Nitrogen and Water Interactions in Subsurface Drip-Irrigated Cauliflower: II. Agronomic, Economic, and Environmental Outcomes

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ABSTRACT

Water × N rate experiments were conducted on subsurface drip-irrigated cauliflower (*Brassica olearacea* L. var. *botrytis* L.) during three winter growing seasons in southern Arizona. A range of water and N rates were selected to permit the calculation of appropriate water × N production functions. The objectives were to (i) determine the effects and interactions of irrigation water and N inputs on crop N uptake, residual soil NO_3–N, N-use efficiency, and unaccounted fertilizer N, and (ii) evaluate agronomic, economic, and environmental production criteria during three growing seasons. Spatial analysis was used to identify overlap of acceptable zones of marketable yield, net return, and unaccounted fertilizer N within each growing season. Acceptable yields and net return were defined as ≥95% of the maximum predicted response within the range of the treatments; acceptable unaccounted fertilizer N was defined as ≤40 kg ha^{-1}. Net returns and aboveground plant biomass N were significantly affected ($P < 0.01$) by N rate and in 2 yr by irrigation. There were also significant irrigation treatment × N rate interactions for net returns and biomass N. Residual soil NO_3–N concentrations increased with N rate and decreased with soil water tension (SWT). Average amounts of residual soil NO_3–N (0–0.9 m) for the highest N rate during the three seasons were 317, 296, and 180 kg ha^{-1} for the low, medium, and high irrigation treatments, respectively. Unaccounted fertilizer N was significantly affected ($P < 0.05$) by irrigation treatment, N rate, and irrigation treatment × N rate interactions each year. Overlap of acceptable zones of marketable yields, net returns, and unaccounted N was achieved in one of the three years. The single combination of SWT and N rate that came closest to producing optimal or near-optimal agronomic, economic, and environmental outcomes in all three years was 10 to 12 kPa and 350 to 400 kg N ha^{-1}.

CONCERN OVER THE IMPACTS OF AGRICULTURAL PRACTICES on the environment is increasing. These concerns include the leaching of nitrate from crop production areas into aquifers. Nitrate contamination of aquifers is especially pronounced in the irrigated Southwest. The percentage of wells testing above the federal drinking water standard of 10 mg NO_3–N L^{-1} in Arizona, California, and Texas ranges from 9.4 to 13.9%. In contrast, an average of 6.4% of all wells sampled in the U.S. were above 10 mg L^{-1} (Fedkiw, 1991).

The approach to minimizing groundwater pollution with nitrate in Arizona involves the use of best management practices (BMPs) (Doerge et al., 1991). These include attention to rate, timing, and placement of N fertilizers and irrigation water and utilization of appropriate tillage practices. Growers who apply N fertilizers are mandated to demonstrate compliance with these BMPs (Arizona Legislature, 1987). Best management practices are designed to maintain or enhance yields and profitability, and to minimize future additions of N to groundwater. The use of subsurface drip irrigation offers the potential for increased water- and N fertilizer-use efficiency and is increasing in the desert Southwest and California. Currently 3600 ha in Arizona and 22 300 ha in California are irrigated with subsurface drip systems (Anonymous, 1994; Anonymous, 1998). Several recent studies have illustrated the efficient nature of subsurface drip irrigation for delivery of water and nutrients (Pier and Doerge, 1995b; Thompson and Doerge, 1996b).

Evaluation of any crop production system should address agronomic, economic, and environmental outcomes. Drip irrigation allows great flexibility in both water and N management. Water and N are the two inputs to irrigated cropping systems that have the most impact on agronomic, economic, and environmental outcomes (Letey et al., 1977). These three criteria have only recently been evaluated simultaneously for drip-irrigated crops. The interactive effects of water and N management on yields are reported for drip-irrigated corn (*Zea mays* L.) (Phene and Beale, 1976; Yanuka et al., 1982), tomato (*Lycopersicum esculentum* L.) (Bar-Yosef and Sagiv, 1982a, 1982b), celery (*Apium graveolens* L.) (Feigin et al., 1982), watermelon (*Citrillus lanatus* [Thumb.] Matsu and Nakai) (Pier and Doerge, 1995b), leaf lettuce (*Lactuca sativa* L.) (Thompson and Doerge, 1996a), romaine lettuce (Thompson and Doerge, 1995a), collard (*Brassica oleracea* L. var. *acephala* DC., p.p.), mustard (*Brassica juncea* [L.] Czerniak), and spinach (*Spinacea oleracea* L.) (Thompson and Doerge, 1995b).

There is a general lack of information regarding the effects of N and water management for drip-irrigated cauliflower production. Therefore, additional research is needed to examine the agronomic, economic, and environmental response of this crop to N and water inputs under subsurface drip irrigation. We used the methods of Pier and Doerge (1995a) and Thompson and Doerge (1996b) to simultaneously evaluate marketable yield, net economic return, and unaccounted fertilizer N for subsurface drip-irrigated cauliflower.

The objectives of this study were to (i) determine the effects and interactions of irrigation water and N inputs on crop N uptake, residual soil NO_3–N, N-use efficiency, and unaccounted fertilizer N in subsurface drip-irrigated cauliflower and (ii) use spatial analysis techniques to simultaneously evaluate agronomic, eco-

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Published in Soil Sci. Soc. Am. J. 64:412–418 (2000).

Abbreviations: ANUE, apparent N-use efficiency; BMP, best management practices; SWT, soil water tension.

nomic, and environmental production functions during three growing seasons.

MATERIALS AND METHODS

A detailed description of the field experiments is given in the companion paper (Thompson et al., 2000). During each year, harvested cauliflower curds were trimmed to "U.S. No. 1" specifications for cauliflower (USDA, 1968). Marketable heads and trimmings were weighed fresh and dried separately at 65°C in a forced-air oven, ground, and analyzed for total N by the micro-Kjeldahl method (Bremner and Mulvaney, 1982). Soil samples were taken from each plot immediately after harvest at the end of each growing season using a hydraulic drill rig and a 1.5-m long steel coring device. Groupings of three adjacent soil cores were taken at distances of 0, 0.25, and 0.50 m from the drip tubing at three randomly selected locations within the harvest area in each plot. Soil samples, up to 0.9 m in depth, were separated into 0- to 0.30-, 0.30- to 0.60-, and 0.60- to 0.90-m depth increments. The nine subsamples from each depth increment were composited within each plot, thoroughly mixed, subsampled, air-dried, and ground to <2 mm. Analysis of 1 *M* KCl extractable NH_4–N and NO_3–N was performed by steam distillation (Keeney and Nelson, 1982).

Estimates of net return were calculated as

$$R_{\mathrm{net}} = (R_{\mathrm{gross}} - C_{\mathrm{input}} - C_{\mathrm{harvest}}) \times Y_{\mathrm{mar}} \qquad [1]$$

where R_{net} = net return (ha^{-1}), R_{gross} = commodity price (Mg^{-1}), C_{input} = cost of N plus water (Mg^{-1}), C_{harvest} = cost of cutting, loading, and hauling (Mg^{-1}), and Y_{mar} = marketable yield (Mg ha^{-1}). Gross return was calculated by assuming a unit price of \$669.90 Mg^{-1}, the average price in Arizona during the period 1990–1995 (Sherman and Erwin, 1996). Harvest cost was assumed to be \$451 Mg^{-1} (Wade and Harper, 1991). The cost of N was assumed to be \$0.35 kg N^{-1} and the cost of water to be \$260.00 ha^{-1} m^{-1}. This is the approximate current price for Central Arizona Project water. All other production costs were assumed constant across all N by water treatments.

A partial N mass balance was developed using the difference method (Bock, 1984) for cauliflower grown during each season. This approach allowed us to confine our interpretations to the in-season fate of fertilizer N. Postharvest unaccounted fertilizer N was calculated as

$$\begin{aligned} \mathrm{UN_i} = {} & \mathrm{FN_i} + (\mathrm{WN_i} - \mathrm{WN_0}) \\ & - (\mathrm{SN_i} - \mathrm{SN_0}) - (\mathrm{PN_i} - \mathrm{PN_0}) \end{aligned} \qquad [2]$$

where $\mathrm{UN_i}$ = unaccounted fertilizer N in plot i, $\mathrm{FN_i}$ = fertilizer N applied to plot i, $\mathrm{WN_i}$ = N applied in irrigation water to plot i, $\mathrm{WN_0}$ = N applied in irrigation water to control plot, including water used for stand establishment, $\mathrm{SN_i}$ = residual soil NH_4–N plus NO_3–N to a depth of 0.9 m in plot i, $\mathrm{SN_0}$ = residual soil NH_4–N plus NO_3–N to a depth of 0.9 m in unfertilized control plot harvest areas, $\mathrm{PN_i}$ = total crop N uptake in plot i, and $\mathrm{PN_0}$ = total crop N uptake in control plot harvest areas receiving no N fertilizer. All equation variables are in units of kg ha^{-1}. Average irrigation water NO_3–N was 2.0 mg L^{-1}.

The average total plant N uptake in the control plots was 20, 28, and 20 kg ha^{-1} for the three growing seasons, respectively. These values represent crop N uptake from this field following exhaustive cropping. It was assumed that the fate of indigenous N in control and fertilized plots was the same. The entire experimental area was subjected to exhaustive removal of available soil N by multiple harvests of unfertilized sudangrass as well as leaching by several flood irrigation events. This should result in a low potential for soil N mineralization during the cauliflower growing season. Therefore, any differences in N losses observed between fertilized and control plots were assumed to be the result of the N and water treatments or their effects on cauliflower growth and N recovery in plant in plant biomass. Apparent N-use efficiency was calculated as

$$\mathrm{ANUE} = \frac{\mathrm{PN_i} - \mathrm{PN_0}}{\mathrm{FN_i}} \qquad [3]$$

Response surfaces for marketable yield, net return, and unaccounted fertilizer N were determined using the SAS statistical procedure PROC RSREG. Analysis of variance procedures were performed using the SAS statistical procedure PROC GLM (SAS Institute, 1988). Spatial analysis techniques (Laurini and Thompson, 1992; Pier and Doerge, 1995a; Thompson and Doerge, 1996b) were used to concurrently evaluate the response surfaces.

RESULTS AND DISCUSSION

Maximum net return each year was obtained at N rates of 200 to 500 kg ha^{-1} (Table 1). During each year net return was significantly affected ($P < 0.01$) by N rate and in 2 yr by irrigation treatment (Table 2). There was a significant irrigation treatment × N rate interaction during two of the three seasons. In most cases net returns for a given N rate were lowest in the wettest irrigation treatment. This is most likely due to the effects of excessive irrigation on marketable yields, but may also in part result from the costs of applying excessive irrigation water. Net return was a direct reflection of marketable yields, as is observed for most high-value crops. Therefore, the cost alone of excessive water and N applications had little effect on net returns other than their adverse effect on marketable yields. This situation may lead to a tendency for growers to apply excessive amounts of these inputs to high-value crops such as cauliflower. Sanchez et al. (1996) also reported that excessive irrigation reduced net returns for sprinkler-irrigated cauliflower grown in southern Arizona. They found that profit-maximizing N and water rates changed little regardless of input or crop prices.

Aboveground plant biomass N was as high as 295 kg ha^{-1} (Table 1). It increased with N rate and usually decreased at the lowest soil water tension. Similar to net return, biomass N was significantly affected ($P < 0.01$) by N rate during 3 yr and by irrigation treatment during 2 yr (Table 2). In eight of the nine season × irrigation treatment combinations, biomass N was maximized at the highest N rate. This N uptake was not always accompanied by an increase in marketable yield or net return. Therefore, excessive N rates resulted in luxury uptake of N. However, excessive applications of N are rarely harmful to cauliflower (Stivers et al., 1993). Biomass N was affected more by N rate than by irrigation treatment. For example, the 3-yr averages for N uptake at the highest N rate were 247, 253, and 219 kg ha^{-1} in plots receiving the low, medium, and high irrigation treatments, respectively.

Postharvest residual soil NO_3–N concentrations were

Table 1. Net return, plant biomass N, residual soil NO_3–N, and unaccounted fertilizer N for cauliflower, 1993–1996.

Season	Irrigation treatment	N treatment	Net return	Plant biomass N	Residual soil NO_3–N	Unaccounted fertilizer N	ANUE†
	kPa	kg ha^{-1}	\$1000 ha^{-1}	kg ha^{-1}			%
1993–94	17.5	60	0.9	73	127	−10	89
		340	6.6	238	200	33	64
		450	5.7	258	192	116	53
		600	6.6	293	330	150	46
	7.8	60	0.8	63	99	27	70
		340	5.4	231	155	83	62
		450	5.8	250	146	152	51
		600	5.9	295	363	105	46
	4.2	60	0.8	65	112	6	75
		340	5.1	181	102	180	47
		450	5.0	239	141	192	48
		600	6.0	254	195	273	39
1994–95	12.6	100	1.1	75	61	68	47
		200	3.7	152	122	31	62
		300	5.0	182	205	14	51
		500	4.4	216	441	−52	38
	9.4	100	1.1	88	75	41	60
		200	3.6	147	135	22	60
		300	4.9	196	171	44	56
		500	4.2	197	331	87	34
	4.0	100	1.0	72	90	34	44
		200	2.5	132	97	67	52
		300	3.3	156	112	146	43
		500	4.7	183	222	196	31
1995–96	23.2	100	2.9	103	23	15	83
		200	3.9	183	73	−16	82
		300	3.4	187	63	90	55
		500	3.6	231	180	129	42
	10.0	100	2.6	100	21	21	97
		200	4.2	166	63	14	73
		300	4.2	250	60	32	77
		500	4.0	266	195	82	50
	4.0	100	1.6	95	27	28	75
		200	3.4	135	50	65	58
		300	4.1	226	55	68	69
		500	5.0	220	124	206	40

† ANUE, apparent N-use efficiency.

significantly affected ($P < 0.05$) by irrigation treatment and N rate during each season. There were also significant N × irrigation treatment interactions during each season (Table 2). In the low and medium irrigation treatments significant amounts of NO_3 accumulated in the 0 to 0.9 m depth when optimum N rates were exceeded. The maximum amounts of residual NO_3–N occurred under conditions of high N rates and high soil water tension. Overirrigation affected residual soil inorganic N to a greater degree than it affected plant biomass N. Average amounts of residual soil NO_3–N (0–0.9m) for the highest N rate during the three seasons were 317, 296, and 180 kg ha^{-1} for the low, medium, and high irrigation treatments, respectively. In comparison, the

Table 2. Analysis of variance summary for net return, plant biomass N, residual soil NO_3–N, and unaccounted fertilizer N for cauliflower, 1993–1996, as affected by N rate (N) and average soil water tension (SWT).

Season	Source	df	Net return	Plant biomass N	Residual NO_3–N	Unaccounted fertilizer N	ANUE
1993–94	Replication	3	NS	NS	NS	NS	NS
	N	3	**	**	**	**	**
	SWT	2	**	**	**	**	*
	N × SWT	6	NS	**	**	**	NS
	Error	33					
	CV %		5	7	9	12	18
1994–95	Replication	3	NS	NS	*	NS	NS
	N	3	**	**	**	**	**
	SWT	2	**	**	**	**	**
	N × SWT	6	*	NS	**	**	NS
	Error	33					
	CV %		12	9	8	11	11
1995–96	Replication	3	NS	NS	NS	NS	NS
	N	3	**	**	**	**	**
	SWT	2	NS	NS	*	**	NS
	N × SWT	6	*	NS	*	*	NS
	Error	33					
	CV %		24	17	30	33	24

*, ** Significant at $P \leq 0.05$ and 0.01, respectively; NS, not significant.
ANUE, apparent N-use efficiency.

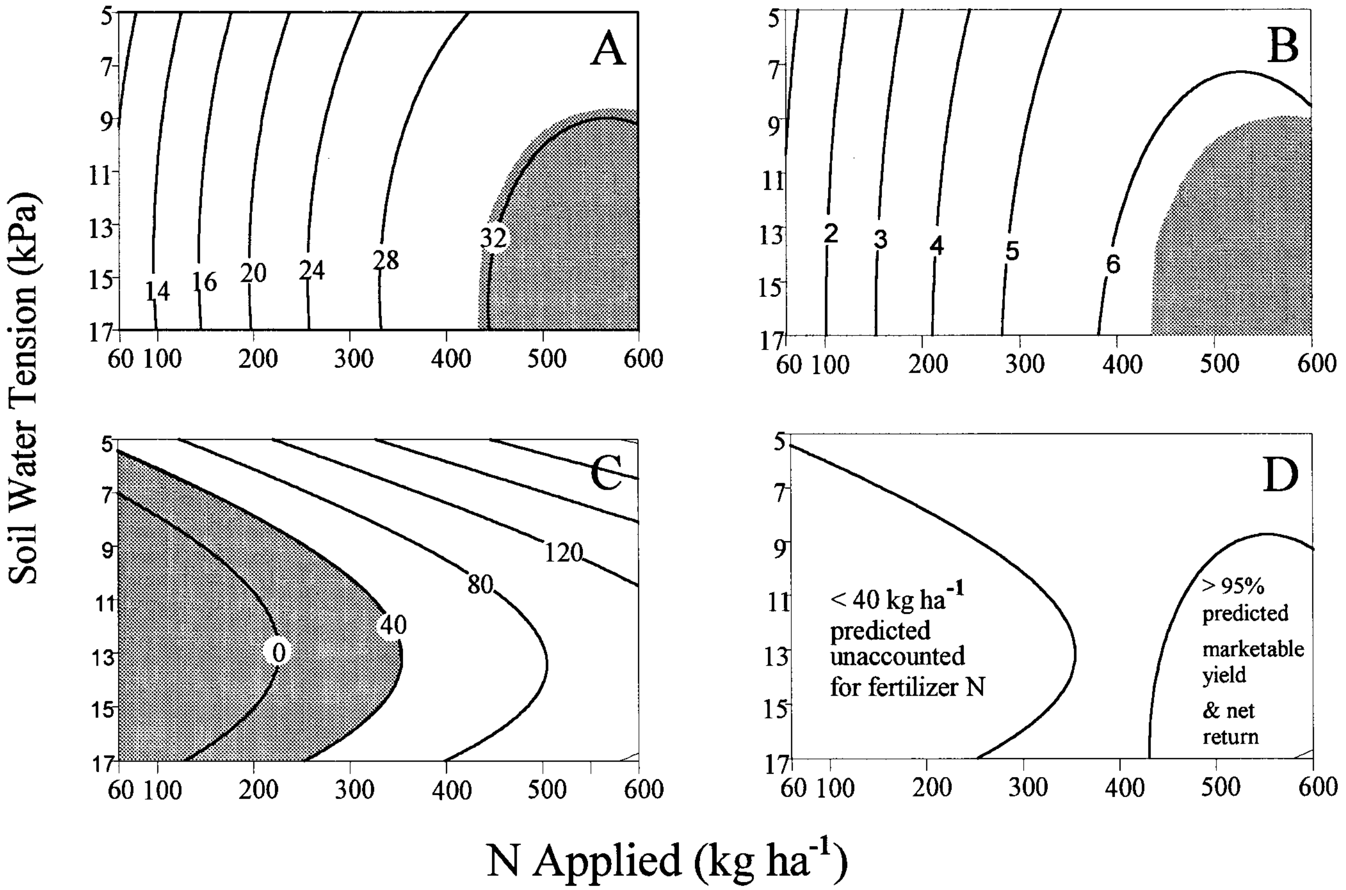

Fig. 1. Response surfaces for cauliflower grown during the 1993–1994 season. (A) Predicted marketable yield (Mg ha^{-1}). The shaded area represents ≥95% of the maximum predicted value. (B) Predicted net return (\$1000 ha^{-1}). The shaded area represents ≥95% of the maximum predicted value. (C) Predicted unaccounted fertilizer N (kg ha^{-1}). The shaded area represents ≤40 kg ha^{-1} of unaccounted fertilizer N. (D) Spatial analysis of response surfaces of marketable yield, net return, and unaccounted fertilizer N.

average residual soil NO_3–N for the control plots was 80 kg ha^{-1} during the three seasons.

The lower amounts of residual NO_3 under conditions of low soil water tension (wettest soils) probably reflect increased N losses caused by leaching and denitrification, which are favored under these wet conditions (Ryden and Lund, 1980). Pier and Doerge (1995a) and Thompson and Doerge (1996b) reported similar results for residual soil NO_3 after subsurface drip-irrigated watermelon and leaf lettuce. Availability to subsequent crops of this residual NO_3 will be highly dependent on factors such as the rooting depth of the subsequent crop, rainfall, and irrigation management.

Apparent N-use efficiency ranged from 31 to 97% (Table 1) and was significantly affected by N rate in all three seasons and by SWT in two seasons. There were no significant N × SWT interactions (Table 2). The average apparent N-use efficiency (ANUE) in the low, medium, and high irrigation treatments was 55, 61, and 52%, respectively. At excessive N rates, ANUE decreased significantly; ANUE averaged 58% for N rates of 300 to 340 kg ha^{-1} and only 41% for N rates of 500 to 600 kg ha^{-1}.

Accounting for all known inputs and outputs of N within a cropping season allows calculation of unaccounted fertilizer N. This includes N lost by gaseous emissions from soils or plants or that leached below the root zone. We assume no net change in soil organic matter or microbial biomass. Unaccounted fertilizer N was significantly affected ($P < 0.05$) by both N rate and irrigation treatment and showed N rate × irrigation treatment interactions during all three seasons (Table 2). In a few cases, unaccounted fertilizer N was ≤ 0 kg ha^{-1}. This apparent overaccounting of fertilizer N is most likely due to errors in soil and plant sampling caused by the natural spatial variability of the system. Overaccounting of N in any single plot was never greater than 97 kg ha^{-1}.

Increasing N rate usually resulted in increased unaccounted fertilizer N. Lower soil water tensions resulted in much higher amounts of unaccounted N (Table 1). This N loss is undoubtedly due to increased leaching and/or denitrification under wet soil conditions. Pier and Doerge (1995a) found similar results for subsurface drip-irrigated watermelon and Thompson and Doerge (1996b) found similar results for leaf lettuce. Feigin et al. (1982) also observed increased N losses, presumably by leaching, due to excessive irrigation applied to drip-irrigated celery. Sexton et al. (1996) estimated NO_3 leaching in sprinkler-irrigated corn by the difference method. Leaching losses of N increased when optimum N rates were exceeded. They recommended fertilizing

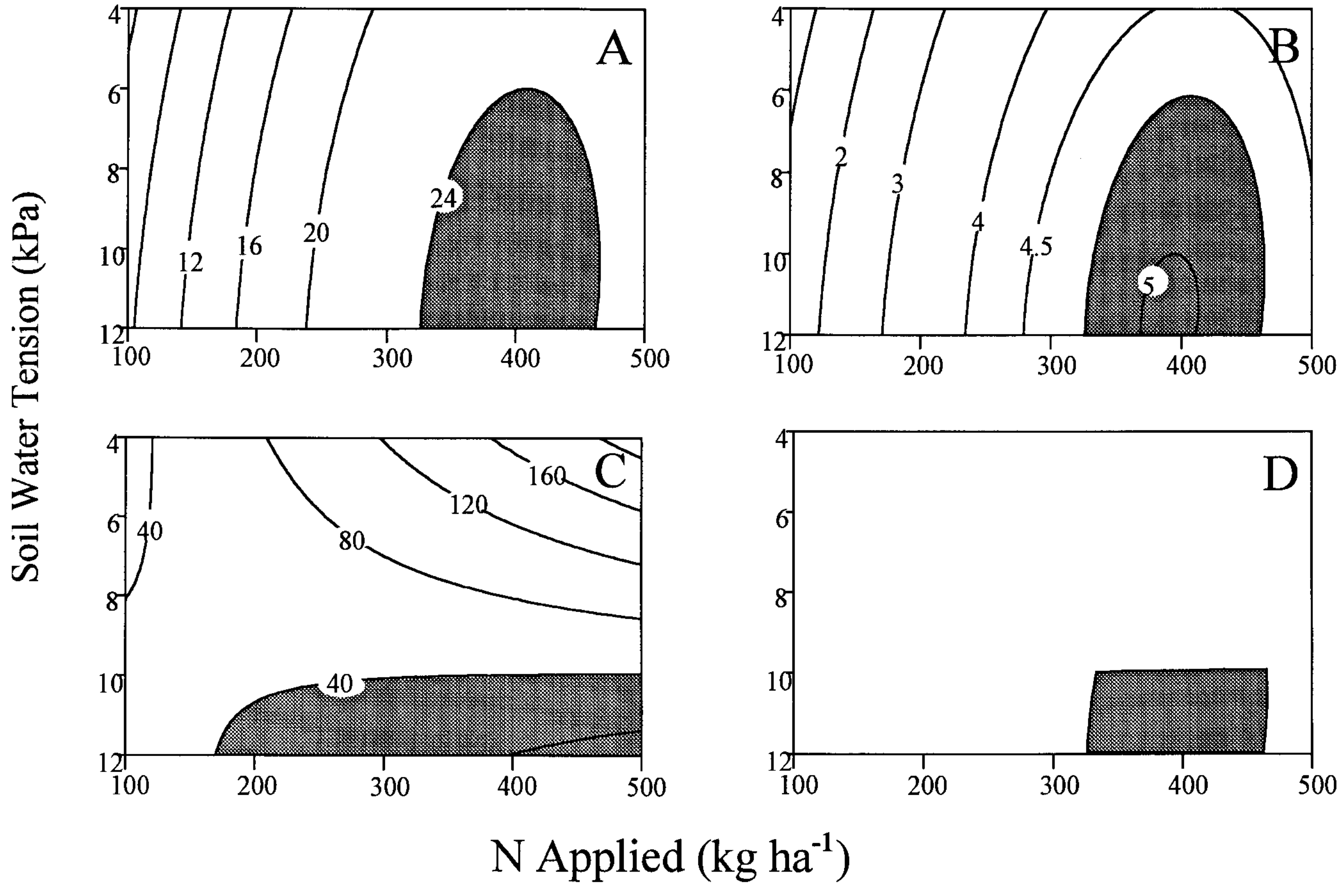

Fig. 2. Response surfaces for cauliflower grown during the 1994–1995 season. (A) Predicted marketable yield (Mg ha^{-1}). The shaded area represents ≥95% of the maximum predicted value. (B) Predicted net return (\$1000 ha^{-1}). The shaded area represents ≥95% of the maximum predicted value. (C) Predicted unaccounted fertilizer N (kg ha^{-1}). The shaded area represents ≤40 kg ha^{-1} of unaccounted fertilizer N. (D) Spatial analysis of response surfaces of marketable yield, net return, and unaccounted fertilizer N. The shaded area represents overlap of zones of ≥95% maximum predicted marketable yield and net return, and ≤40 kg ha^{-1} of unaccounted fertilizer N.

for 95% of maximum yield to minimize NO_3 leaching losses. Nitrate leaching losses as high as 40% of applied N were reported in California cauliflower fields by Lund (1979). In our study, unaccounted N was equivalent to as much as 45, 39, and 41% of fertilizer N in the first, second, and third seasons, respectively. The highest amounts of unaccounted N (as high as 293 kg ha^{-1}) were always in the plots receiving the highest N treatment and the lowest soil water tension. Our results show that while excessive irrigation had only moderate effects on crop yields and quality (Thompson et al., 2000), net returns, and biomass N, it resulted in much higher N losses from the top 0.9 m of the soil profile.

Concurrent evaluation of agronomic, economic, and environmental outcomes was accomplished with spatial analysis (Pier and Doerge, 1995a). An acceptable response for marketable yield and net economic return was defined as ≥95% of the maximum predicted response within the range of the treatments. Acceptable zones for marketable yield are represented by shaded areas in Fig. 1A, 2A, and 3A. Acceptable zones for net return are represented by shaded areas in Fig. 1B, 2B, and 3B. Regression equations are shown in Table 3.

An acceptable range for unaccounted N was defined as ≤40 kg ha^{-1} of unaccounted fertilizer N. This is an estimate of the quantity of N that could have been leached and still maintain a NO_3–N concentration of ≤10 mg L^{-1} in the drainage water. This assumes a consumptive water use of 470 mm (Erie et al., 1981), an irrigation efficiency of 85% (state-mandated), 80 mm of rainfall (average rainfall), 300 mm of water containing 2 mg NO_3–N L^{-1} applied during stand establishment, and the same amounts of water in the soil profile at the beginning and end of the experiment. All excess irrigation water, rainfall, and water applied during stand establishment was assumed to leach below the root zone. Because this does not account for immobilization or denitrification of fertilizer N, this should result in an environmentally conservative interpretation (i.e., a worst case scenario). Values of unaccounted fertilizer N of ≤40 kg ha^{-1} are shaded in Fig. 1C, 2C, and 3C. During the 3 yr of this experiment, applications of no more than 350 kg N ha^{-1} and maintenance of soil water tensions of 12 to 17 kPa would have resulted in acceptable amounts of unaccounted fertilizer N. This is very near the range of N rates and soil water tensions where crop yields and quality were maximized (Thompson et al., 2000).

Spatial analysis was used to identify overlap in the acceptable zones for each of these three production

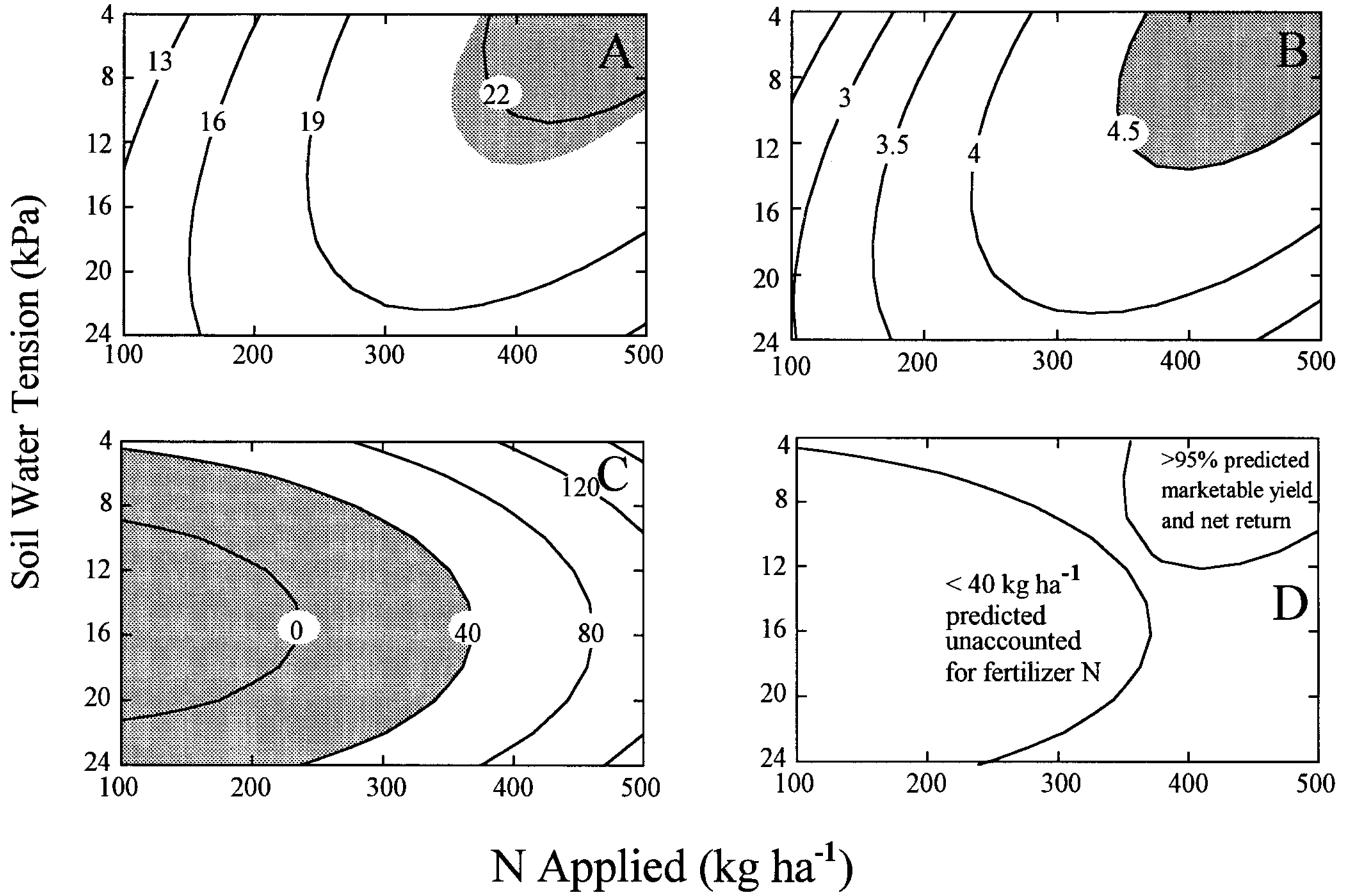

Fig. 3. Response surfaces for cauliflower grown during the 1995–1996 season. (A) Predicted marketable yield (Mg ha^{-1}). The shaded area represents ≥95% of the maximum predicted value. (B) Predicted net return ($1000 ha^{-1}). The shaded area represents ≥95% of the maximum predicted value. (C) Predicted unaccounted fertilizer N (kg ha^{-1}). The shaded area represents ≤40 kg ha^{-1} of unaccounted fertilizer N. (D) Spatial analysis of response surfaces of marketable yield, net return, and unaccounted fertilizer N.

criteria. The spatial analysis of response surfaces for marketable yield, net return, and unaccounted fertilizer N (Fig. 1D, 2D, 3D) showed that only during the 1994–1995 season were these three criteria optimized simultaneously (Fig. 2D). During this season, applications of 325 to 460 kg N ha^{-1} and an average soil water tension of 10 to 12 kPa would have resulted in conditions where all three criteria were optimized simultaneously.

Overlap of acceptable zones of the three production criteria was not achieved during the 1993–1994 and 1995–1996 seasons. However, the region where marketable yield and net return were optimized closely approached that for unaccounted fertilizer N. During 1993–1994 this region of *closest approach* was bounded by N rates of 350 to 425 kg ha^{-1} and soil water tensions of 11 to 14 kPa (Fig. 1D). During 1995–1996 this region was bounded by N rates of 350 to 375 kg ha^{-1} and soil water tensions of 8 to 12 kPa (Fig. 3D). Therefore, although true overlap was obtained during only one of three seasons, the results suggest that similar conditions resulted in optimal or near-optimal production conditions in each season. Pier and Doerge (1995a) found that overlap of these three production criteria occurred at N rates of 60 to 315 kg N ha^{-1} and soil water tensions of 7 to 17 kPa for subsurface drip-irrigated watermelon grown in southern Arizona. Their large zone of overlap, compared to the current study, may have been due to the relative lack of responsiveness of watermelon to N fertilizer. Thompson and Doerge (1996b) reported that all three criteria were optimized simultaneously for sub-

Table 3. Regression equations for response surfaces shown in Fig. 1–3; N = N rate (kg ha^{-1}), SWT = average soil water tension (kPa).

Year	Response variable	Regression equation	R^2	Lack of fit $P > F$
1993–94	Marketable yield	$Y = -5134 - 62\ SWT + 116\ N - 0.23\ SWT^2 - 0.032\ SWT(N) - 0.11\ N^2$	0.84	0.01
	Net return	$Y = -1095 - 10\ SWT + 24\ N - 0.03\ SWT^2 - 0.008\ SWT(N) - 0.02\ N^2$	0.87	0.09
	Unaccounted N	$Y = -219 + 4.86\ SWT + 0.5\ N + 0.02\ SWT^2 + 0.0007\ SWT(N) - 0.0002\ N^2$	0.65	0.14
1994–95	Marketable yield	$Y = -20.7 - 0.13\ SWT + 0.2\ N - 0.0005\ SWT^2 + 0.0001\ SWT(N) - 0.0003\ N^2$	0.75	0.01
	Net return	$Y = -2909 - 20.9\ SWT + 32.9\ N - 0.07\ SWT^2 + 0.007\ SWT(N) - 0.04\ N^2$	0.76	0.01
	Unaccounted N	$Y = -72 + 6.6\ SWT + 1.7\ N - 0.05\ SWT^2 + 0.009\ SWT(N) - 0.0015\ N^2$	0.61	0.40
1995–96	Marketable yield	$Y = -0.70 + 0.7\ SWT + 0.09\ N - 0.012\ SWT^2 - 0.001\ SWT(N) - 0.00009\ N^2$	0.50	0.31
	Net return	$Y = -314 + 168\ SWT + 20\ N - 3.15\ SWT^2 - 0.31\ SWT(N) - 0.02\ N^2$	0.48	0.31
	Unaccounted N	$Y = -96 - 16\ SWT + 0.009\ N - 0.54\ SWT^2 - 0.002\ SWT(N) + 0.0005\ N^2$	0.61	0.02

surface drip-irrigated leaf lettuce at N rates of 240 to 250 kg N ha^{-1} and soil water tensions of 6.6 to 7.3 kPa.

These results illustrate the challenge posed by high-yielding vegetable crops such as cauliflower. Optimal irrigation and N management are important for maximizing yield and profit while minimizing environmental impacts. During three winter experiments in southern Arizona, maintaining an SWT of approximately 10 to 12 kPa for subsurface drip-irrigated cauliflower and application of appropriate rates of N fertilizer led to conditions resulting in $\geq$95% of maximum yields and net returns. In addition, these conditions resulted in acceptable or near-acceptable amounts of unaccounted N, which is presumed to be lost as NO_3 by leaching.

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