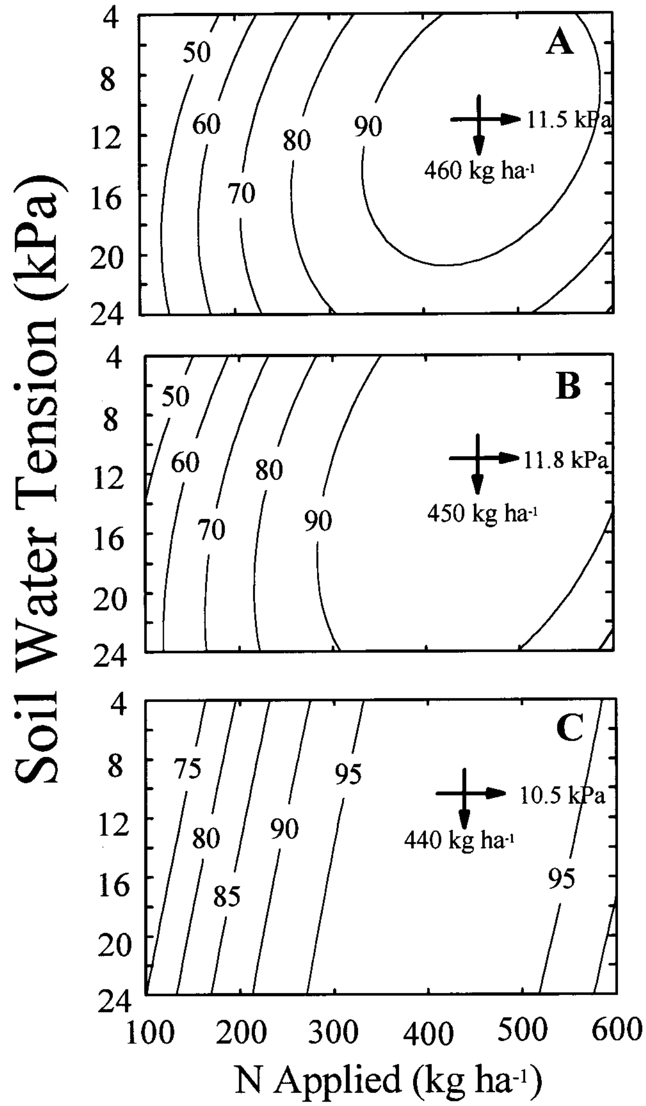

Fig. 1. Normalized yield response variables for cauliflower, 1993–1996 growing seasons. Contour lines represent relative response (%), SWT is soil water tension (kPa), N = N rate (kg ha^{-1}). The intersection of the arrows indicates the point of maximum predicted response. (A) Relative yield = $-28 + 3.58 \times SWT + 0.45 \times N - 0.083 \times SWT^2 - 0.0036 \times N \times SWT - 0.0004 \times N^2$, model R^2 = 0.75; (B) relative curd weight = $-13 + 2.91 \times SWT + 0.42 \times N - 0.054 \times SWT^2 - 0.0036 \times N \times SWT - 0.0004 \times N^2$, model R^2 = 0.70; (C) relative curd diameter = $37 + 0.75 \times SWT + 0.27 \times N + 0.003 \times SWT^2 - 0.0017 \times N \times SWT - 0.0003 \times N^2$, model R^2 = 0.78.

soil water tension differences than were curd weight and diameter.

The optima for normalized marketable yield, curd weight, and curd diameter for these three seasons each fell within a soil water tension range of 10 to 12 kPa, although yield was apparently more sensitive to differences in soil water tension than were the quality parameters. Therefore, this range of values can be designated as an approximate *optimum* soil water tension range for subsurface drip-irrigated cauliflower. Depending on the year, maximum yields were observed at soil water tensions ranging from 4 to 17.5 kPa during this study (Table

4). Therefore, further study may be needed, with larger extremes in soil water tensions, to more precisely define an optimum value for subsurface drip-irrigated cauliflower.

The optimum soil water tension value of 10 to 12 kPa compares favorably to the optimum tension values reported for some other subsurface drip-irrigated crops. For example, Pier and Doerge (1995) reported an optimum soil water tension of 7 kPa for watermelon. Thompson and Doerge (1995a, 1995b, 1996) reported optimum values of >6.5 kPa for romaine lettuce, 6 to 10 kPa for collard (*Brassica oleracea* L. var. *acephala* DC., p.p.), mustard (*Brassica juncea* [L.] Czerniak), and spinach (*Spinacea oleracea* L.), and 6 kPa for leaf lettuce in a sandy loam soil. Feigin et al. (1982) reported that subsurface drip irrigated celery produced the greatest yield when soil water tension in the root zone was maintained at 7 kPa. Smajstrla and Locascio (1996) found that tomato yields decreased when soil water tension was maintained at 15 or 20 kPa, compared to an average tension of 10 kPa. Phene and Beale (1976) reported an optimum soil water tension of 20 kPa for sweet corn (*Zea mays* L.) grown on a sandy soil in the southeastern U.S. The soil used in this study was sandy loam in texture. It is reasonable to assume that the optimum tension for subsurface drip-irrigated cauliflower may be lower than 10 to 12 kPa in very coarse-textured soils, and somewhat greater than 10 to 12 kPa in fine-textured soils.

During the second and third seasons, ≈200 mm of irrigation plus rainfall were applied to the medium treatments after stand establishment. We applied significantly more water to the transplanted cauliflower during the first season. In comparison, Erie et al. (1981) reported a seasonal consumptive use of 470 mm by furrow-irrigated cauliflower grown in southern Arizona. Our results illustrate the more efficient water delivery that is possible with subsurface drip irrigation. The allowable depletion of soil water for furrow- or sprinkler irrigated cauliflower has been reported as 34 to 45% (Stivers et al., 1993). Our results suggest, however, that these numbers are not transferable to subsurface drip-irrigated cauliflower. Our optimum soil water tension range (10–12 kPa) corresponds approximately to the normally accepted value for *field capacity*, and therefore would represent 0% depletion of available soil water. Use of allowable depletion thresholds would have resulted in significant yield losses in our experiment.

Total and marketable yield, and curd weight and diameter, were generally more responsive to N applications than to soil water tension within the range of these treatments (Table 4). Cauliflower is highly responsive to N, but application of excessive rates of N rarely negatively affects quality (Stivers et al., 1993). In addition to curd diameter and weight, we measured other quality parameters including riciness, discoloration, hollow stem, and green stem. Except for curd diameter and weight, quality parameters were generally not affected by N or irrigation treatments, except in the control plots. There was no marketable yield in the control plots. Except at the lowest N rate, this variety showed excellent yield and quality across a wide range of N × water treatments during all three seasons.

Table 4. Total yield, marketable yield, curd weight, and curd diameter for cauliflower, 1993–1996.

Season	Irrigation treatment†	N treatment	Total yield	Marketable yield	Curd weight	Curd diameter
	kPa	kg ha^{-1}	Mg ha^{-1}		kg	cm
1993–94	17.5	60	7.0	4.6	0.34	10.7
		340	32.6	32.6	1.05	18.4
		450	29.3	28.5	1.03	18.4
		600	33.5	33.5	1.11	19.2
	7.8	60	7.4	4.5	0.34	10.4
		340	26.9	26.9	1.01	18.0
		450	29.3	29.3	0.98	17.9
		600	32.1	32.1	1.05	18.1
	4.2	60	7.0	5.1	0.29	10.6
		340	26.1	26.1	0.92	17.3
		450	25.7	25.7	1.00	18.1
		600	31.2	31.0	1.10	18.7
1994–95	12.6	100	5.6	5.6	0.15	8.3
		200	18.3	18.3	0.68	16.3
		300	24.7	24.7	0.73	17.1
		500	22.1	22.1	0.72	17.3
	9.4	100	5.7	5.7	0.20	10.1
		200	18.0	18.0	0.60	16.1
		300	24.0	24.0	0.65	16.6
		500	21.0	21.0	0.72	17.1
	4.0	100	5.5	5.5	0.19	9.9
		200	12.9	12.9	0.35	12.1
		300	16.8	16.8	0.62	16.1
		500	24.1	24.1	0.73	17.3
1995–96	23.2	100	14.1	13.4	0.44	13.2
		200	20.6	18.4	0.60	15.0
		300	17.5	16.4	0.53	14.2
		500	21.3	17.5	0.54	14.5
	10.0	100	12.8	11.2	0.36	12.7
		200	23.7	21.3	0.65	15.2
		300	21.5	19.9	0.63	15.2
		500	19.7	19.0	0.52	14.0
	4.0	100	11.2	8.0	0.32	11.7
		200	18.4	16.4	0.53	14.5
		300	20.2	19.5	0.62	15.2
		500	24.4	24.4	0.67	16.0

† Average soil water tension measured two or more times per week before irrigation.

Marketable yields were highest during 1993–1994, largely because the crop was harvested at a more mature stage than during the subsequent seasons. During 1993–1994 maximum marketable yields were achieved at 17.5 kPa and 600 kg N ha^{-1}; during 1994–1995 at 12.6 kPa and 300 kg N ha^{-1}; and during 1995–1996 at 4.0 kPa and 500 kg N ha^{-1}. These N rates are higher than the rates currently recommended for cauliflower grown in Arizona (Doerge et al., 1991) and are likely higher than would be needed in a normal production situation, because in our experiments we exhaustively cropped the soil each summer to minimize residual available N. Within an irrigation treatment, the N rate needed to achieve maximum yield was usually highest in the high treatment, probably because of the effects of N loss by leaching and/or denitrification. Ryden and Lund (1980) observed considerable denitrification losses from surface drip-irrigated vegetables. They hypothesized that the high water and N inputs commonly used for vegetables created conditions conducive to denitrification.

There were significant soil water tension × N rate interactions for all yield parameters during 1994–1995, and for marketable yield and curd weight during 1995–1996 (Table 5). For example, during 1994–1995, yields were lower at the 500 kg N ha^{-1} rate than at the 300 kg

Table 5. Analysis of variance summary for total biomass, marketable yield, curd weight, and curd diameter as affected by N rate (N) and average soil water tension (SWT).

Season	Source	df	Total yield	Marketable yield	Curd weight	Curd diameter
1993–94	Replication	3	NS	NS	NS	NS
	N	3	**	**	**	**
	SWT	2	NS	NS	NS	NS
	N × SWT	6	NS	NS	NS	NS
	Error	33				
	CV%		14	15	14	6
1994–95	Replication	3	NS	NS	NS	NS
	N	3	**	**	**	**
	SWT	2	**	**	*	NS
	N × SWT	6	**	**	*	**
	Error	33				
	CV%		2	8	21	10
1995–96	Replication	3	NS	NS	NS	NS
	N	3	**	**	**	**
	SWT	2	NS	NS	NS	NS
	N × SWT	6	NS	*	*	NS
	Error	33				
	CV%		17	20	18	9

*,** Significant at $P \leq 0.05$ and 0.01, respectively; NS, not significant.

ha^{-1} rate in the low and medium irrigation treatments, perhaps because of an adverse effect of excessive N on yields. However, in the high irrigation treatment the highest yields were achieved at 500 kg N ha^{-1} (Table 4). High marketable yields were often achieved in the high irrigation treatment, but always at the highest N rate.

The N uptake by plants in plots receiving the medium irrigation treatment and the 300 to 340 kg N ha^{-1} treatment (Table 2) was determined five times during each growing season (Table 3). As much as 250 kg N ha^{-1} were accumulated in the aboveground biomass in these plots (Fig. 2A). The greatest N accumulation was observed in 1993–1994 because the plants were harvested at a more mature stage than in subsequent years. The N-uptake patterns were similar during 1994–1995 and 1995–1996, when the crops were direct-seeded. Cauliflower in the 1994–1995 and 1995–1996 seasons showed very little N uptake during the first 40 d after planting. Welch et al. (1987) reported a similar pattern of N uptake for furrow-irrigated cauliflower grown in California. The transplanted cauliflower grown during 1993–1994 took up significant amounts of N about 25 to 30 d sooner than the subsequent direct-seeded crops.

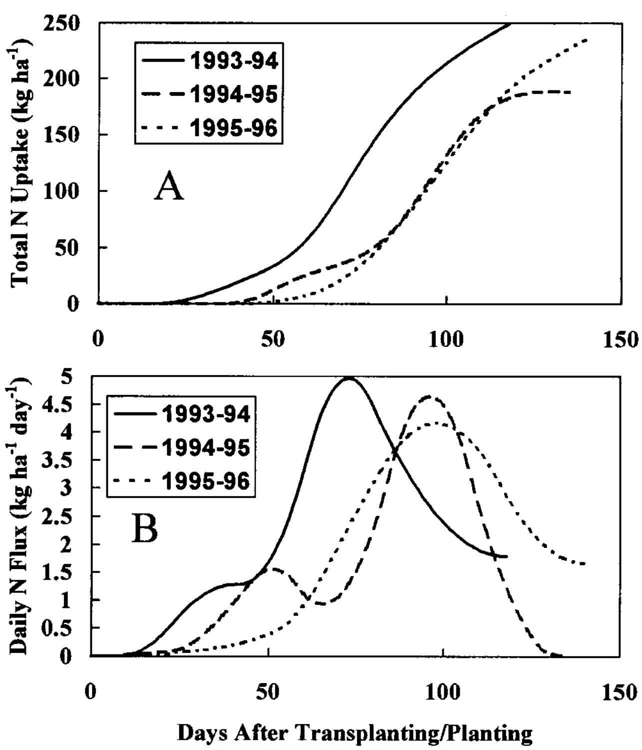

Fig. 2. Nitrogen accumulations for cauliflower receiving the medium irrigation treatment and 340 kg N ha^{-1} (1993–1994) or 300 kg N ha^{-1} (1994–1995 and 1995–1996). (A) Cumulative N uptake; (B) daily N flux.

The N in the aboveground biomass of cauliflower generally ranges from 40 to 263 kg N ha^{-1} (Stivers et al., 1993). During the 3 yr of this study an average of 29.4% of all aboveground plant N was contained in the harvested portion (data not shown). Stivers et al. (1993) reported that 26 to 34% of aboveground N was contained in the harvested portion in previous research. Therefore, a high-yielding cauliflower crop may be expected to return as much as 175 kg N ha^{-1} to the soil after harvest.

Daily N uptake rates as high as 5 kg ha^{-1} d^{-1} were observed in this study (Fig. 2B). This compares to 7 to 8 kg ha^{-1} d^{-1} reported by Doerge et al. (1991) for sprinkler-irrigated cauliflower at 55 000 plants ha^{-1}, versus 30 000 plants ha^{-1} in this study. The N-flux curve for the 1993–1994 season shows a more rapid initiation of N uptake because the cauliflower was transplanted at the 5 to 6 leaf stage during this season. The curves for the 1994–1995 and 1995–1996 seasons were relatively similar, although there was a dip in N flux between 50 and 60 days after planting (DAP) during 1994–1995. Karlen et al. (1987) pointed out that such a pause in the flux curve can be caused by errors in data or to environmental influences. During this period, there were several days when heat unit accumulations averaged 5 DCD d^{-1} and temperatures <-3°C were experienced. These low temperatures probably slowed plant growth and N uptake, which is reflected in the N-flux curves. During all three seasons the maximum N-flux rate was 4.1 to 5.0 kg N ha^{-1} d^{-1}. The maximum N flux occurred at the 12-leaf to folding growth stages. During the 1994–1995 and 1995–1996 seasons this corresponded to ≈900 HUAP (heat units after planting).

This pattern of N uptake illustrates the management challenge posed by cauliflower production. An adequate supply of N is required all season. However, preplant or early-season applications of N are likely to be inefficiently used. The use of subsurface drip irrigation with fertigation guided by preplant soil testing and plant N tissue testing (Gardner and Roth, 1990; Doerge et al., 1991; Kubota et al., 1996) can help maximize N fertilizer-use efficiency. Other researchers have recommended splitting N applications to cauliflower in order to match N supply to crop needs (Hochmuth et al., 1991;

Tyler and Lorenz, 1991). Hochmuth (1992) recommended a maximum N application rate of 2.8 kg ha^{-1} d^{-1} to drip-irrigated cauliflower grown in Florida.

CONCLUSIONS

The response of subsurface drip-irrigated cauliflower to water and N inputs was examined during three field experiments in southern Arizona. Response-surface analysis of normalized data suggested that optimum soil water tension, with respect to crop yield and quality, was approximately 10 to 12 kPa. However, during this 3-yr study yield losses were more common due to excessive irrigation rather than deficient irrigation. This optimum soil water tension is comparable to values reported for other crops. Maintaining soil water tension near this level, along with appropriate split applications of N fertilizer, should result in acceptable yield and quality. Marketable yield and quality showed irrigation treatment × N rate interactions during 2 of the 3 yr. In these 2 yr higher rates of N were needed to maximize yields when excessive amounts of irrigation water were applied. Cauliflower accumulated up to 250 kg N ha^{-1} in the aboveground biomass. Very little N uptake occurred prior to 40 d after planting. Nitrogen-uptake fluxes were as high as 5 kg N ha^{-1} d^{-1} and peaked ≈100 d after planting (approximately the 12-leaf to folding growth stage or 900 HUAP) for direct-seeded cauliflower.

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