Economic Responses of Broccoli and Cauliflower to Water and Nitrogen in the Desert

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Additional index words. *Brassica oleracea*, economic maximum yield, irrigation, response surface

Abstract. Field studies were conducted to develop water and N response surface models for broccoli and cauliflower (*Brassica oleracea* L., Botrytis Group) produced in the low desert of the southwestern United States and to estimate profit maximizing combinations of water and N over a range of realistic price situations. Marketable broccoli and cauliflower yields were increased by water and N inputs in all experiments. Generalized response equations indicate maximum broccoli yields with 43 cm of water and N at 267 kg·ha⁻¹ and maximum cauliflower yields with 65 cm of water and N at 338 kg·ha⁻¹. Least-cost combinations of water and N changed with the costs of these inputs for yield levels below the economic maximum. However, profit maximizing N and water rates changed little regardless of input or crop prices investigated.

The low desert region of the southwestern United States is a major production area for cool-season vegetables during the winter months. Favorable temperatures in this region allow for production of a continuous supply of produce from November through March. Although lettuce (*Lactuca sativa* L.) has traditionally occupied the most acreage, the acreage of broccoli and cauliflower produced in the desert has increased by 225% during the past 10 years (Howell et al., 1993).

Vegetables produced in the low desert almost totally depend on irrigation for their water requirement. Nitrogen is the nutrient most limiting to crop production in this region. In irrigated agriculture, water management has a pronounced influence on N management, and an understanding of this interaction is needed for selecting N management practices that optimize crop yield and minimize N losses (Letey et al., 1983; Sanchez et al., 1994; Stark et al., 1983). Furthermore, response surfaces describing the interaction between water and N can be used in determining economic optimum combinations of inputs under differing price behaviors (Beverly et al., 1986).

The cost of irrigation water in the low desert can vary substantially among areas. For example, surface water in several irrigation districts adjacent to the Colorado River costs

only \$0.40 per ha-cm. However, many growers in central Arizona pay as much as \$3.00 per ha-cm for Central Arizona Project water, and many growers outside surface water districts pay as much as \$4.00 per ha-cm to pump and apply well water. Nitrogen prices are more stable, but can vary 2-fold depending on formulation and vending source. The objective of these studies was to develop water and N response surfaces for broccoli and cauliflower grown in the desert. Using generalized response surface models, economic optimum combinations of water and N over a range of realistic price situations were determined.

Materials and Methods

Studies were conducted on a Superstition sand (Typic calciorthid, sandy, mixed, hyperthermic 95% sand) at the Yuma Mesa Agricultural Research Center. Preliminary soil samples collected at each site and water analyses indicated adequate levels of all nutrients, except N and P. Phosphorus, from triple superphosphate, was applied at 224 kg·ha⁻¹ and disked into the soil before each planting. Insect and disease control measures were implemented, as needed, using practices standard for the area.

The plots were irrigated using a modified, self-moving, lateral, sprinkler irrigation system (Roth and Gardner, 1989) that applied five rates of water and five rates of N (solution NH₄NO₃) in specified combinations (see Table 1). The treatments were arranged in a central composite rotatable design (Cochran and Cox, 1960). The statistical design included a total of nine treatments (see 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 1.44 m (four rows) wide. Two replications of the design were planted with the treatments randomized differently for each replication to give a total of 26 plots, which 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 the remaining spray line was used for uniform irrigation during germination and stand establishment.

Colorado River water, with an average electrical conductivity of 1.4 dS·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% consumptive use (CU) level in each irrigation was estimated from Erie et al. (1982). The amounts of water applied each season were recorded (see 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 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 NH₄NO₃ fertilizer solution into the irrigation water of each plot.

Broccoli, 'Excalibur' in 1981 and 1982 and 'Citation' in 1983, was seeded at 0.36 m between rows. Planting dates were 30, 14, and 19 Sept. in 1981–83, respectively. A flat-bed culture system was used to facilitate the use of the overhead sprinkler system. At the three- to four-leaf stage, plants were thinned to a spacing of 0.3 m within the row to give an approximate plant population of 92,000 plants/ha. Mature broccoli heads were harvested four to six times depending on uniformity of maturity [U.S. Dept. of Agriculture (USDA), 1943].

Table 1. Water and N treatment combinations of central composite design used in broccoli and cauliflower field experiments, 1981–84.

Treatment ^a	Water ^c applied (%)	N ^b applied (%)
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

^aWater applied at the 100% level each week was estimated after Erie et al. (1982). Other treatments were applied in the proportional amounts indicated.

^bNitrogen applied to the 100% level each week was based on existing fertilizer recommendations. Other treatments were applied in the proportional amounts indicated.

^cThe 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 re-randomized down two lines to give a total of 26 plots.

Received for publication 26 June 1995. Accepted for publication 30 Oct. 1995. This research was supported by the Water and Power Resource Service, U.S. Dept. of the Interior. We thank G. Tritz and H. Hernandez for their valuable technical assistance. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

CROP PRODUCTION

Table 2. Bimonthly irrigation, rainfall, and N application for 100% water and N treatments in all broccoli and cauliflower experiments from 1981 through 1984.

Period	1981-82			1982-83			1983-84		
	Irrig. ^z H ₂ O applied (cm)	Rain (cm)	N ^y applied (kg·ha ⁻¹)	Irrig. ^z H ₂ O applied (cm)	Rain (cm)	N ^y applied (kg·ha ⁻¹)	Irrig. ^z H ₂ O applied (cm)	Rain (cm)	N ^y applied (kg·ha ⁻¹)
<i>Broccoli</i>									
1-15 Sept.	---	---	---	4.29*	0	0	---	---	---
16-30 Sept.	2.49*	0	0	5.94*	0	22.5	13.3*	0.56	0
1-15 Oct.	8.51*	0.08	0	11.91	0	22.4	3.99*	1.12	21.3
16-31 Oct.	3.40	0	34.2	6.86	0	24.8	5.28	0	24.6
1-15 Nov.	3.99	0	22.3	4.67	0.06	51.1	7.34	0	55.4
16-30 Nov.	3.38	0.25	22.7	7.16	0.61	77.5	8.05	0.18	39.3
1-15 Dec.	3.58	0	59.4	2.34	4.19	24.5	5.18	1.40	38.5
16-31 Dec.	4.06	0	38.5	4.42	0.03	0	6.27	1.14	22.2
1-15 Jan.	4.04	0.56	19.4	---	---	---	5.23	0.66	0
Total	33.5	0.89	196.5	47.6	4.88	222.8	54.6	5.05	201.4
<i>Cauliflower</i>									
1-15 Sept.	---	---	---	4.29*	0	0	---	---	---
16-30 Sept.	2.49*	0	0	5.94*	0	22.5	13.25*	0.56	0
1-15 Oct.	8.53*	0.08	0	10.34	0	22.4	3.99*	1.12	21.3
16-31 Oct.	3.33	0	33.6	8.43	0	24.8	5.16	0	21.4
1-15 Nov.	3.81	0	22.6	4.67	0.05	51.1	7.26	0	54.8
16-30 Nov.	3.33	0.25	22.1	7.16	0.61	52.4	8.03	0.17	38.5
1-15 Dec.	3.68	0	39.6	1.5	4.19	49.7	4.37	1.40	38.5
16-31 Dec.	3.91	0	36.2	5.97	0.03	46.9	5.77	1.14	43.8
1-15 Jan.	4.62	0.53	37.1	4.75	0	0	6.48	0.66	43.6
16-31 Jan.	3.99	0.25	37.4	2.36	0.03	0	6.50	0	0
1-15 Feb.	3.38	0.05	19.2	---	---	0	---	---	0
Total	41.1	1.2	248	55.4	4.9	270	60.8	5.1	262

^zIrrigation (Irrig.) treatments were 50%, 65%, 100%, 135%, and 150% of these levels.

^yNitrogen fertilizer treatments were 33%, 53%, 100%, 147%, and 167% of these levels.

*Uniform irrigation before treatments applied.

Table 3. Equation constants for yield response of broccoli and cauliflower to water and N.

Year of experiment	Equation constants ^z							Required for maximum yield	
	C ₀	C ₁	C ₂	C ₃	C ₄	C ₅	R ²	Water (cm)	N (kg·ha ⁻¹)
<i>Broccoli</i>									
1981-82	-2.70	0.49	0.070	-0.0056	-0.00015	-0.00012	0.62	41.7	220
1982-83	-9.27	0.56	0.066	-0.0064	-0.00011	-0.00012	0.78	47.1	332
1983-84	-16.08	0.55	0.131	-0.0047	-0.00025	-0.00014	0.64	55.0	248
Overall	4.71	0.06	0.065	-0.0016	-0.00015	0.00030	0.51	43.3	267
<i>Cauliflower</i>									
1981-82	-78.60	3.97	0.081	-0.0447	-0.00019	0.00064	0.79	46.5	295
1982-83	-39.23	1.24	0.129	-0.0153	-0.00044	0.00266	0.75	72.7	369
1983-84	-18.27	0.63	0.126	-0.0082	-0.00033	0.00131	0.69	63.9	316
Overall	-13.65	0.62	0.107	-0.0096	-0.00031	0.00187	0.59	65.2	338

^zAll equations follow the form: yield (Mg·ha⁻¹) = C₀ + C₁W + C₂N + C₃W² + C₄N² + C₅WN, where C₀ through C₅ are constants and W = water (cm) and N = nitrogen (kg·ha⁻¹).

Table 4. Profit maximizing water and N rates for various input and product prices for broccoli.

Price situation ^z			Profit maximizing inputs		Profit maximizing optimum yield (Mg·ha ⁻¹)
Water (\$/cm)	N (\$/kg)	Broccoli (\$/Mg)	Water (cm) ^y	N (kg·ha ⁻¹)	
0.40	0.4	600	42.9	265	14.6
	0.8	600	42.7	263	14.6
4.00	0.4	600	40.8	263	14.6
	0.8	600	40.9	263	14.6
0.40	0.4	1500	43.2	267	14.6
	0.8	1500	43.1	266	14.6
4.00	0.4	1500	42.4	266	14.6
	0.8	1500	42.3	265	14.6

^zThese prices represent extremes encountered for low desert winter-vegetable region.

^yWater is priced at cost per centimeter applied over a hectare.

Fig. 1. Predicted marketable yield ($\text{Mg}\cdot\text{ha}^{-1}$) response of broccoli to water and N from three field experiments (1981-84).

Fig. 2. Predicted marketable yield ($\text{Mg}\cdot\text{ha}^{-1}$) response of cauliflower to water and N from three field experiments (1981-84).

The first and last harvest dates were 3 and 14 Jan. in 1982, 10 Dec. and 13 Jan. in 1983, and 5 and 16 Jan. in 1984.

'Snowball 123' cauliflower was seeded at 0.36 m between rows with planting dates being the same as for broccoli. Plants were thinned at the two- to three-leaf stage to a spacing of 0.46 m within the row to give an approximate population of 61,000 plants/ha. Mature cauliflower was harvested from the center two rows of each plot and marketable yields were determined after grading (USDA, 1968). First and last harvest dates were 29 Jan. and 11 Feb. in 1982, 17 and 24 Jan. in 1983, and 23 Jan. and 1 Feb. in 1984. Midribs were collected from all plots beginning at the four- to six-leaf stage of growth and thereafter at ≈ 14 -day intervals until just before harvest. The midribs were dried at 65°C for 48 h and ground to pass a 0.417-mm (40-mesh) screen. Nitrate-N in the midrib tissue was determined potentiometrically (Baker and Smith, 1969). Critical nitrate-N levels for broccoli and cauliflower have been reported previously (Doerge et al., 1991; Gardner and Roth, 1989, 1990).

Crop production functions were fit to quadratic equations using SAS-REG and SAS-RSREG (SAS Inst., 1982). Generalized response equations for broccoli and cauliflower were calculated using the data from all three seasons. Profit-maximizing yields were calculated by setting the partial derivatives of the generalized response functions (dy/dW and dy/dN) equal to the price ratios of inputs and product (P_w/P_y and P_n/P_y) and solving the equations simultaneously (Heady et al., 1955; Hexem and Heady, 1978).

Results and Discussion

Crop production. All plots received uniform irrigation during the first 3 weeks after seeding. After plant stands were established, the irrigation treatments imposed were proportional to the 100% CU treatment (Table 1). Deviation from the planned irrigation treatments occurred during November through December in 1982-83 and 1983-84 when more than normal rainfall was received (Table 2). Cumulative N fertilization treatments were

Table 5. Profit maximizing water and N rates for various input and product prices for cauliflower.

Price situation ²			Profit maximizing inputs		Profit maximizing optimum yield
Water (\$/cm)	N (\$/kg)	Broccoli (\$/Mg)	Water (cm) ³	N ($\text{kg}\cdot\text{ha}^{-1}$)	($\text{Mg}\cdot\text{ha}^{-1}$)
0.40	0.4	500	65.2	336	24.8
	0.8	500	65.0	334	24.8
4.00	0.4	500	64.7	334	24.8
	0.8	500	64.5	333	24.8
0.40	0.4	2000	65.3	337	24.8
	0.8	2000	65.3	337	24.8
4.00	0.4	2000	65.2	337	24.8
	0.8	2000	65.2	336	24.8

²These prices represent extremes encountered for low desert winter-vegetable region.

³Water is priced at cost per centimeter applied over a hectare.

Fig. 3. Yield isoquants showing predicted yield ($\text{Mg}\cdot\text{ha}^{-1}$) response of broccoli to water and N using a generalized equation from data for all three years. Straight lines are isoclines showing substitution rates between inputs at various price ratios ($P_w/P_n = 10, 5, 1$, and 0.5).

Fig. 4. Yield isoquants showing predicted yield ($\text{Mg}\cdot\text{ha}^{-1}$) of cauliflower to water and N using a generalized equation from data for all three years. Straight lines are isoclines showing substitution rates between inputs at various price ratios ($P_w/P_n = 10, 5, 1$, and 0.5).

proportional to the 100% level in each experiment (Tables 1 and 2). Marketable broccoli and cauliflower yields were increased quadratically by water and N in all experiments (Figs. 1 and 2).

Maximum broccoli yields ranged from $10.8 \text{ Mg}\cdot\text{ha}^{-1}$ in 1982–83 to $15.2 \text{ Mg}\cdot\text{ha}^{-1}$ in 1983–84 (Fig. 1). Rates of water required for maximum yield ranged from 42 to 55 cm and rates of N required for maximum yield ranged from 221 to $332 \text{ kg}\cdot\text{ha}^{-1}$ (Table 3). The generalized response surface using the combined data from all 3 years indicates that 43 cm of water and N at $267 \text{ kg}\cdot\text{ha}^{-1}$ are required for maximum broccoli yield of $14.6 \text{ Mg}\cdot\text{ha}^{-1}$ (Fig. 3 and Table 3). Total water required in this experiment included water used for germination and stand establishment, while the estimates of Erie et al. (1982) do not. Therefore, under the conditions of these experiments, less water was required for broccoli production than the 50 cm estimated by Erie et al. (1982) when germination water is excluded. However, the N required for maximum yield exceeded rates required on loam and clay loam soils of the river valleys that are often used for vegetable production (Doerge et al., 1991). Rates of N required on the finer-textured soils seldom exceed $200 \text{ kg}\cdot\text{ha}^{-1}$.

Maximum cauliflower yields ranged from $21.8 \text{ Mg}\cdot\text{ha}^{-1}$ in 1983–84 to $29.1 \text{ Mg}\cdot\text{ha}^{-1}$ in 1982–83 (Fig. 2). Ranges of water and N required for maximum yield were 47 to 73 cm and 295 to $369 \text{ kg}\cdot\text{ha}^{-1}$, respectively (Table 3). The generalized response predicts 65 cm of water and N at $338 \text{ kg}\cdot\text{ha}^{-1}$ to achieve a maximum yield of $24.8 \text{ Mg}\cdot\text{ha}^{-1}$ (Fig. 4 and Table 3). Excluding the water required for germination and stand establishment, water consumptive use during the growing season was close to the 47 cm estimated by Erie et al. (1982). As with broccoli, rates of N required for maximum cauliflower yield exceed those typically required on finer-textured soils in the river valleys (Doerge et al., 1991).

The highest amounts of water reduced marketable yield for both crops. While there are several ways excess water can reduce yields, the major effect on this coarse-textured soil was probably leaching of N below the rooting zone. This conclusion is supported by midrib analysis that showed that nitrate-N values for broccoli and cauliflower were below critical levels at the 150% CU level (Figs. 5 and 6). This result explains the seemingly higher rates of N required on this coarse-textured soil compared to finer-textured valley soils.

Economic implications. The generalized equations can be used for calculating least-cost combinations of water and N to achieve specified yields. Isoclines, which are lines denoting economic substitution rates between inputs, were calculated for specified price ratios from the relationship $dW/dN = P_n/P_w$, where P_w and P_n are prices for water and N, respectively (Figs. 3 and 4). For example, when water costs are \$0.40 per cm-ha and N costs are \$0.40 per kg (price ratio of 1 or when 1 cm-ha of water is of equal value to 1 kg N), it takes 31 cm of water and N at $175 \text{ kg}\cdot\text{ha}^{-1}$ to achieve a broccoli yield of $13 \text{ Mg}\cdot\text{ha}^{-1}$ (Fig. 3).

Fig. 5. Midrib $\text{NO}_3\text{-N}$ concentrations for broccoli at three irrigation levels compared to critical concentration. Solid line shows critical concentrations (CL).

However, when water costs go up to \$4.00 per ha-cm (price ratio of 10 or 1 cm-ha of water is of equal value to 10 kg N), the least-cost combination for a $13\text{-Mg}\cdot\text{ha}^{-1}$ yield becomes N at $220\text{ kg}\cdot\text{ha}^{-1}$ and <20 cm of water. Similarly, for cauliflower, the least-cost combination is 47 cm of water and N at $200\text{ kg}\cdot\text{ha}^{-1}$ for a yield of $20\text{ Mg}\cdot\text{ha}^{-1}$ when the price ratio is 1, but becomes 40 cm of water and N at $225\text{ kg}\cdot\text{ha}^{-1}$ when the price ratio is 10 (Fig. 4).

The sale price of broccoli often varies 2-fold and the price of cauliflower 4-fold within a given production season. We were interested in calculating the profit maximizing rates of water and N over the range of realistic water, N, and crop prices (Tables 4 and 5). Interestingly, the amounts of water and N required to

Fig. 6. Midrib $\text{NO}_3\text{-N}$ concentrations for cauliflower at three irrigation levels compared to critical concentration. Solid line shows critical concentrations (CL).

maximize profits changed little over the wide range of prices considered. Water application for profit maximizing yield varied <3 cm for broccoli and <1 cm for cauliflower. The variation in N rates was $<3\text{ kg}\cdot\text{ha}^{-1}$ for broccoli and cauliflower. This small variation in water and N rates for profit maximizing yield across a broad price range for inputs and product is because economic optimal yields were close to maximum yields ($>99\%$), which is predicted by a unique combination of water and N with the model used.

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