Subsurface Drip Irrigation and Fertigation of Broccoli: I. Yield, Quality, and Nitrogen Uptake

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ABSTRACT

Production of broccoli (*Brassica olearacea* L. *Italica*) in the southwestern USA is highly dependent on inputs of water and N fertilizer to achieve optimum yields and quality. The water and N-response characteristics of subsurface drip-irrigated broccoli have not previously been reported. Field experiments were conducted in southern Arizona during 1993 through 1996. The objectives were to determine: (i) subsurface drip-irrigated broccoli response to a range of soil water tension (SWT), (ii) effects and interactions of water and N fertilizer inputs on crop yield and quality, and (iii) seasonal and daily N uptake. Experiments consisted of factorial combinations of three irrigation regimes (low, medium, and high) and four N rates (60–500 kg N ha^{-1}). Irrigation was applied daily to maintain target SWT, and all N was applied by fertigation. With respect to marketable yield, the optimum SWT was ~10 kPa in this sandy loam soil, as indicated by response surface models. Marketable yields across all treatments ranged from <3 to >18 Mg ha^{-1}. Marketable yield was significantly affected by N rate during all three seasons, and by SWT during two of three seasons. There were no significant SWT × N interactions for marketable yield. Quality parameters (head weight and diameter) were much more responsive to N rate than to SWT, and there were few significant SWT × N interactions for broccoli quality. Broccoli accumulated up to 320 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 first bud growth stage (825–1000 heat units after planting [HUAP]).

Water and N-response characteristics have been documented simultaneously for only a few drip-irrigated crops. Pier and Doerge (1995) determined water and N response for watermelon (*Citrullus lanatus* [Thunb.] Matsu and Nakai), and found that yield was maximized when SWT in the root zone was maintained at an average of 7 kPa. Thompson and Doerge (1995a, 1995b, 1996) have reported that yields of drip-irrigated mustard [*Brassica juncea* (L.) Czern.], spinach (*Spinacea oleracea* L.), collards (*Brassica oleracea* L. Acephela), romaine lettuce (*Lactuca sativa* L.), and leaf lettuce were maximized when SWTs were maintained at an average of 6 to 10 kPa. Phene and Beale (1976) found that sweet corn (*Zea mays* L.) yields were maximized with automated high frequency drip irrigation and maintaining root-zone SWT no >20 kPa. Thompson et al. (2000) reported that yield of drip-irrigated cauliflower (*Brassica olearacea* L. botrytis) was maximized when SWT was maintained at an average of 10 to 12 kPa. Approaches used to establish schedules for drip irrigation include estimates based on evapotranspiration (Bar-Yosef and Sagiv, 1982; McNeish et al., 1985; Clough et al., 1990; Hartz, 1993), allowable soil-water depletion (Bogle et al., 1989), and target SWT. There are several advantages of using tensiometer feedback for drip-irrigation scheduling; these are discussed by Pier and Doerge (1995). Camp et al. (1993) applied irrigation to subsurface drip-irrigated broccoli when SWT reached a threshold of 30 kPa, but included no other SWT values in their experiment. To date, subsurface drip-irrigated broccoli response to variations in SWT has not been reported.

Nitrogen uptake by broccoli typically ranges from 150 to 280 kg ha^{-1} (Doerge et al., 1991; Stivers et al., 1993). Rates of N used by western broccoli growers may be as high as 400 kg ha^{-1} (Stivers et al., 1993). Broccoli heads typically account for 10 to 45% of the N taken up by the crop. Broccoli is a rapidly-growing crop that takes up little N in its first 40 d of growth, and 90% or more of its total N accumulation may occur during the final 30 to 50 d preceding harvest (Doerge et al., 1991). Broccoli is highly responsive to N fertilizer inputs, and excessive N inputs can result in decreased quality from hollow stem (Stivers et al., 1993).

In arid regions of the USA, high rates of water and N inputs are commonly used for broccoli production. High rates of water and N inputs, and rapid rates of nitrification typical of thermic and hyperthermic soils, can contribute to increased production costs and losses of water and N. Subsurface drip irrigation can be a highly efficient delivery system for N fertilizers. However, accurate guidelines for water and N management for drip-irrigated broccoli are needed.

The objectives of these experiments were to determine: (i) subsurface drip-irrigated broccoli response to a range of SWT, (ii) the effects and interactions of water and N fertilizer inputs on crop yield and quality, and (iii) seasonal patterns of N uptake.

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 randomized complete block factorial designs with three irrigation regimes (low, medium, and high; Table 1), and four N-application rates ranging from deficient to excessive (Table 2). An additional control treatment received no N fertilizer and the medium irrigation treatment. Each treatment was replicated four times. The soil is a Casa Grande sandy loam [reclaimed fine-loamy, mixed, superactive, 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

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Abbreviations: DAP, days after planting; DCD, degree C days; HUAP, heat units after planting; SWT, soil water tension.

Table 1. Target and actual soil water tensions (SWTs), and amounts of water applied to 'Claudia' broccoli during the 1993 to 1996 winter growing seasons.

Season	Irrigation treatment	Target SWT	Average SWT†	Water applied‡
		kPa		mm
1993–1994	Low	12	15.6	226
	Medium	7	6.8	475
	High	4	4.2	728
1994–1995	Low	12	13.4	187
	Medium	7	11.5	200
	High	4	3.7	489
1995–1996	Low	20	25.0	150
	Medium	10	12.3	220
	High	4	4.0	440

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

4 mg kg^{-1} before broccoli planting each season. The experimental area was cropped with unfertilized, flood irrigated sudangrass [*Sorghum sudanenses* (Piper) Stapf] for 5 mo before planting of broccoli 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. The soil beds were 1.0 m apart and ~50 cm wide at the top. A commercially important broccoli cultivar (Claudia) was planted. Two seedlines per bed (25 cm apart) were planted into dry soil using a Stanhay precision planter (Stanhay Webb Co., Suffolk, England). Planting dates were 13 Sep. 1993, 16 Sep. 1994, and 26 Sep. 1995. Plants were thinned at the 2 to 3 leaf stage to final plant populations of 100 000 plants ha^{-1}. Plots consisted of four beds 12.2 m long. Drip irrigation was commenced after planting and uniform irrigation was continued on all plots until the stand was established (1–2 leaf stage). Water amounts used for germination and stand establishment were 320, 314, and 310 mm for 1993, 1994, and 1995, 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 inline 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 broccoli roots under subsurface drip irrigation is at a depth of 15 to 40 cm surrounding the tubing (T. Thompson, unpublished data, 1995). Soil water tensions were measured in the morning, before irrigation, 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 SWTs, except when rainfall or cool weather made irrigation unnecessary. Changes in irrigation scheduling were determined empirically based upon deviations of daily SWT from target SWT. Target and average seasonal SWTs, and total postestablishment irrigation and rainfall amounts for the low, medium, and high irrigation treatments are shown in Table 1. The target SWTs

Table 2. Nitrogen-fertilizer applications made to 'Claudia' broccoli during the 1993 to 1996 winter growing seasons.

Season	DAP†	HUAP‡	Nitrogen rate treatment 1	2	3	4
			kg N ha^{-1}			
1993–1994	22	383	0	55	70	85
	43	683	20	0	80	135
	64	861	20	125	80	150
	92	1036	20	60	120	130
	Total		60	240	350	500
1994–1995	23	384	0	20	40	60
	49	659	20	40	60	90
	70	777	50	80	110	210
	94	902	30	60	90	140
	Total		100	200	300	500
1995–1996	22	324	0	20	40	60
	43	541	20	40	60	90
	66	750	50	80	110	210
	93	875	30	60	90	140
	Total		100	200	300	500

† DAP = days after planting.
‡ HUAP = heat units (degree C days) after planting.

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, Inc., Coolidge, AZ). The N applications were scheduled at ~3 wk intervals (Table 2). Phosphorus (120 kg P ha^{-1}) was broadcast-applied as granular triple superphosphate before planting each season, and was incorporated into soil beds. All other plant nutrients were present in adequate amounts. During each of the 3 yr, insecticides (acephate ['Orthene'] and imidacloprid ['Admire']) were applied as needed at labeled rates during early season growth, and weed control was accomplished by hand hoeing.

During the 1993–1994 and 1995–1996 growing seasons, aboveground portions of the plants were collected from 1-m^2 sections of one of the two center beds of plots receiving the medium irrigation treatment and 350 kg N ha^{-1} (1993–1994) or 300 kg N ha^{-1} (1995–1996) four or five times per season. Sampling dates, growth stages, and heat unit accumulations are shown in Table 3. Samples were dried at 65°C in a forced-air oven and dry matter content was calculated. Dried plant samples were then ground to <0.6 mm 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, broccoli heads were harvested from a 3-m^2 section of each plot when plants were at harvestable size. Heads were trimmed to 'U.S. Fancy' specifications for broccoli (USDA, 1943) and individually graded for diameter, weight, discoloration, and hollow stem. Harvest dates were 6 Jan. to 20 Jan. 1994, 5 Jan. to 20 Jan. 1995, and 25 Jan. to 6 Feb. 1996.

Nitrogen uptake was calculated as the product of the crop biomass (dry weight) and the N concentrations in plant mate-

Table 3. Sampling events for whole plant samples.

Season	Date	DAP†	HUAP‡	Growth stage
1993–1994	26 Oct. 1993	43	683	6 leaf
	4 Nov. 1993	52	777	7–8 leaf
	23 Nov. 1993	71	917	12 leaf
	7 Dec. 1993	85	999	1-cm buds
	20 Jan. 1994	129	1217	Harvest
1995–1996	9 Nov. 1995	38	488	4–5 leaf
	1 Dec. 1995	60	700	9–10 leaf
	21 Dec. 1995	80	824	First buds
	9 Jan. 1996	99	909	Preharvest

† DAP = days after planting.
‡ HUAP = heat units (degree C days) after planting.

Table 4. Yield, quality, and N uptake for broccoli, 1993 to 1996.

Season	Irrigation treatment†	N treatment	Marketable yield	Head weight	Head diameter	Biomass N
	kPa	kg ha^{-1}	Mg ha^{-1}	g	cm	kg ha^{-1}
1993–1994	15.6	60	2.7	41	4.0	70
		240	9.9	109	7.4	210
		250	11.1	127	8.5	238
		500	11.1	131	8.8	295
	6.8	60	3.9	56	5.3	66
		240	9.8	109	7.3	208
		350	12.3	130	8.6	277
		500	13.0	131	8.8	320
	4.2	60	3.3	66	5.7	60
		240	9.4	107	7.8	138
		350	11.8	123	8.5	240
		500	9.5	115	8.2	217
1994–1995	13.4	100	9.4	99	6.6	92
		200	14.5	156	10.5	160
		300	17.1	180	11.4	183
		500	18.8	200	12.4	169
	11.5	100	9.7	89	6.5	115
		200	15.6	171	11.6	151
		300	17.4	188	12.1	172
		500	18.9	215	13.2	236
	3.7	100	8.7	95	6.9	92
		200	13.1	140	9.6	111
		300	15.7	172	11.6	172
		500	16.9	184	12.1	186
1995–1996	25.0	100	1.9	77	6.6	106
		200	8.0	107	7.5	196
		300	9.7	120	7.8	258
		500	9.6	111	7.3	301
	12.3	100	0.9	68	6.0	116
		200	8.6	112	7.8	206
		300	10.4	120	8.0	275
		500	10.6	123	7.8	300
	4.0	100	1.7	68	6.0	90
		200	7.5	92	6.9	168
		300	10.3	117	7.9	251
		500	10.2	125	8.4	264

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

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

Season	Source	df	Marketable yield	Head weight	Head diameter	Biomass N
1993–1994	Rep	3	**	NS†	NS	NS
	N	3	**	**	**	**
	SWT	2	**	NS	NS	**
	N × SWT	6	NS	NS	NS	**
	Error	33				
	CV%‡		13	14	13	10
1994–1995	Rep	3	NS	NS	NS	NS
	N	3	**	**	**	**
	SWT	2	**	NS	*	**
	N × SWT	6	NS	NS	NS	**
	Error	33				
	CV%		7	29	8	7
1995–1996	Rep	3	*	*	*	NS
	N	3	**	**	**	**
	SWT	2	NS	NS	NS	*
	N × SWT	6	NS	NS	*	*
	Error	33				
	CV%		17	13	22	14

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† NS, not significant.
‡ CV represents coefficient of variation.

rial at each plant sampling date. Smoothed cumulative N uptake curves were constructed for each season 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).

Response surfaces for marketable yield, head diameter, head weight, and biomass N were derived for each season using the SAS procedure RSREG (SAS Institute, 1988), which fits a two-variable quadratic response model. This procedure also allows for determination of critical values on the response surface, such as maxima and minima, if they exist. The general model for each dependent variable was:

$$\text{Response} = \text{Intercept} + \beta_1 N + \beta_2 N^2 + \beta_3 \text{SWT} + \beta_4 \text{SWT}^2 + \beta_5 N \times \text{SWT} \quad [1]$$

where N is N fertilizer applied (kg ha^{-1}), and SWT is mean soil water tension (kPa). Twelve response surface models (year by variable combinations) were generated in this manner. In most cases, the lack-of-fit statistic for the model was not significant ($P < 0.1$), thus indicating that the fit of the model was adequate and no higher-order terms were needed to improve the fit of the model. In such cases, the full quadratic model was retained and plotted as a response surface. In three cases (1993–1994 biomass N, 1994–1995 head diameter, 1994–1995 biomass N) the lack-of-fit statistic was significant ($P < 0.1$). In these cases, higher-order terms ($N^2 \times$ SWT, SWT$^2 \times N$, N^3) were added to the base model using the SAS procedure SAS REG. These additional terms were retained if they were significant at $P < 0.5$.

RESULTS AND DISCUSSION

Seasonal rainfall amounts were 81, 115, and 51 mm, and seasonal reference crop evapotranspiration amounts were 427, 346, and 395 mm for the three growing seasons, respectively. During each season, average SWTs were generally close to target values. The target SWTs were changed during 1995–1996 to encompass a wider range of soil moisture availability (Table 1). Irrigation plus rainfall amounts applied during 1993–1994 after establishment were generally greater than in the other seasons. This likely reflects the high reference crop evapotranspiration (427 mm) during this season.

Treatment means and summary statistics for marketable yield, head weight, head diameter, and biomass N are presented in Tables 4 and 5. However, treatments effects are most readily illustrated using response surfaces (Fig. 1). With the exception of head weight during the 1994–1995 season, model R^2 values were >0.69 (Table 6). For all models shown in Table 6, F values were significant at $P < 0.001$. The crosshairs shown on five of the response surfaces in Fig. 1 illustrate cases in which a predicted maximum response occurred within the range of the treatments. Response surfaces without crosshairs did not have predicted maxima within the range of the treatments. The predicted maximum marketable yield was within the range of the treatments, and occurred at 9 to 10 kPa SWT during each season. Therefore, we can designate 10 kPa as an approximate optimum SWT for subsurface drip-irrigated broccoli in this sandy loam soil. However, because of the lack of large yield depressions at tensions greater or less than 10 kPa, experiments using a wider range of SWT may be needed to more precisely define the optimum SWT.

This optimum SWT of 10 kPa compares favorably with optimum values for other crops. For example, Thompson et al. (2000) reported that subsurface drip-irrigated cauliflower response was maximized at a SWT

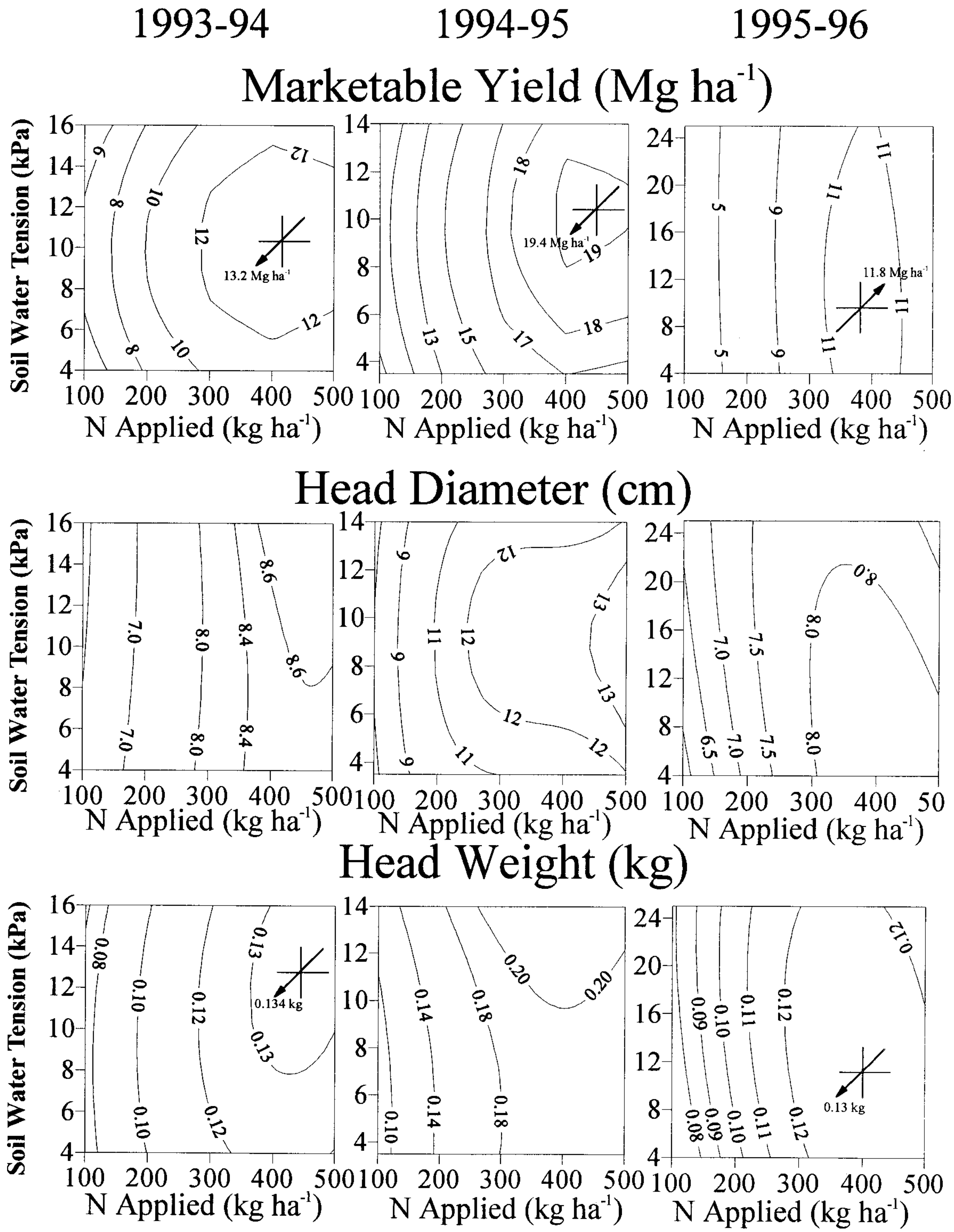

Fig. 1. Response surfaces for marketable yield, head diameter, and head weight. Response surface equations are given in Table 6. Where response surface maxima occurred within the range of the treatments, this point is indicated by a crosshair. The arrow denotes the predicted maximum response at the optimum.

of 10 to 12 kPa. Thompson and Doerge (1995a,b, 1996) have reported that yields of drip-irrigated mustard, spinach, collards, romaine lettuce, and leaf lettuce were maximized at SWTs of 6 to 10 kPa. Bar-Yosef and Sagiv (1982) reported that subsurface drip-irrigated tomato (*Lycopersicon esulentum* Mill.) yields decreased when SWT increased from 5 to 15 kPa. Phene and Beale (1976) found that sweet corn yields were maximized with root-zone SWTs no greater than 20 kPa. Feigin et al. (1982) reported that subsurface drip-irrigated celery (*Apium graveolens* L.) produced the greatest yield when SWT in the root zone was maintained at 7 kPa. Smajstrla and Locascio (1996) found that tomato yields decreased when SWT was maintained at 15 or 20 kPa, compared

Table 6. Regression equations for response surfaces shown in Fig. 1 and 2; N = N rate (kg ha^{-1}), SWT = average soil water tension (kPa).

Year	Response variable	Regression equation	R^2
1993–1994	Marketable yield	$Y = -3.5 + 1.02\text{SWT} + 0.056N - 0.054\text{SWT}^2 + 2 \times 10^{-4}N \times \text{SWT} - 7 \times 10^{-5}N^2$	0.86
	Head diameter	$Y = 4.9 - 0.082\text{SWT} + 0.017N + 1.77 \times 10^{-3}\text{SWT}^2 + 1.5 \times 10^{-4}N \times \text{SWT} - 1.95 \times 10^{-5}N^2$	0.82
	Head weight	$Y = 0.03 + 1.8 \times 10^{-3}\text{SWT} + 4.0 \times 10^{-4}N - 1.34 \times 10^{-4}\text{SWT}^2 + 3.7 \times 10^{-6}\text{SWT} \times \text{N} - 5.0 \times 10^{-7}N^2$	0.83
	Biomass N	$Y = 34.5 - 0.64\text{SWT} - 0.22N + 0.0019N^2 - 3.36 \times 10^{-6}N^3 + 0.11\text{SWT}^2 + 0.14N \times \text{SWT} + 1.4 \times 10^{-5}\text{SWT} \times N^2 - 7.2 \times 10^{-3}\ \text{N} \times \text{SWT}^2$	0.95
1994–1995	Marketable yield	$Y = -0.06 + 0.893\text{SWT} + 0.068N - 0.048\text{SWT}^2 + 2.5 \times 10^{-4}\ \text{N} \times \text{SWT} - 8.0 \times 10^{-5}N^2$	0.94
	Head diameter	$Y = -1.5 - 0.097N - 3.0 \times 10^{-4}N^2 + 2.9 \times 10^{-7}\text{N}^3 + 2.9 \times 10^{-3}\ \text{SWT} \times N - 1.3 \times 10^{-6}\text{SWT} \times N^2 - 1.2 \times 10^{-4}N \times \text{SWT}^2$	0.89
	Head weight	$Y = 11.8 - 4.04\text{SWT} + 0.94N + 0.433\text{SWT}^2 - 8.9 \times 10^{-4}\ N \times \text{SWT} - 1.2 \times 10^{-3}N^2$	0.43
	Biomass N	$Y = 93.5 - 12.3\text{SWT} + 0.76\text{SWT}^2 + 0.145N \times \text{SWT} - 3.8 \times 10^{-5}\text{SWT} \times N^2 - 7.6 \times 10^{-3}\ N \times \text{SWT}^2$	0.87
1995–1996	Marketable yield	$Y = -7 + 0.10\text{SWT} + 0.094N - 0.0022\text{SWT}^2 - 1.4 \times 10^{-4}\ N \times \text{SWT} - 1.2 \times 10^{-4}\text{N}^2$	0.90
	Head diameter	$Y = 3.7 + 0.084\text{SWT} + 0.021\ N - 9.2 \times 10^{-4}\text{SWT}^2 - 2.1 \times 10^{-4}\ N \times \text{SWT} - 2.37 \times 10^{-5}N^2$	0.69
	Head weight	$Y = 8.8 \times 10^{-3} + 2.1 \times 10^{-3}\text{SWT} + 5.4 \times 10^{-4}N - 3.7 \times 10^{-5}\text{SWT}^2 - 3.15 \times 10^{-6}N \times \text{SWT} - 6.2 \times 10^{-6}N^2$	0.80
	Biomass N	$Y = -58 + 6.75\text{SWT} + 1.37N - 0.215\text{SWT}^2 + 1.94 \times 10^{-3}\ N \times \text{SWT} - 1.55 \times 10^{-3}N^2$	0.84

with an average tension of 10 kPa. We determined this optimum SWT in a sandy loam soil; it is reasonable to assume that the optimum tension for subsurface drip-irrigated broccoli may be <10 kPa in very coarse-textured soils, and somewhat >10 kPa in fine-textured soils.

An average of 300 mm of postestablishment irrigation plus precipitation were applied in our medium irrigation treatments, which approximated the optimum SWT. In comparison, Sanchez et al. (1996) reported that broccoli yields in southwestern Arizona were maximized with 430 mm of irrigation water applied using an overhead sprinkler system. Erie et al. (1981) reported that broccoli water consumptive use in southern Arizona was 500 mm, not including that used for germination and stand establishment. These comparisons illustrate the potential water savings when broccoli is irrigated using subsurface drip irrigation. In addition to the irrigation water applied after crop establishment, we used ~300 mm of water for crop germination and establishment during each season. Because of our distance from the experimental site (150 km), our objective was to keep the seedbed moist rather than to efficiently manage water during stand establishment. It is likely that, with careful management, <300 mm of irrigation water would suffice for germination and stand establishment.

Head diameter and head weight were more responsive to N rates than to SWT across the range of treatments used (Table 4, Fig. 1). No quality parameter maxima were predicted within the range of treatments, except for head weight in 1993–1994 and 1995–1996. Two other quality parameters, hollow stem and discoloration, were measured, but were not different across the treatments. Except at the lowest N rate, this variety showed excellent yield and quality across a wide range of N × SWT treatments during all three seasons. There were no SWT × N rate interactions for marketable yield, and the only significant SWT × N interaction for yield quality parameters was for head diameter in 1995–1996 (Table 5).

Predicted maximum yields and quality occurred at N rates of 380 to 450 kg ha^{-1} (Fig. 1). These N rates are higher than currently recommended rates (Doerge et al., 1991). However, Stivers et al. (1993) reported that Western broccoli growers may apply as much as 400 kg N ha^{-1}. Other researchers have noted a positive broccoli yield response to N rates as high as 330 kg ha^{-1} in California (Beverly et al., 1986) and >500 kg ha^{-1} in British Columbia (Zebarth et al., 1995). The N rates associated with maximum yield in our experiments are likely higher than would be needed in a normal produc-

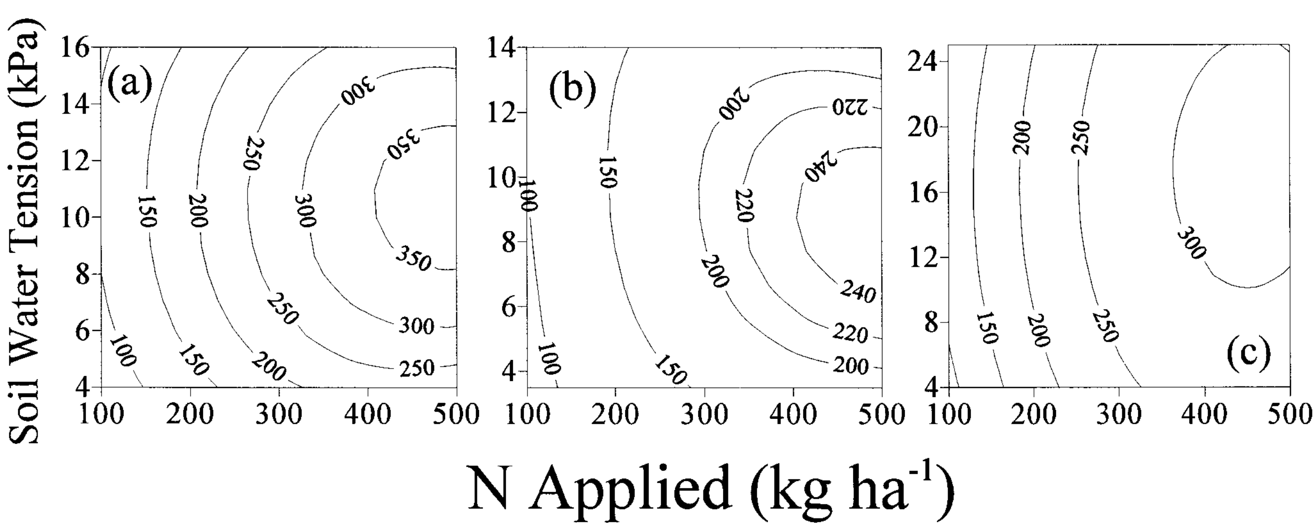

Fig. 2. Response surfaces for broccoli aboveground biomass N for (a) 1993–1994, (b) 1994–1995, and (c) 1995–1996. Contour lines are in units of kg N ha^{-1}. Response surface equations are given in Table 6.

tion situation, because in our experiments we exhaustively cropped the soil each summer to minimize residual available N.

Two published reports have shown water by N response surfaces for sprinkler-irrigated broccoli. Beverly et al. (1986) reported no predicted maximum within the range of treatments, but yields of 20 Mg ha^{-1} were predicted with ~350 mm of water and 350 kg N ha^{-1} applied. Sanchez et al. (1996) found that broccoli yields were maximized with 430 mm of irrigation water and 267 kg N ha^{-1} applied in western Arizona, with yields as high as 15 Mg ha^{-1}. They observed no yield decrease with excessive water, but yields decreased with excessive N applications, especially with inadequate water applied. Our response surfaces (Fig. 1) illustrate the positive effects of water and N inputs on broccoli yields, but show little yield decrease at high N rates.

Aboveground broccoli biomass N was highly responsive to both N rate and SWT (Table 4; Fig. 2). During each season there were significant effects of N, SWT, and significant N $\times$ SWT interactions for biomass N (Table 5). Nitrogen accumulations as high as 320 kg ha^{-1} were observed, higher than is normally observed for broccoli crops in Arizona (Doerge et al., 1991). Other researchers have reported broccoli aboveground N uptake well in excess of 300 kg ha^{-1} (Magnifico et al., 1979; Zebarth et al., 1995). Interestingly, biomass N accumulation was lowest during 1994–1995, the year in which marketable yields were the highest. Zebarth et al. (1995) also observed that, among different dates of broccoli planting in British Columbia, the crop with the highest marketable yield did not take up the greatest amount of N. Biomass N accumulation in our experiments showed no predicted maxima within the range of treatments, however N uptake was highest at SWTs of 8 to 14 kPa (1993–1994), 6 to 11 kPa (1994–1995), and >10 kPa (1995–1996) (Fig. 2). The wettest irrigation treatment resulted in reduced crop N uptake. The 3-yr mean crop N uptake at 500 kg N applied ha^{-1} was 255, 285, and 222 kg ha^{-1} in the low, medium, and high irrigation treatments, respectively (Table 4).

Data from in-season aboveground biomass samples were fitted to cubic spline functions and the cubic spline functions were differentiated and plotted to define trends in daily N uptake (Fig. 3). By definition, cubic spline functions pass through each data point. As much as 300 kg N ha^{-1} was accumulated in the aboveground biomass in these plots (Fig. 3A). The cumulative uptake curves were similar between the two seasons, although total N uptake was higher during 1993–1994. The daily N flux curves were also similar, and indicated a maximum N uptake of 5 kg N ha^{-1} d^{-1}. The period of highest N uptake (>3 kg ha^{-1} d^{-1}) lasted longer during 1993–1994 (22 d) than during 1995–1996 (13 d). This is one reason cumulative N uptake was higher during 1993–1994. During 1993–1994, there was a decrease in the rate of N flux between 50 and ~60 d after planting (DAP). Karlen et al. (1987) noted that such a pause in the flux curve can be because of data errors or to environmental influences. During and after this period there was a period of several days in which daily heat unit accumulations (degree C days [DCD]) averaged 7, compared with an average of 14 for the preceeding and following periods. These lower heat unit accumulations may have slowed down plant growth and N flux. The maximum N flux of 5 kg N ha^{-1} d^{-1} occurred at approximately the first bud growth stage, or at 825 to 1000 HUAP (Table 3). Doerge et al. (1991) reported a maximum broccoli N uptake of 9 kg N ha^{-1} d^{-1} with plant populations of 74 000 to 86 000 plants ha^{-1}. Hartz (1994) also reported that the highest N flux in broccoli occurred at the first bud growth stage, and recommended N applications of 17 to 34 kg N ha^{-1} wk^{-1} during this period.

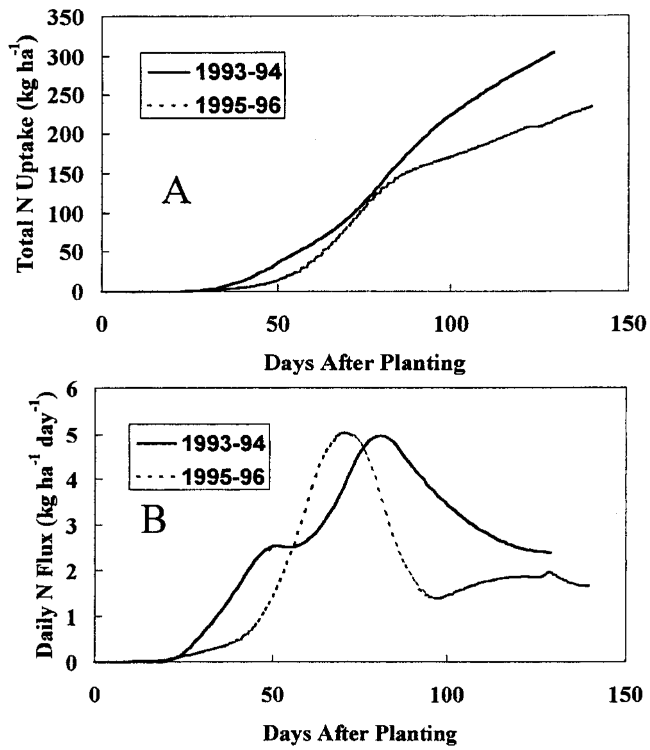

Fig. 3. (a) Cumulative N uptake and (b) daily N flux of broccoli receiving the medium irrigation treatment and 350 kg N ha^{-1} (1993–1994) or 300 kg N ha^{-1} (1995–1996).

This pattern of N uptake, with low N uptake early in the season followed by a period of rapidly increasing uptake, illustrates the management challenge posed by broccoli production. An adequate supply of N is required all season. However, preplant or early-season applications of N may be inefficiently used because of low plant N demand.

CONCLUSIONS

The response of subsurface drip-irrigated broccoli to water and N inputs was examined during three field experiments in southern Arizona. Response surfaces suggested that the optimum SWT, with respect to marketable crop yield, was ~10 kPa at 30-cm depth in this sandy loam soil. Maintaining SWT near this level, along with appropriate applications of N fertilizer, should result in high yield and quality. Quality parameters (head weight and diameter) were less responsive to differences in SWT than was marketable yield, but they were highly responsive to N inputs. Maximum marketable broccoli yields occurred at N rates of 300 to 500 kg ha^{-1}. There were no SWT $\times$ N interactions for marketable yield, and very few interactions for yield quality (head weight and diameter). In contrast, significant SWT $\times$ N interactions were observed for biomass N in each year. Broccoli accumulated up to 320 kg N ha^{-1} in the aboveground biomass. Plant N uptake was adversely affected by the wettest irrigation treatment. Very little N uptake ($<$20 kg N ha^{-1}) occurred in the first 40 d after planting. Nitrogen uptake fluxes were as high as 5 kg N ha^{-1} d^{-1}, and peaked ~80 to 85 DAP (approximately the first bud growth stage or 825–1000 HUAP).

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