HORTSCIENCE 37(3):520–524. 2002.

Pre-sidedress Soil Nitrate Testing Identifies Processing Tomato Fields Not Requiring Sidedress N Fertilizer

H.H. Krusekopf, J.P. Mitchell, and T.K. Hartz
Department of Vegetable Crops, University of California, Davis, CA 95616

D.M. May
University of California Cooperative Extension Farm Advisor, Fresno County, Fresno, CA 93702

E.M. Miyao
U.C. Cooperative Extension Farm Advisor, Yolo and Solano Counties, Woodland, CA 95695

M.D. Cahn
U.C. Cooperative Extension Farm Advisor, Yuba and Sutter Counties, Yuba City, CA 95991

Additional index words. PSNT, residual soil N, nitrogen fertilization, nitrogen sufficiency

Abstract. **Overuse of chemical N fertilizers has been linked to nitrate contamination of both surface and ground water. Excessive use of fertilizer also is an economic loss to the farmer. Typical N application rates for processing tomato (*Lycopersicon esculentum* Mill.) production in California are 150 to 250 kg·ha^{-1}. The contributions of residual soil NO_3-N and in-season N mineralization to plant nutrient status are generally not included in fertilizer input calculations, often resulting in overuse of fertilizer. The primary goal of this research was to determine if the pre-sidedress soil nitrate test (PSNT) could identify fields not requiring sidedress N application to achieve maximum tomato yield; a secondary goal was to evaluate tissue N testing currently used for identifying post-sidedress plant N deficiencies. Field experiments were conducted during 1998 and 1999. Pre-sidedress soil nitrate concentrations were determined to a depth of 60 cm at 10 field sites. N mineralization rate was estimated by aerobic incubation test. Sidedress fertilizer was applied at six incremental rates from 0 to 280 kg·ha^{-1} N, with six replications per field. At harvest, only four fields showed a fruit yield response to fertilizer application. Within the responsive fields, fruit yields were not increased with sidedress N application above 112 kg·ha^{-1}. Yield response to sidedress N did not occur in fields with pre-sidedress soil NO_3-N levels >16 mg·kg^{-1}. Soil sample NO_3-N levels from 30 cm and 60 cm sampling depth were strongly correlated. Mineralization was estimated to contribute an average of 60 kg·ha^{-1} N between sidedressing and harvest. Plant tissue NO_3-N concentration was found to be most strongly correlated to plant N deficiency at fruit set growth stage. Dry petiole NO_3-N was determined to be a more accurate indicator of plant N status than petiole sap NO_3-N measured by a nitrate-selective electrode. The results from this study suggested that N fertilizer inputs could be reduced substantially below current industry norms without reducing yields in fields identified by the PSNT as having residual pre-sidedress soil NO_3-N levels >16 mg·kg^{-1} in the top 60 cm.**

Excessive N application is an economic loss to growers in terms of unnecessary input costs, and may also result in greater pest management problems (Jannson and Smilowitz, 1986; Rossi and Strong, 1991). From an environmental perspective, overuse of chemical N fertilizer has been associated with increased levels of nitrate-nitrogen (NO_3-N) in ground and surface water (Blackmer, 1987). For these reasons, development of a better system for recommending fertilizer rates is a major goal of agricultural research.

Nitrogen is a major yield-limiting factor in row-crop production systems in California's Central Valley (Clark et al., 1999). Processing tomatoes are one of the state's most important crops in value and acreage, and California accounts for ≈90% of total United States production (Flint, 1998). The largest N fertilizer input for processing tomatoes generally occurs at sidedressing when plants are 10 to 15 cm tall. Recommended sidedress N application rates for processing tomato production are 134 to 202 kg·ha^{-1} N (Flint, 1998), but growers typically apply 150 to 250 kg·ha^{-1} N to ensure maximum yield (Hartz, personal communication). Fall and early spring soil NO_3-N analyses are often conducted prior to planting as part of routine, comprehensive soil analysis (P, K, micronutrients, etc.), but results are not commonly used for determining sidedress N inputs.

Research by Magdoff et al., 1984; Magdoff, 1991, and others (Fox et al., 1989; Heckman et al., 1995; Schmitt and Randall, 1994; Spellman et al., 1996) has shown a correlation between NO_3-N concentration in the top 30 cm of soil prior to sidedressing and corn yield response to sidedress N. Additional research by Hartz et al. (2000) has documented a similar correlation for California coastal valley lettuce and celery production. The evidence suggests that a pre-sidedress soil nitrate test (PSNT) can indicate a critical level of soil NO_3-N above which crop yield will not be increased by subsequent sidedress N application. Although the PSNT method has not been widely used to determine specific sidedress N application rates in fields testing below a critical level, it has been found helpful at identifying fields where no sidedress N fertilizer is required to maintain yields (Fox et al., 1989; Heckman et al., 1995; Meisinger et al., 1992).

The main objective of our research was to determine if the PSNT technique was useful for predicting the necessity of sidedress N fertilizer on a field-by-field basis in conventional processing tomato production in California. We further sought to establish a critical level of pre-sidedress soil NO_3-N above which no fruit yield increase would occur with subsequent sidedress N application. A secondary goal was to test methods of plant tissue analyses for indicating post-sidedress N deficiency.

Materials and Methods

California's Central Valley is characterized by a semi-arid Mediterranean climate. Total annual rainfall in the Central Valley ranges from 400 to 500 mm in the north to 180 to 200 mm in the south, with rainfall occurring almost exclusively during the winter months (November–March). Summer irrigation of crops is required with water typically supplied from river-fed canal systems, on-farm wells, or both. NO_3-N concentration in irrigation water is typically <5 mg·kg^{-1}. Mean daytime Central Valley temperatures are 23 to 35 °C during the summer growing season. Most agricultural soils in the Central Valley are recently deposited alluvium. Soil organic matter is typically <10 g·kg^{-1}, and organic N content <1 g·kg^{-1}. Predominate soil classification at each site was: Cerini sandy loam (field 1), fine-loamy, mixed, superactive, thermic Fluventic Haplocambids; Ciervo, wet-Ciervo complex, saline-sodic (field 2), fine, smectitic, thermic Vertic Haplocambids; Cerini clay loam (fields 3, 4, 6, 7, 8), fine-loamy, mixed, superactive, thermic Fluventic Haplocambids; Excelsior sandy loam (field 5), coarse-loamy, mixed, superactive, calcareous, thermic Typic Torrifluvents; Yolo silt loam (field 9), fine-silty, mixed, nonacid, thermic Mollic Xerofluvents; and Shanghai Variant (field 10),

Received for publication 18 Dec. 2000. Accepted for publication 5 Sept. 2001. This paper is a portion of a thesis by H.H.K. in partial fulfillment of MS degree requirements at the Univ. of California, Davis. This research was supported in part by grants from the California Dept. of Food and Agriculture's Fertilizer Education and Research Program (CDFA FREP), the California Tomato Research Institute, Inc., and support from the Univ. of California Division of Agricultural and Natural Resources (U.C. DANR).

sandy over loamy, mixed, nonacid, thermic Aquic Xerofluvents.

The project was carried out at three commercial farm sites and one research station site in 1998, and five farm sites and one research station site in 1999 (Table 1). At the two research station sites (fields 4 and 8), an unfertilized winter cover crop of wheat (*Triticum aestivum* L.) and a summer crop of Sudangrass [*Sorghum sudanense* (Piper) Stapf] were grown, mowed, and all aboveground residue removed prior to planting of tomatoes in order to reduce soil nitrate concentrations. Commercial tomato plantings followed standard crop rotations for the region and the individual grower's cultural practices including pre-plant, pre-sidedress N fertilization, or both (Table 1). Common hybrid processing tomato varieties were grown at all locations (Table 1).

All fields received a single sidedress application of urea at rates between 0 to 280 kg·ha^{-1} N in six increments (0, 56, 112, 168, 224, 280 kg·ha^{-1} N) when plant height was ≈10–15 cm. Fertilizer was banded using a standard applicator to a depth of 15 cm, and at a distance of 15 cm from the plant row. The Experimental design in all fields was a randomized complete block with all treatments represented in each field. Research station fields had four replicates (22 m × 1.5 m) and farm sites had six replicates (30 to 60 m × 1.5 m). All fields were furrow irrigated, and other cultural practices typical of the commercial tomato industry were followed.

Prior to sidedress N application, pre-sidedress soil nitrate testing was conducted at all sites to a depth of 60 cm in 30 cm increments. Soil cores (2.5 cm diameter) were taken from shoulders of beds ≈60 cm away from bed centers to avoid pre-sidedress fertilizers applied by individual growers (Table 1). Each soil sample consisted of eight subsamples per replicate block per depth; all samples were stored at 4 °C to inhibit N mineralization until processed. A 10 g subsample of field-moist soil from each sample was placed in a tube with 40 mL of 2 N KCl, shaken by hand until soil aggregates were thoroughly dispersed, allowed to settle until the supernatant was cleared, then the liquid decanted. Samples were sent to the Univ. of California's Division of Agriculture and Natural Resources (UC DANR) Analytical Laboratory for determination of NO_3-N concentration using a diffusion-conductivity analyzer (Carlson et al., 1990). Dry weight NO_3-N concentration was calculated for each sample by using pre- and post-oven-dried weights.

Soil samples from the 0 to 30 cm depth from three replicate blocks in each field were mixed together to make composite samples that were air-dried, ground, and assayed for total N (combustion gas analyzer method; Pella, 1990), and organic matter (modified Walkley-Black; Nelson and Sommers, 1982).

Net mineralization of soil N was determined following eight-week aerobic incubations of the composite samples described in the preceding paragraph. Samples were air-dried, sieved through 5-mm mesh screen, and moisture equilibrated at 0.03 MPa in a pressure apparatus for 3 d. Subsamples of each field soil were then immediately extracted in 2 N KCl for determination of dry weight mineral N (NH_4-N plus NO_3-N) using a diffusion-conductivity analyzer (Carlson et al., 1990) and the procedures described previously. The remainder of each subsample was incubated aerobically at 29 °C in sealed 800 mL containers to maintain moisture content. Head space in each container was over 700 mL, providing sufficient oxygen for microbial activity. Containers were also opened after 4 weeks for additional aeration. After 8 weeks, four subsamples of each field soil were analyzed for dry weight mineral N concentration using a diffusion-conductivity analyzer (Carlson et al., 1990) and the procedure previously described. Nitrogen mineralization rate was calculated as the increase in mineral N over the incubation period. Total soil N was determined by the method of Pella (1990), and soil organic matter by the method of Nelson and Sommers (1982).

Table 1. Soil N concentration prior to sidedress fertilizer application, soil organic matter (SOM) and soil organic N as measured by depth, grower's fertilizer N inputs, and tomato cultivar.

		NO_3-N (mg·kg^{-1})		SOM (g·kg^{-1})	Organic N (g·kg^{-1})	Grower inputs (kg·ha^{-1} N)		
Year	Field	0–30 cm	0–60 cm	0–30 cm	0–30 cm	Pre-sidedress	Sidedress[z]	Cultivar
1998	1	6.3	7.2	7.9	0.8	30	119	BOS 3155
	2	7.4	8.8	8.3	0.9	51	99	La Rossa
	3	22.3	28.5	8.3	0.8	30	119	BOS 3155
	4[y]	8.5	6.1	7.3	0.7	28	---	Heinz 8892
1999	5	7.2	10.9	6.8	0.7	127	146	Lipton 599
	6	23.7	20.7	6.8	0.9	64	198	Heinz 9557
	7	16.0	13.3	7.1	0.8	44	198	CXD 152
	8[y]	4.7	3.5	8.0	0.8	13	---	Heinz 8892
	9	15.7	15.8	22.5	1.8	7	134	BOS 3155
	10	10.1	12.2	15.2	1.1	16	134	RC 32

[z]Sidedress N inputs by growers in non-experimental rows within trial fields.
[y]Fields at Univ. of California's Westside Research and Extension Center received only experimental sidedress N inputs.

About 30 petioles (third petiole from a growing point) were collected from plants in all field plots at three plant growth stages: early bloom, fruit set (earliest fruit ≈2.5 cm diameter), and fruit bulking/early fruit color development. Petioles were oven-dried, ground, extracted with 2% acetic acid solution and analyzed for NO_3-N using the method of Carlson et al. (1990). During the 1999 growing season, additional plant tissue sampling was conducted. Fresh petiole samples from plants in each plot in all fields were mechanically squeezed with a modified 5-ton arbor press immediately following collection to extract fresh sap for NO_3-N measurement by a battery-operated nitrate-selective electrode (Cardy Meter; Horiba Corp., Kyoto, Japan). Whole-leaf samples (third leaf from a growing point) were collected from plants in all fields at fruit set, oven-dried, ground, and tested for total N concentration using the method of Sweeney (1989).

Fruit yields were determined by mechanically harvesting plots into a scale-equipped GTO dumpster weigh wagon (Gilmore-Tatge Mfg. Co., Clay Center, Kans.). Samples of unsorted fruit were collected from the harvester from each plot for determination of fruit maturity and percent defects. Fifty red fruit from each plot were evaluated for soluble solids content (SS, °Brix) and blended juice color [ratio of green (566 nm) to red (650 nm) light reflected from the juice]. Relative fruit yield for each treatment was calculated by dividing the mean yield for each treatment by the mean of the highest yielding treatment in that field. Fields described by the terms N-limited or N-responsive were defined as those showing significant yield response to fertilizer treatment.

Results

Concentrations of soil NO_3-N, organic matter (SOM), and total organic N as measured by pre-sidedress soil testing varied widely among fields (Table 1). Pre-sidedress soil NO_3-N levels across all fields ranged from 3.5 to 28.5 mg·kg^{-1} N. However, there was little difference (r^2 = 0.84) in soil NO_3-N levels within individual fields between 0 to 30 cm and 0 to 60 cm soil depth. SOM (6.8 to 22.5 g·kg^{-1}) and total soil organic N content (0.7 to 1.7 g·kg^{-1}) were within typical ranges observed for California Central Valley soils. Total N application (pre-sidedress plus sidedress N) by commercial growers in non-experimental rows at project sites ranged from 140 to 274 kg·ha^{-1} N, consistent with typical input rates used by the industry.

Significant yield response to sidedress N application was found in only 4 of 10 fields (Table 2). This overall lack of response to sidedress N, and the observation that even in responsive fields yield increase was limited to the lower treatment levels, suggested that linear and quadratic trend analysis was not the most appropriate analytical technique. Therefore, yield data were analyzed by orthogonal contrasts comparing each N treatment level against all higher N treatment rates. In fields 8, 9 and 10 the application of any sidedress N increased yield compared to unfertilized plots, but yields at 56 kg·ha^{-1} N were not significantly different to those achieved with higher fertilization rates. In field 4, a significant yield increase was observed up to 112 kg·ha^{-1} N. There were no fields with yield response to sidedress N application that had pre-sidedress soil NO_3-N concentrations >15.7 mg·kg^{-1} at 0 to

Table 2. Effect of sidedress N rate on fruit yield in fields with significant N response.

Sidedress	Fruit yield (t·ha^{-1})			
kg·ha^{-1} N	Field 4	Field 8	Field 9	Field 10
0	97.2^z	88.9^z	112.0^z	77.5^z
56	118.5	115.6	119.4	88.5
112	129.5	123.0	121.4	90.3
168	138.0	120.7	118.5	91.2
224	137.8	121.0	124.1	89.4
280	141.6	95.4	116.3	87.8

^{z}Indicates that mean yield of treatment level was significantly different P = 0.05 than the combined mean yield of all higher treatment rates, as determined by orthogonal contrast.

30 cm depth (Fig. 1A) or 15.8 mg·kg^{-1} at 0 to 60 cm depth (Fig. 1B).

Fruit maturity and quality parameters (percent red or percent rotten fruit, blended fruit color, and SS) were unaffected by N treatment in most fields. In field 4 there was a significant quadratic response of fruit color to N rate (Table 3), with the unfertilized and the 280 treatments showing the lowest color score (most intense red color). Similarly, fruit SS showed a quadratic relationship to N rate in field 4, with the intermediate N rates having lower SS. In field 8, fruit SS decreased linearly with increasing N. Percent red and rotten fruit did not show any significant response to N rate.

Petiole NO_3-N concentration was most closely related to relative yield at the fruit set growth stage (Fig. 2). Petiole NO_3-N concentration from treatments with significant yield response to N application were most clearly demarcated from non-responsive treatments at fruit set (Fig. 2B). In N-responsive fields, all plants with <2300 mg·kg^{-1} petiole NO_3-N concentration at fruit set had positive yield response to sidedress N. Plants in ≈80% of plots with dry petiole NO_3-N levels >2300 mg·kg^{-1} at fruit set achieved at least 95% relative yield (Fig. 2B).

There was considerable variability in the relationship of petiole sap and dry petiole NO_3-N concentration. Pearson correlation (SAS Institute, 1998) determined the strongest linear relationship of petiole sap and dry petiole NO_3-N concentration was found at fruit set (r^2 = 0.64; Fig. 3). All treatments with significant yield response to N application had <40 g·kg^{-1} total leaf N at fruit set (Fig. 4).

Discussion

This study showed that both university recommended and common industry sidedress N application rates for processing tomato production in California are excessive and could be substantially reduced without loss of yield or fruit quality. Of the 10 fields utilized in this study, only 4 fields had any significant yield response to sidedress N, and none of these fields demonstrated yield response to sidedress N application above 112 kg·ha^{-1} N. Furthermore, fruit quality was virtually unaffected by sidedress N rate.

Pre-sidedress soil nitrate testing was a useful indicator of soil NO_3-N availability. No fields used for this study that had >16 mg·kg^{-1} NO_3-N in the top 60 cm of soil (≈140 kg·ha^{-1} NO_3-N, at a typical bulk density of 1.35 g·cm^{-3}) prior to sidedress demonstrated any yield response to sidedress N application. This observation indicates the possibility of a critical level of residual soil NO_3-N that will be sufficient to sustain proper plant growth and maximum yield without sidedress N application. The similarities between soil NO_3-N levels at the 0 to 30 cm and 0 to 60 cm depths suggested that either sampling depth could be used to estimate NO_3-N availability. Similarly, Binford et al. (1992) found that the predictive value of soil nitrate tests was only slightly improved by sampling to 60 cm depth instead of 30 cm, and that the difference was probably not great enough to justify additional costs for deeper sampling. Pottker et al. (1987) found nitrate concentration in the top 0 to 30 cm of soil to be proportional to nitrate distribution in the surface 1.5 m layer of soil.

The lack of yield response to sidedress N application in fields with >16 mg·kg^{-1} NO_3-N prior to sidedressing was not surprising, since these soil NO_3-N levels represented more than 60% of seasonal total N uptake (200 kg·ha^{-1} N) for high-yield tomato production (Maynard and Hochmuth, 1997). Pre-sidedress residual soil N in project fields was augmented by in-season N mineralization of soil organic matter. Based on the incubation results, N mineralization could have provided an additional 40 to 80 kg·ha^{-1} N to plants during the growing season (Fig. 5). Therefore, in-season mineralization of organic N, coupled with existing soil NO_3-N estimated by PSNT, are likely factors in the overall weak crop response to sidedress N.

Two of four fields with yield response to fertilizer treatment (4, 8) were located at the Westside Research Station, where an unfertilized winter cover crop had been grown, harvested, and all crop residue removed prior to tomato planting in order to lower soil nitrate concentrations (Table 1). Fields 1, 2 and 5 also had low PSNT levels, but did not show yield response to sidedress N application. This result suggested that in-season N mineralization may have been higher than the estimated range, or the crop was able to access mineral N at soil depth >60 cm.

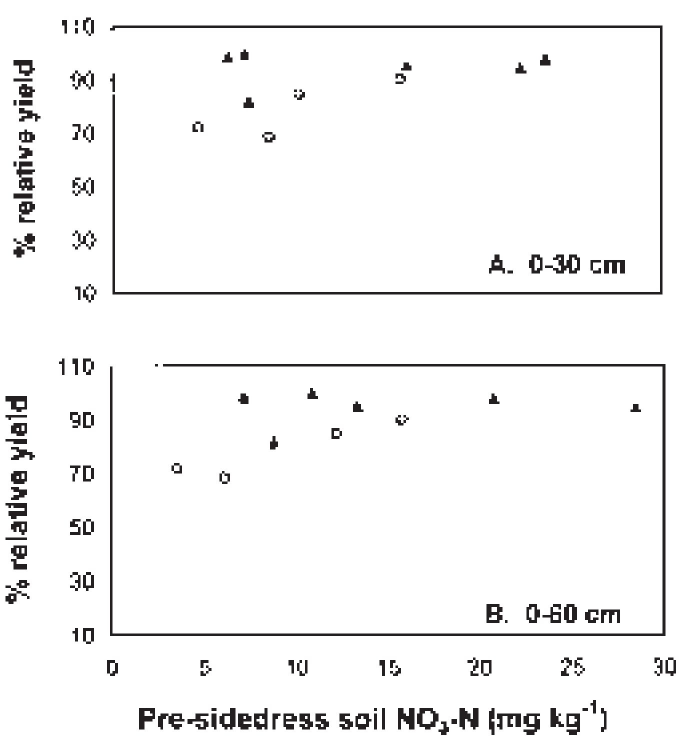

Fig. 1. Relationship of pre-sidedress soil NO_3-N as measured at (**A**) 0 to 30 cm and (**B**) 0 to 60 cm depths and field mean of relative fruit yield by N treatment rate. Symbols indicate fields with (❍) or without (▲) si

Table 3. Effect of sidedress N rate on fruit quality paramaters.

Field	Sidedress kg·ha^{-1} N	Fruit quality indicator color^z	solids^y
4	0	20.0	4.9
	56	22.0	4.9
	112	22.8	4.9
	168	23.0	4.5
	224	21.8	4.7
	280	21.5	5.0
Linear		NS	NS
Quadratic		*	*
8	0		4.4
	56		4.5
	112		4.4
	168		4.1
	224		4.2
	280		4.1
Linear			*
Quadratic			*

^{z}Soluble solids content (SS °Brix).
^{y}Blended juice color, ratio of green (566 nm) to red (650 nm) reflected from juice.
NS, *Nonsignificant or significant at P = 0.05.

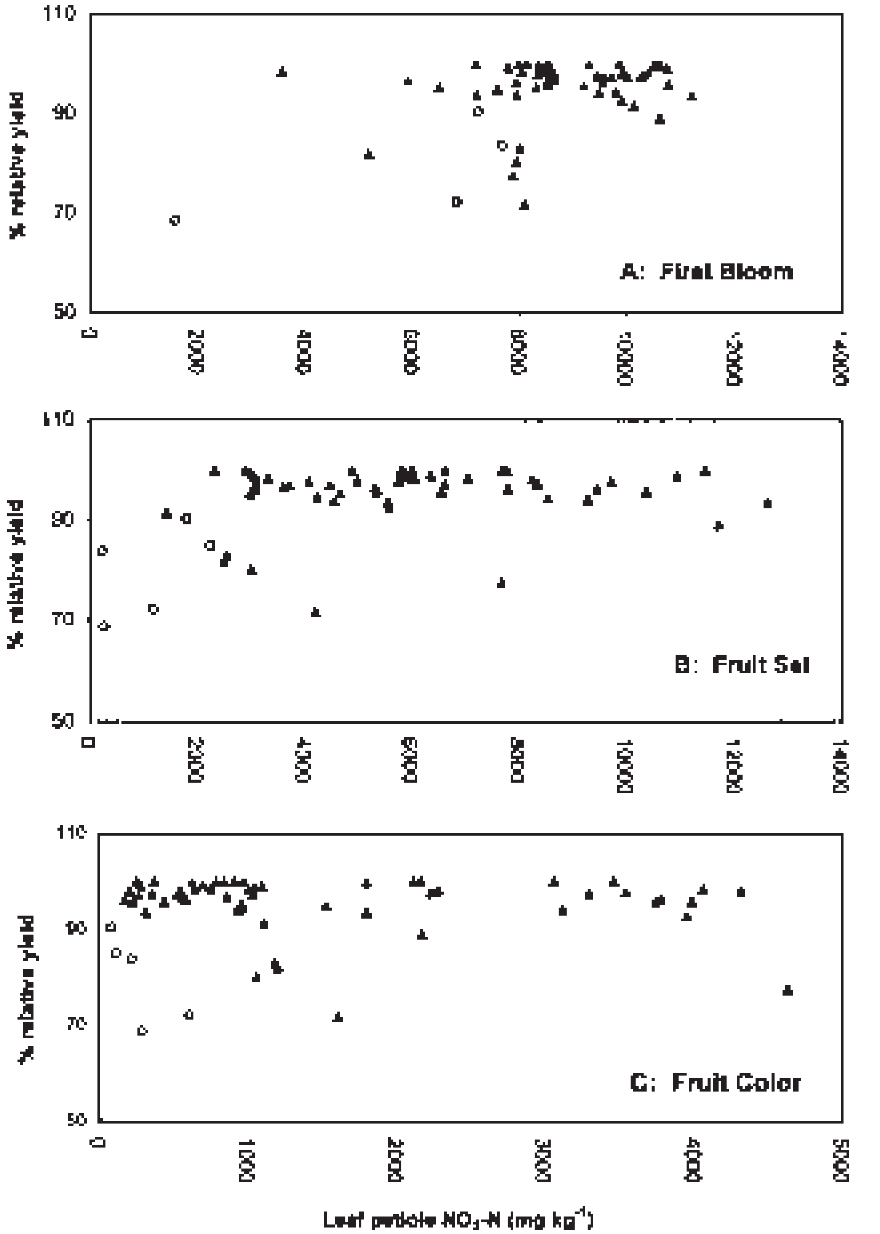

Fig. 2. Relationship of petiole NO_3-N from all fields at all N treatment means at (**A**) first bloom, (**B**) fruit set and (C.) fruit color sampling stages to relative fruit yield. Symbols indicate whether treatment means were (❍) or were not (▲) N-limited, as determined by orthogonal contrast.

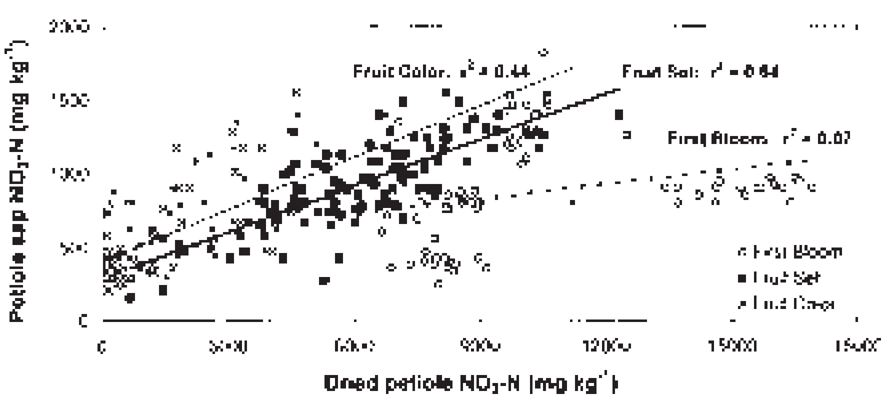

Fig. 3. Linear relationships between treatment means of fresh petiole sap and dried petiole NO_3-N concentrations measured at first bloom, fruit set, and fruit color sampling.

A PSNT level of ≈16 mg·kg^{-1} NO_3-N in the top 0 to 60 cm (or 0 to 30 cm) of soil could represent a conservative threshold level for determining whether sidedress fertilization is required. This suggested PSNT threshold level for processing tomatoes is slightly lower than those determined for corn (*Zea mays* L.) production in the Northeastern and Midwestern U.S. (Fox et al., 1989; Heckman et al., 1995; Magdoff, 1991; Schmitt and Randall, 1994; Spellman et al., 1996), and California coastal valley lettuce (*Lactuca sativa* L.) and celery (*Apium graveolens* L.) production (Hartz et al., 2000). These studies generally set PSNT thresholds between 20 to 25 mg·kg^{-1} NO_3-N.

Petiole NO_3-N at fruit set stage proved to be the most accurate indicator of plant N status. Data from this study suggested a sufficiency threshold level for dried petiole NO_3-N concentration of 2300 mg·kg^{-1} at fruit set, below which post-sidedress plant N deficiency was likely. A more conservative deficiency level of 2500 mg·kg^{-1} NO_3-N at fruit set would still be considerably lower than the 4000 mg·kg^{-1} NO_3-N threshold suggested by Lorenz and Tyler (1983) for the same growth stage. Fruit set petiole sampling was also early enough in crop development that corrective action could be taken through later-season N fertilizer applications.

Petiole sap NO_3-N concentration as measured by the nitrate-selective electrode showed a modest relationship ($r^2 = 0.64$) with dried petiole NO_3-N at fruit set, but there was no relationship at first bloom, and had a weaker correlation ($r^2 = 0.44$) at fruit. Although portable nitrate-selective electrodes could be advantageous by providing results quickly in the field, evidence from this study suggested that those results would be less accurate in determining plant N deficiencies than dried petiole NO_3-N sampling.

All treatments in all fields exceeded the 30 g·kg^{-1} N sufficiency threshold for leaf total N suggested by Lorenz and Tyler (1983). Plants in all treatment replications defined as N-limited had ≤40 g·kg^{-1} total leaf N (Fig. 4). Although there was only one year of data for whole leaf sampling in this study, the high total leaf N levels may indicate a sufficiency threshold >30 g·kg^{-1} at fruit set.

The results of this study support the use of a pre-sidedress soil nitrate test (PSNT) to identify California processing tomato fields that are unlikely to respond to sidedress N application. Fields with pre-sidedress soil nitrate concentrations of >16 mg·kg^{-1} NO_3-N in the top 30 cm of soil would have a low probability of increased yields with sidedress N application. Furthermore, the limited response to sidedress N application, even in fields with minimal residual NO_3-N levels, suggested that sidedress N rates currently used by the commercial tomato industry could be substantially reduced with no loss of yield or fruit quality. Dry petiole NO_3-N sampling at the fruit set stage was determined to be the most effective indicator of post-sidedress plant N deficiency. Plants with dry petiole tissue nitrate-N levels of <2500 mg·kg^{-1} NO_3-N at fruit set are likely to be N-deficient and could

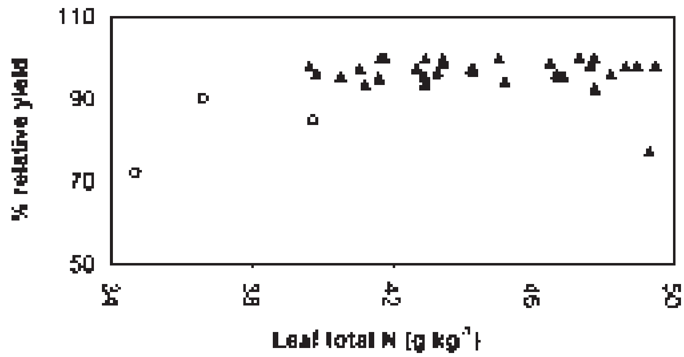

Fig. 4. Relationship of whole-leaf total N at fruit set stage and relative fruit yield. Symbols indicate whether treatment means were (❍) or were not (▲) N-limited, as determined by orthogonal contrast.

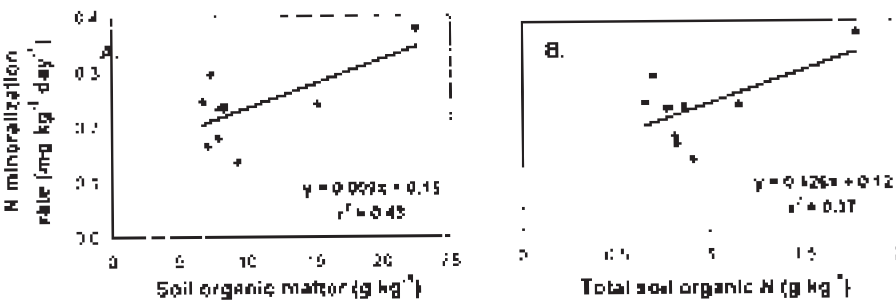

Fig. 5. Relationships of (**A**) soil organic matter and (**B**) total soil organic N with net N mineralization in an 8-week aerobic incubation at 29 °C.

benefit from late-season fertilizer applications.

Literature Cited

Binford, G.D., A.M. Blackmer, and M.E. Cerrato. 1992. Relationships between corn yields and soil nitrate in late spring. Agron. J. 84:53–59.

Blackmer, A.M. 1987. Losses and transport of nitrogen from soils. In: F.M. D'Itri and L.G. Wolfson (eds.). Rural groundwater contamination. Lewis Publ., Chelsea, Mich.

Carlson, R.M., R.I. Cabrera, J.L. Paul, J. Quick, and R.Y. Evans. 1990. Rapid direct determination of ammonium and nitrate in soil and plant tissue extracts. Commun. In Soil Sci. Plant Anal. 21:1519–1529.

Clark, M.S., W.R. Horwath, C. Shennan, K.M. Scow, W.T. Lanini, and H. Ferris. 1999. Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems. Agr. Ecol. Environ. 73:257–270.

Flint, M.L. (ed.). 1998. Integrated pest management for tomatoes. 4th ed. Univ. of California Div. of Agr. and Natural Resources. Publ. 3274.

Fox, R.H., G.W. Roth, K.V. Iversen, and W.P. Piekielek. 1989. Soil and tissue nitrate tests compared for predicting soil nitrogen availability to corn. Agron. J. 81:971–974.

Hartz, T.K., W.E. Bendixen, and L. Wierdsma. 2000. The value of presidedress soil nitrate testing as a nitrogen management tool in irrigated vegetable production. HortScience 35:651–656.

Heckman, J.R., W.T. Hlubik, D.J. Prostak, and J.W. Paterson. 1995. Pre-sidedress soil nitrate test for sweet corn. HortScience 30:1033–1036.

Jannson, R.K. and Z. Smilowitz. 1986. Influence of nitrogen on population parameters of potato insects: abundance, population growth, and within-plant distribution of the green peach aphid, *Myzus persicae* (Homoptera: Aphididae). Environ. Entomol. 15:49–55.

Lorenz, O.A. and K.B. Tyler. 1983. Plant tissue analysis of vegetable crops, p. 24–29. In: H.M. Reisenauer (ed.). Soil and plant tissue testing in California. Univ. of California Div. of Agr. Sci. Bul. 1879:28.

Magdoff, F.R., D. Ross and J. Amadon. 1984. A soil test for nitrogen availability to corn. Soil Sci. Soc. Am. J. 48:6:1301–1305.

Magdoff, F.R. 1991. Understanding the Magdoff presidedress nitrate test for corn. J. Prod. Agr. 4:3:297–305.

Maynard, D.N. and G.J. Hochmuth. 1997. Knott's handbook for vegetable growers. 4th ed. Wiley, New York.

Meisinger, J.J., V.A. Bandel, J.S. Angle, B.E. O'Keefe, and C.M. Reynolds. 1992. Presidedress soil nitrate test evaluation in Maryland. Soil Sci. Soc. Amer. J. 56:1527–1532.

Nelson, D.W. and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter, p. 539–579. In: A.L. Page (ed.). Methods of soil analysis. Part 2: Chemical and microbiological properties. Monogr. 9, 2nd ed. Amer. Soc. Agron., Madis, Wis.

Pella, E. 1990. Elemental organic analysis: Part 2: State of the art. Amer. Lab. 22:12:28–32.

Pottker, D., A.M. Blackmer, and J. Webb. 1987. Amounts and distribution of nitrate in Iowa soils under corn in various cropping systems, p. 213. In: D. Hold (ed.). Agronomy abstracts. Amer. Soc. Agron, Madison, Wisc.

Rossi, A.M. and D.R. Strong. 1991. Effects of host-plant nitrogen on the preference and performance of laboratory populations of *Carneocephala floridana* (Homoptera: Cicadellidae). Entomol. 91:1349–1355.

SAS Institute. 1998. The SAS system for Windows, version 7. SAS Institute, Cary, N.C.

Schmitt, M.A. and G.W. Randall. 1994. Developing a soil nitrogen test for improved recommendations for corn. J. Prod. Agr. 7:328–334.

Spellman, D.E., A. Rongni, D.G. Westfall, R.M. Waskom, and P. Soltanpour. 1996. Pre-sidedress nitrate soil testing to manage nitrogen fertility in irrigated corn in a semi-arid environment. Commun. Soil Sci. Plant Anal. 27:561–574.

Sweeney, R.A. 1989. Generic combustion method for determination of crude protein in feeds: Collaborative study. J. Assoc. Off. Anal. Chem. 72:770–774.