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Subsurface Drip Irrigation and Fertigation of Broccoli: II. Agronomic, Economic, and Environmental Outcomes

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ABSTRACT

Subsurface drip irrigation offers potential for increased water and N fertilizer use efficiency, and decreased groundwater NO_3 pollution. Replicated factorial experiments consisting of four rates of N fertilizer application (60–500 kg ha^{-1}) and three target soil water tensions (SWT) (low, medium, and high) were conducted on subsurface drip-irrigated broccoli (*Brassica olearacea* L. *Italica*) during three winter growing seasons in southern Arizona. Objectives were to (i) determine effects and interactions of irrigation water and N inputs on net economic return, residual soil NO_3-N, and unaccounted fertilizer N, and (ii) use abstract spatial analysis techniques to simultaneously evaluate agronomic, economic, and environmental production functions during three growing seasons. Spatial analysis was used to identify overlap of acceptable zones of marketable yield, net return, and unaccounted fertilizer N. Acceptable yields and net return were defined as $\geq$95% of maximum predicted response within the range of the treatments, and acceptable unaccounted fertilizer N was defined as $\leq$40 kg ha^{-1}. During this study, $>$95% of maximum net return encompassed N rates of 300 to 500 kg ha^{-1}, and SWTs of 7 to 25 kPa. There was little accumulation of NO_3 in the top 0.9 m of soil when $\leq$350 kg N ha^{-1} were applied. Unaccounted N increased with excessive N and water inputs, and accounted for as much as 46% of N applied. Overlap of acceptable zones of agronomic, economic, and environmental production criteria was achieved in each year. Areas of overlap were bounded by 300 to 325 kg N ha^{-1} and 8.5 to 12 kPa in 1993–1994, 350 to 500 kg N ha^{-1} and 11 to 14 kPa in 1994–1995, and 340 to 410 kg N ha^{-1} and 11 to 24 kPa in 1995–1996.

Concern about 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 USA were above 10 mg L^{-1} (Fedkiw, 1991).

The use of subsurface drip irrigation is a practice that offers the potential for increased water and N fertilizer use efficiency, and decreased groundwater NO_3 pollution (Phene, 1999). The use of subsurface drip irrigation is increasing in the desert Southwest and California. Currently, 3600 ha in Arizona and 22 300 ha in California are irrigated in this manner (Anonymous, 1994; 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).

Water and N are the two inputs to irrigated cropping systems having 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 have been reported for several drip-irrigated vegetable crops (Phene and Beale, 1976; Bar-Yosef and Sagiv, 1982a, 1982b; Feigin et al., 1982; Yanuka et al., 1982; Pier and Doerge, 1995b; Thompson and Doerge, 1996a). Recently, Pier and Doerge (1995a), Thompson and Doerge (1996b), and Thompson et al. (2000) have evaluated agronomic, economic, and environmental outcomes for several subsurface drip-irrigated crops. Similar methods were used in this study to simultaneously evaluate marketable yield, net economic return, and unaccounted fertilizer N for subsurface drip-irrigated broccoli.

The objectives of this study were to (i) determine effects and interactions of irrigation water and N inputs on net economic return, residual soil NO_3-N, and unaccounted fertilizer N, and (ii) use abstract spatial analysis techniques to evaluate agronomic, economic, and environmental production functions during three growing seasons.

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Published in Soil Sci. Soc. Am. J. 66:178–185 (2002).

Abbreviation: SWT, soil water tension.

MATERIALS AND METHODS

A detailed description of the field experiments is given in the companion paper (Thompson et al., 2002). During each year, harvested broccoli heads were trimmed to ‘U.S. Fancy’ specifications (USDA, 1943). 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 modified to recover NO_3 (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 to 0.9-m 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, and 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 by:

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

where R_{net} equals the net return (\$ ha^{-1}), R_{gross} is the commodity price (\$ Mg^{-1}), C_{input} represents the cost of N plus water (\$ Mg^{-1}), C_{harvest} signifies the cost of cutting, loading, and hauling (\$ Mg^{-1}), and Y_{mar} is the marketable yield (Mg ha^{-1}). Gross return was calculated by assuming a unit price of \$482.2 Mg^{-1}. This is the average price in Arizona during the period 1990–1995 (Sherman and Erwin, 1996). Harvest cost was assumed to be \$265 Mg^{-1} (Wade and Harper, 1991). The cost of N was assumed to be \$0.35 kg^{-1} and the cost of water was assumed 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 broccoli grown during each season. Postharvest unaccounted fertilizer N was calculated as:

$$\mathrm{UN_i} = \mathrm{FN_i} + (\mathrm{WN_i} - \mathrm{WN_o}) - (\mathrm{SN_i} - \mathrm{SN_o}) - (\mathrm{PN_i} - \mathrm{PN_o}) \qquad [2]$$

where $\mathrm{UN_i}$ represents unaccounted fertilizer N in plot i; $\mathrm{FN_i}$ is fertilizer N applied to plot i; $\mathrm{WN_i}$ signifies N applied in irrigation water to plot i; $\mathrm{WN_o}$ equals N applied in irrigation water to control plot, including water used for stand establishment; $\mathrm{SN_i}$ corresponds to the residual soil NH_4-N plus NO_3-N to a depth of 0.9 m in plot i; $\mathrm{SN_o}$ accounts for the residual soil NH_4-N plus NO_3-N to a depth of 0.9 m in unfertilized control plot harvest areas; $\mathrm{PN_i}$ represents the total crop N uptake in plot i and; $\mathrm{PN_o}$ equals the total crop N uptake in control plot harvest areas receiving no N fertilizer. All equation variables are in units of kg ha^{-1}.

The average $\mathrm{PN_o}$ was 22, 28, and 20 kg ha^{-1} for the three growing seasons. These values represent crop N uptake from this field following exhaustive cropping. It was assumed that (i) the fate of indigenous N in control and fertilized plots was the same, and (ii) there was no net change in soil organic matter or microbial biomass N. The entire experimental area was subjected to exhaustive removal of available soil N by multiple harvests of unfertilized sudangrass [*Sorghum sudanenses* (Piper) Stapf.] as well as leaching by several flood irrigation events. This should have resulted in a low potential for soil N mineralization during the broccoli 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 broccoli growth and N recovery in plant biomass. Average irrigation water NO_3-N was 2.0 mg L^{-1}.

Table 1. Net return and unaccounted fertilizer N for broccoli, 1993–1996.

Season	Irrigation treatment	N treatment	Net return	Unaccounted fertilizer N
	kPa	kg ha^{-1}	\$ ha^{-1}	kg ha^{-1}
1993–1994	15.6	60	530	−10
		240	2050	48
		350	2260	97
		500	2210	160
	6.8	60	800	−2
		240	2020	33
		350	2530	47
		500	2630	150
	4.2	60	670	5
		240	1920	110
		350	2420	100
		500	1860	230
1994–1995	13.4	100	2000	41
		200	3510	10
		300	3640	31
		500	4080	23
	11.5	100	1890	9
		200	3320	56
		300	3660	52
		500	3920	12
	3.7	100	1700	8
		200	2750	86
		300	3270	120
		500	3550	230
1995–1996	25.0	100	590	8
		200	2600	17
		300	3110	19
		500	3030	58
	12.3	100	214	−9
		200	2770	13
		300	3340	20
		500	3330	95
	4.0	100	429	20
		200	2330	51
		300	3250	52
		500	3140	210

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

$$\mathrm{Response} = \mathrm{Intercept} + \beta_1 N + \beta_2 N^2 + \beta_3 \mathrm{SWT} + \beta_4 \mathrm{SWT}^2 + \beta_5 N \times \mathrm{SWT} \qquad [3]$$

where N is N fertilizer applied (kg ha^{-1}), and SWT is mean soil water tension (kPa). Nine response surface models (year by variable combinations) were generated in this manner. In each case, 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. Therefore, the full quadratic model was retained and plotted as a response surface.

Abstract spatial analysis (Pier and Doerge, 1995a) was used to concurrently evaluate the response surfaces for a given season. For the analysis, an acceptable zone for each of the three production criteria was defined. An acceptable response for marketable yield and net return was defined as ≥95% of the maximum predicted response within the range of the treatments. 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

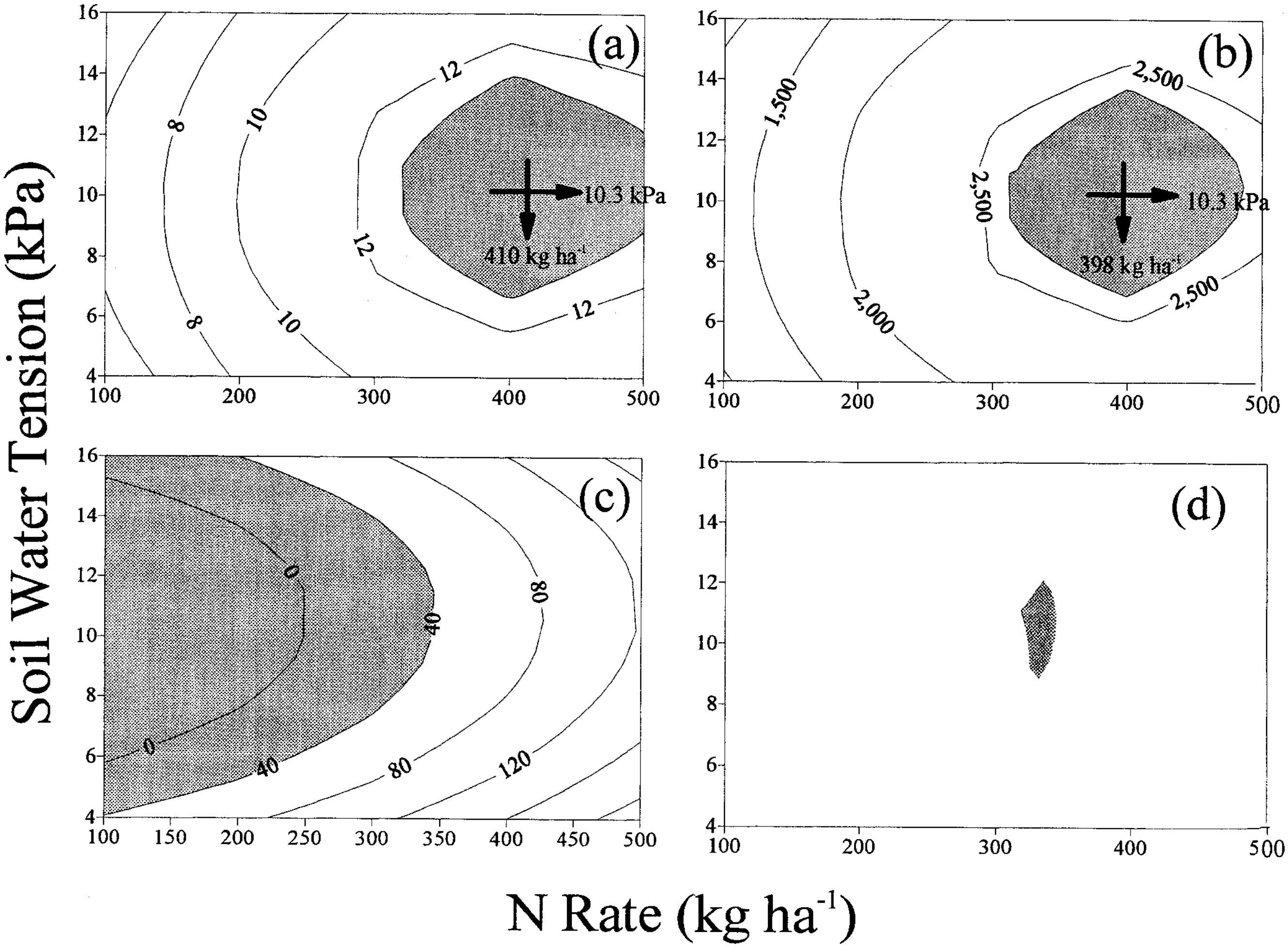

Fig. 1. Response surfaces for broccoli grown during the 1993–1994 season: (a) predicted marketable yield (Mg ha^{-1}), (b) predicted net return (\$ ha^{-1}), (c) predicted unaccounted fertilizer N (kg ha^{-1}), (d) Spatial analysis of response surfaces of marketable yield, net return, and unaccounted fertilizer N. Arrows denote the point of maximum response on the surface. The shaded area in (d) represents overlap of the zones of ≥95% of the maximum predicted marketable yield and net return, and ≤40 kg ha^{-1} of unaccounted fertilizer N.

and still maintain a NO_3-N concentration of ≤10 mg L^{-1} in the drainage water. This assumes a consumptive water use of 500 mm (Erie et al., 1981), an irrigation efficiency of 85% (state-mandated), 80 mm of rainfall (average rainfall), 30 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.

After definition of acceptable zones for production criteria, the three response surfaces for each season were superimposed. Zones of overlap were then identified and delineated visually.

RESULTS AND DISCUSSION

Net Return

Maximum net return each year was obtained at N rates of 300 to 500 kg ha^{-1} (Table 1). During 1993–1994 (Fig. 1b) and 1995–1996 (Fig. 3b), maximum predicted net return occurred very close to the SWT and N values for predicted maximum yield; in 1994–1995 (Fig. 2b) no predicted maximum net return occurred within the range of the treatments. Analysis of variance (Table 2) showed that N rate significantly affected net return in each season ($P < 0.01$), and SWT significantly affected net return in two of three seasons. In none of the three seasons was there a significant SWT × N interaction (Table 2) at $P < 0.05$. During 1994–1995 net return was more adversely affected by low SWT (wet treatment) than by high SWT (dry treatment). Rainfall during this season (115 mm) was the highest of the three seasons during this study, therefore the risk of yield loss in the high irrigation treatment was likely higher than during the other two seasons. The shaded areas in Fig. 1b, 2b, and 3b illustrate zones of ≥95% of maximum net return within the range of the treatments.

With respect to marketable yield, the optimum SWT was about 10 kPa during each season (Thompson et al., 2002). The optimum SWT for maximum net return was similar to that for marketable yield. The close correspondence between the response surfaces for marketable yield (Fig. 1a, 2a, 3a) and net return (Fig. 1b, 2b, 3b) illustrate the overriding importance of yield on eco-

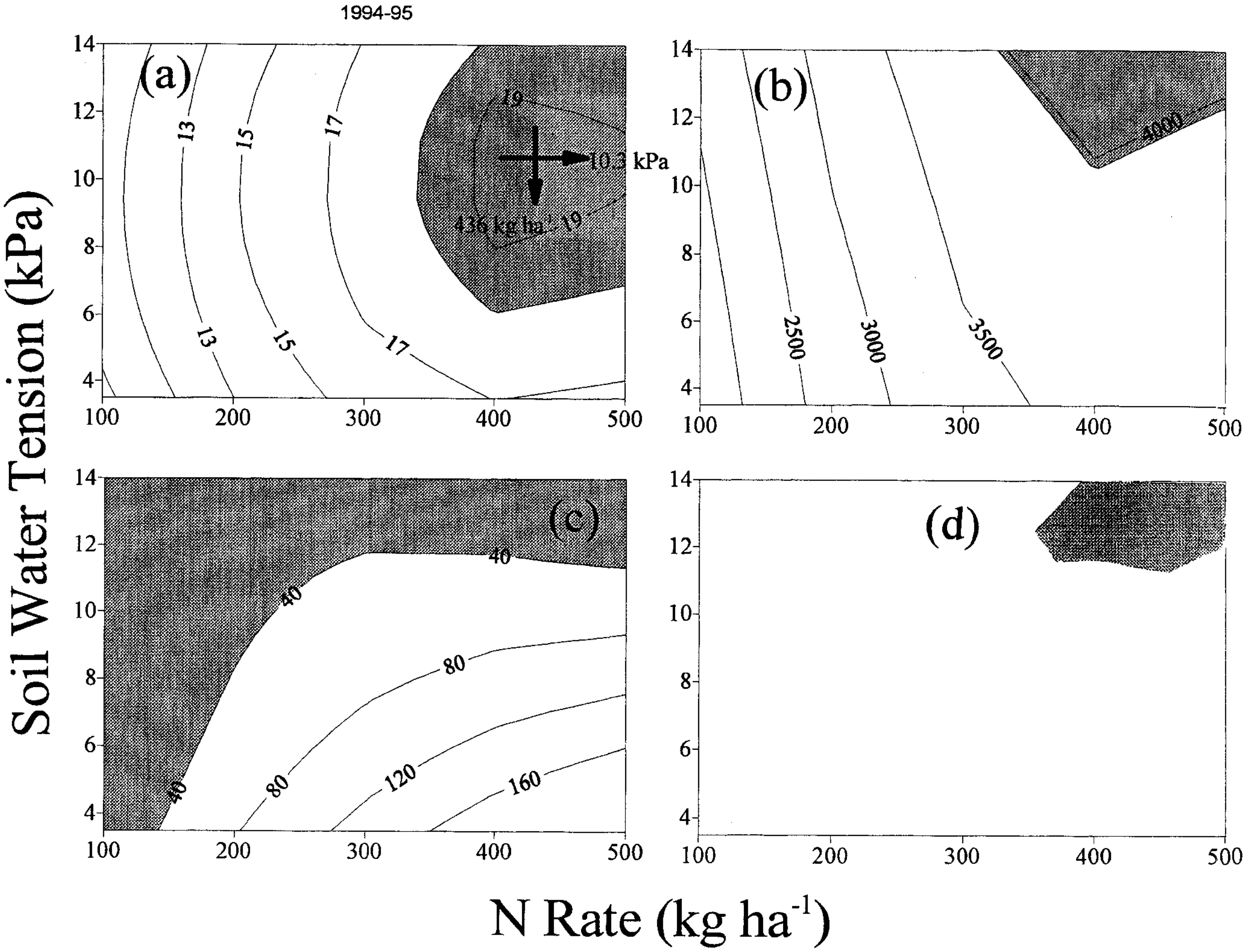

Fig. 2. Response surfaces for broccoli grown during the 1994–1995 season: (a) predicted marketable yield (Mg ha^{-1}), (b) predicted net return ($ ha^{-1}), (c) predicted unaccounted fertilizer N (kg ha^{-1}), (d) Spatial analysis of response surfaces of marketable yield, net return, and unaccounted fertilizer N. Arrows denote the point of maximum response on the surface. The shaded area in (d) represents overlap of the zones of ≥95% of the maximum predicted marketable yield and net return, and ≤40 kg ha^{-1} of unaccounted fertilizer N.

nomic return. Excessive water and N applications had little effect on net returns other than their adverse effect on marketable yields. Similarly, Sanchez et al. (1996) reported that excessive irrigation reduced marketable yields and net returns for sprinkler-irrigated broccoli grown in western Arizona. They found that profit maximizing N and water rates depended mostly on yield and changed little regardless of input or crop prices.

Residual Nitrate

Postharvest soil NO_3-N depth profiles (Fig. 4) show the effects of water and N rates. Trends were similar among years, but the amounts of residual soil NO_3 were highest in 1994–1995 and lowest in 1993–1994. At N rates ≤350 kg ha^{-1}, postharvest soil NO_3-N concentrations never exceeded 10 mg kg^{-1} in any depth increment examined. In contrast, NO_3 accumulated in the soil profile when 500 kg N ha^{-1} were applied, except in the high irrigation treatment. For example, residual NO_3-N in the 0- to 0.9-m depth at rates of 300 to 350 kg N ha^{-1} averaged across all three seasons was 137, 110, and 90 kg ha^{-1}

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

Season	Source	df	Net return	Residual NO_3-N	Unaccounted fertilizer N
1993–1994	**Rep**	**3**	**	**NS†**	**NS**
	N	**3**	**	**	**
	SWT	**2**	**	**	*
	N × SWT	**6**	**NS**	**	**NS**
	Error	**33**			
	CV %‡		**14**	**9**	**32**
1994–1995	**Rep**	**3**	**NS**	**NS**	**NS**
	N	**3**	**	**	**
	SWT	**2**	**	**	**
	N × SWT	**6**	**NS**	**	**
	Error	**33**			
	CV %		**11**	**7**	**11**
1995–1996	**Rep**	**3**	**	**NS**	**NS**
	N	**3**	**	**	**
	SWT	**2**	**NS**	**	**
	N × SWT	**6**	**NS**	**	**NS**
	Error	**33**			
	CV %		**15**	**38**	**103**

* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
† NS, not significant.
‡ Coefficient of variance.

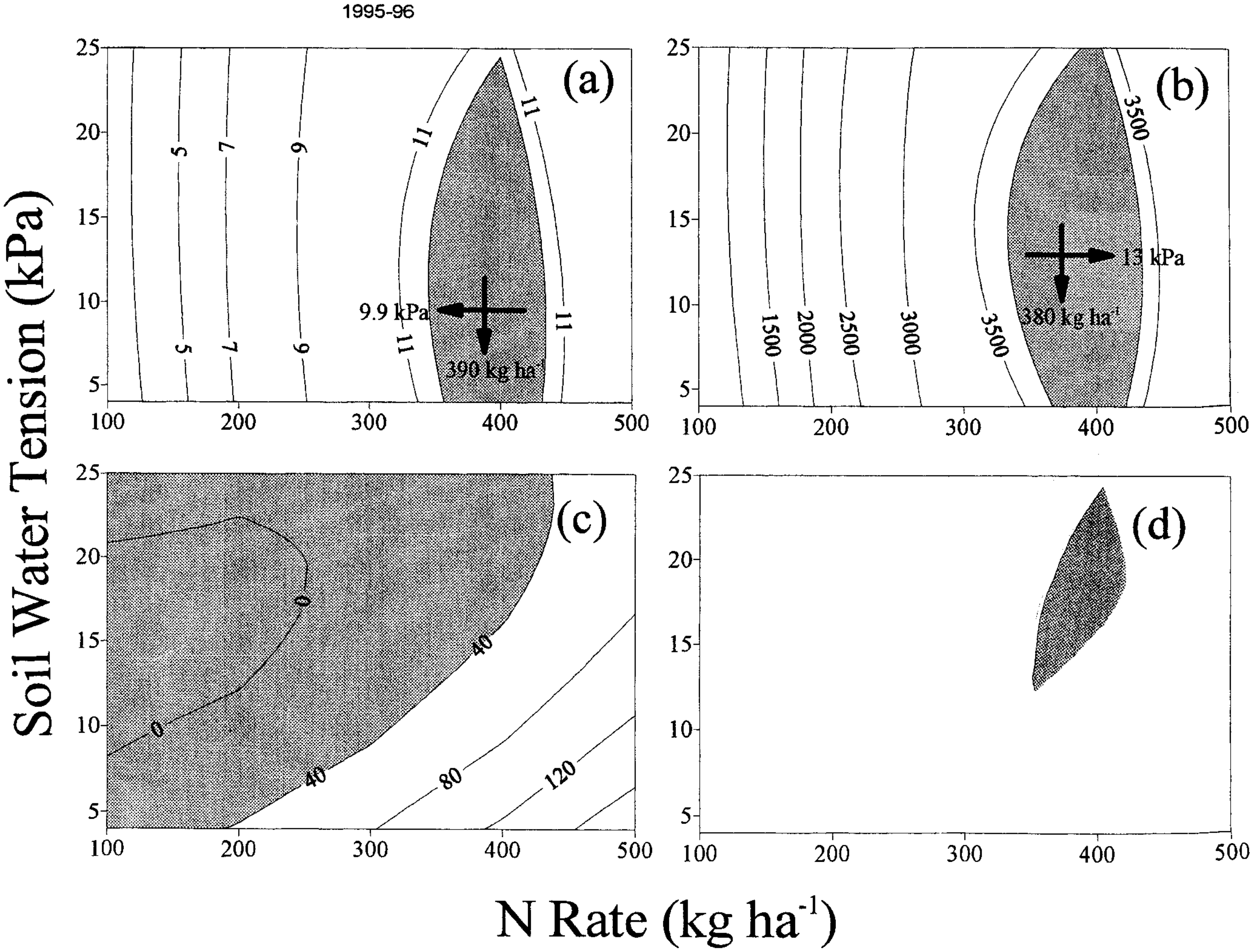

Fig. 3. Response surfaces for broccoli grown during the 1995 to 1996 season: (a) predicted marketable yield (Mg ha^{-1}), (b) predicted net return ($ ha^{-1}), (c) predicted unaccounted fertilizer N (kg ha^{-1}), (d) Spatial analysis of response surfaces of marketable yield, net return, and unaccounted fertilizer N. Arrows denote the point of maximum response on the surface. The shaded area in (d) represents overlap of the zones of ≥95% of the maximum predicted marketable yield and net return, and ≤40 kg ha^{-1} of unaccounted fertilizer N.

for the low, medium, and high irrigation treatments, respectively. In comparison, average amounts of residual soil NO_3-N (0–0.9 m) for plots receiving 500 kg N ha^{-1} during the three seasons were 300, 280, and 130 kg ha^{-1} for the low, medium, and high irrigation treatments. In the low irrigation treatment, NO_3 accumulated mostly in the top 0.3 m of soil, except during 1994–1995 when it accumulated mostly at 0.3 to 0.6 m, probably because of the higher rainfall during that season, compared with the other two seasons. Availability of residual NO_3 to subsequent crops will be highly dependent on factors such as rooting depth, rainfall, and irrigation management. In the high irrigation treatment, NO_3 was lost from the profile, compared with the low and medium treatments.

The lower amounts of residual NO_3 under conditions of low SWT (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 (*Citrullus lanatus* (Thunb.) Matsum. & Nakai var. lanatus) and leaf lettuce (*Lactuca sativa* L. var. *crispa* L.). It is not known whether this N was lost by leaching or denitrification; however, companion studies suggested that leaching was most likely because of low rates of denitrification in these desert soils (Figueroa, 1999).

Unaccounted Fertilizer Nitrogen

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, leached below the root zone, or immobilized in soil organic matter. Unaccounted fertilizer N was significantly affected by both N rate and irrigation treatment (Fig. 1c, 2c, and 3c; Table 2), and increased most dramatically when optimum N rates were exceeded, and under conditions of low SWT. There was a significant N × SWT interaction during 1994–1995, but not during the other two seasons (Table 2). In a few cases, unaccounted fertilizer N was ≤0 kg ha^{-1}. This apparent over-accounting of fertilizer N is

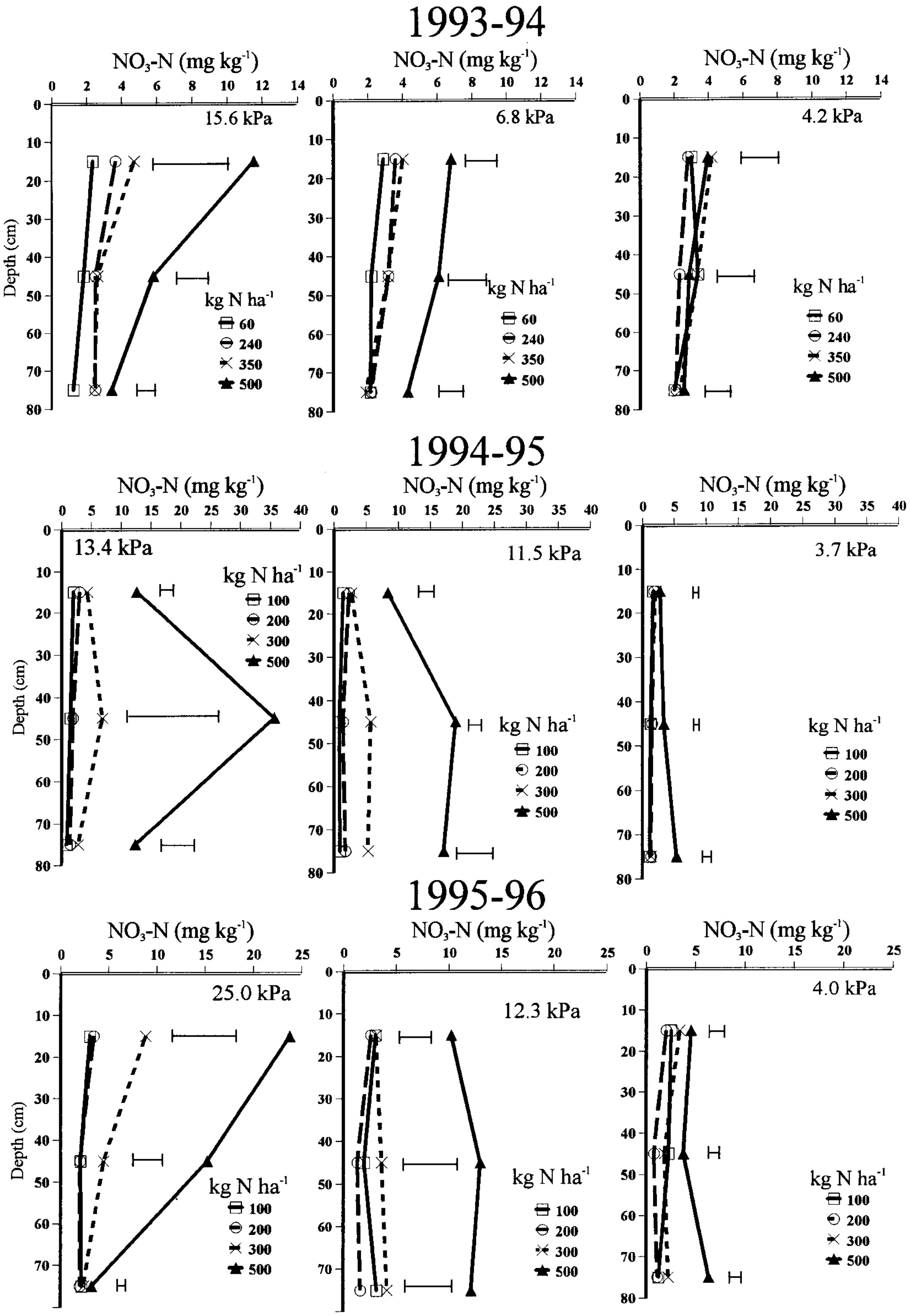

Fig. 4. Postharvest soil NO_3 concentrations for broccoli during the 1993 to 1996 growing seasons. Bars represent Fisher's least significant difference ($P = 0.05$).

most likely because of errors in soil and plant sampling caused by the natural spatial variability of the system. Over-accounting of N averaged only 7 kg ha^{-1} and was <66 kg ha^{-1} in any plot.

Amounts of unaccounted N increased with increasing N rate and lower SWTs (Table 1; Fig. 1c, 2c, 3c). Pier and Doerge (1995a) found similar results for subsurface drip-irrigated watermelon, and Thompson and Doerge (1996b) and Thompson et al. (2000) found similar results for leaf lettuce and cauliflower (*Brassica oleracea* L. var. botrytis L.), respectively. Feigin et al. (1982) also observed increased N losses, presumably by leach-

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

Year	Response variable	Regression equation	R^2
1993–1994	Marketable yield†	$Y = -3.5 + 1.02\mathrm{SWT} + 0.056N - 0.054\mathrm{SWT}^2 + 2 \times 10^{-4}\, N \times \mathrm{SWT} - 7 \times 10^{-5}N^2$	0.86
	Net return	$Y = -803 + 223\mathrm{SWT} + 11.85N - 11.76\mathrm{SWT}^2 + 0.046N \times \mathrm{SWT} - 0.015N^2$	0.85
	Unaccounted N	$Y = 161 - 43\mathrm{SWT} + 0.162N + 2.056\mathrm{SWT}^2 - 0.0037N \times \mathrm{SWT} + 4.9 \times 10^{-4}N^2$	0.67
1994–1995	Marketable yield†	$Y = -0.06 + 0.893\mathrm{SWT} + 0.068N - 0.048\mathrm{SWT}^2 + 2.5 \times 10^{-4}N \times \mathrm{SWT} - 8 \times 10^{-5}N^2$	0.94
	Net return	$Y = 105 + 29.4\mathrm{SWT} + 16.29N + 0.912\mathrm{SWT}^2 + 0.021N \times \mathrm{SWT} - 0.0196N^2$	0.85
	Unaccounted N	$Y = -54 - 3.7\mathrm{SWT} + 0.97N + 0.70\mathrm{SWT}^2 - 0.0616N \times \mathrm{SWT} - 3.5 \times 10^{-4}N^2$	0.93
1995–1996	Marketable yield†	$Y = -7 + 0.10\mathrm{SWT} + 0.094N - 2.2 \times 10^{-3}\mathrm{SWT}^2 - 1.4 \times 10^{-4}N \times \mathrm{SWT} - 1.2 \times 10^{-4}N^2$	0.90
	Net return	$Y = -2491 + 44.52\mathrm{SWT} + 31.0N - 1.01\mathrm{SWT}^2 - 0.047N \times \mathrm{SWT} - 0.0396N^2$	0.89
	Unaccounted N	$Y = 33.6 - 6.75\mathrm{SWT} + 0.086N + 0.285\mathrm{SWT}^2 - 0.015N \times \mathrm{SWT} + 6.6 \times 10^{-4}N^2$	0.61

† First reported in companion paper (Thompson et al., 2002).

ing, because of excessive irrigation applied to drip-irrigated celery (*Apium graveolens* L. var. dulce (mill.) Pers). Sexton et al. (1996) estimated NO_3 leaching in sprinkler-irrigated corn (*zea mays* L.) by the difference method. Leaching losses of N increased when optimum N rates were exceeded. They recommended fertilizing for 95% of maximum yield to minimize NO_3 leaching losses. Nitrate leaching losses of as much 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 46, 46, and 42% of fertilizer N in the first, second, and third seasons. The highest amounts of unaccounted N, as high as 230 kg ha^{-1}, were always in the plots receiving the highest N treatment and the lowest SWT. Our results show that while excessive irrigation had only moderate effects on crop yield, quality, biomass N (see Thompson et al., 2002), and net returns (Table 1), it resulted in much higher N losses from the top 0.9 m of the soil profile.

Response Surface Analysis

Regression equations for response surfaces are shown in Table 3. The F values were significant at $P < 0.001$ for all models. Spatial analysis of response surfaces for marketable yield, net return, and unaccounted fertilizer N (Fig. 1d, 2d, 3d) showed that during each season these three criteria were optimized simultaneously. The areas of overlap were bounded by 300 to 325 kg N ha^{-1} and 8.5 to 12 kPa during 1993–1994, 350 to 500 kg N ha^{-1} and 11 to 14 kPa during 1994–1995, and 340 to 410 kg N ha^{-1} and 11 to 24 kPa during 1995–1996.

Similar production conditions resulted in overlap of acceptable zones of the three production criteria during 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 SWT of 7 to 17 kPa for subsurface drip-irrigated watermelon grown in southern Arizona. Thompson and Doerge (1996b) reported that all three criteria were optimized simultaneously for subsurface drip-irrigated leaf lettuce at N rates of 240 to 250 kg N ha^{-1} and SWT of 6.6 to 7.3 kPa. Thompson et al. (2000) reported that overlap of all three criteria was achieved for subsurface drip-irrigated cauliflower in one of three years. Our results indicate that with proper management of water and N inputs, including maintaining an appropriate SWT, subsurface drip-irrigated broccoli production can result in outcomes that are acceptable to growers, and result in minimal environmental impact.

CONCLUSIONS

Agronomic, economic, and environmental production criteria were evaluated for subsurface drip-irrigated broccoli grown in southern Arizona. During this study, ≥95% of maximum net return encompassed N rates of 300 to 500 kg ha^{-1}, and SWTs of 7 to 25 kPa. Concentrations of postharvest soil NO_3 were <10 mg kg^{-1} in treatments receiving <350 kg N ha^{-1}. Treatments receiving >350 kg N ha^{-1} often had high postharvest soil NO_3, except in the wettest irrigation treatment. Therefore, even though excessive amounts of irrigation water and N had only moderate effects on marketable yield and net returns, they had dramatic effects on residual soil N. The maximum amounts of residual NO_3-N occurred under conditions of high N rates and high SWT. The maximum amounts of unaccounted fertilizer N occurred under conditions of high N rates and low SWT. Overlap of acceptable zones of agronomic, economic, and environmental production criteria was achieved during each season.

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