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Nitrogen Requirements of Drip-irrigated Processing Tomatoes

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Abstract. **As growers of processing tomato (*Lycopersicon esculentum* Mill.) adopt drip irrigation, plant vigor and fruit yield typically increase, suggesting a need for re-evaluation of established nitrogen (N) fertilization practices. Trials were conducted in California in 2007–2008 to evaluate growth and N uptake dynamics of drip-irrigated processing tomatoes across N fertigation regimes ranging from deficient to excessive. Whole plants were collected at 2-week intervals for determination of biomass and N content, recently matured whole leaves for total N and petioles for NO_3-N. Additionally, six commercial fields were sampled at 3- to 4-week intervals to document N uptake and crop N status under conditions representative of the industry. A seasonal N rate of ≈200 kg·ha^{-1} appeared adequate to maximize fruit yield across the range of field conditions encountered. The four highest-yielding fields (143 Mg·ha^{-1} mean fresh fruit mass) averaged 14 Mg·ha^{-1} of above-ground biomass with fruit representing 62%; these fields averaged 296 kg·ha^{-1} biomass N, of which 71% was in fruit. The rate of biomass development and N uptake peaked during the period between early fruit setting and early red fruit development (a period of ≈6 weeks) during which N uptake averaged 4 to 5 kg·ha^{-1}·d^{-1}. Leaf N concentration was highly correlated with whole plant N ($r^2 = 0.83$) and provided a reliable indicator of plant N sufficiency throughout the season. Petiole NO_3-N did not reliably discriminate between crops with adequate or deficient N availability; current petiole NO_3-N sufficiency guidelines are unrealistically high.**

Processing tomato is an important crop in California, where more than 100,000 ha are produced annually (Hartz et al., 2008). In recent years, drip irrigation has revolutionized production and increased fruit yield expectations; some California growers now average greater than 110 Mg·ha^{-1} with individual fields greater than 130 Mg·ha^{-1} not uncommon. Increased yield potential, and the ability to apply nitrogen (N) fertilizer at will with no cultural constraints, have caused growers to re-evaluate their N management practices. In furrow-irrigated culture, a seasonal N rate of 170 kg·ha^{-1}, with the majority applied by early-season sidedressing, was generally sufficient (Hartz et al., 2008); in a study encompassing 10 fields, Krueskopf et al. (2002) reported that fruit yield maximization with furrow irrigation required a seasonal total of no more than 112 kg·ha^{-1} N. However, with processing tomato fruit N content reported to range from 2 to more than 3 kg·Mg^{-1} fresh weight (Blaesing et al., 2006; de C. Carmello and Anti, 2006; Vazquez et al., 2006), such low seasonal N rates would appear insufficient to support high-yield (greater than 130 Mg·ha^{-1}) drip production.

Several studies on crop N uptake and N fertilizer requirement of drip-irrigated processing tomatoes have been reported, with widely varying results. In Turkey, Erdal et al. (2006) found above-ground biomass N content of a yield-maximizing N treatment (160 kg·ha^{-1}) to be only 222 kg·ha^{-1} N. Christou et al. (1999), working in Greece, reported a seasonal N uptake of ≈300 kg·ha^{-1} but no significant N fertilization effects on fruit yield over the range of 50 to 150 kg·ha^{-1} N. In Italy, Tei et al. (2002) showed that a seasonal N rate of 200 kg·ha^{-1} was sufficient to maximize fruit yield with biomass N varying from 233 to 347 kg·ha^{-1} depending on year and N rate. However, a survey of 20 commercial fields in Australia (Blaesing et al., 2006) reported a mean crop N uptake of 466 kg·ha^{-1}. de C. Carmello and Anti (2006; Brazil) and Vazquez et al., (2006; Spain) also reported seasonal N uptake exceeding 400 kg·ha^{-1}. Such high N uptake suggests that significantly higher N fertilization rates might be required under some field conditions.

Plant tissue analysis is a common practice in drip-irrigated culture to inform N fertigation decisions. The principle of "critical plant N concentration" (N_c, the minimum whole plant N concentration required to maximize growth; Greenwood et al., 1991) has been validated for processing tomatoes (Tei et al., 2002). They showed that the critical plant N concentration declined through the season on the basis of above-ground dry matter (DM) accumulation and was described by the equation $N_c = 45.3\ DM^{-0.327}$. However, whole plant N monitoring is impractical; whole leaf total N and petiole NO_3-N are the diagnostic measures widely used by commercial growers. Although a variety of tissue diagnostic standards have been published for tomato (Hartz et al., 1998; Jones et al., 1991; Lorenz and Tyler, 1983; Piggott, 1986), none have been validated for high-yield drip-irrigated production.

In this study, N fertigation trials and commercial field monitoring were conducted in California to document the N uptake pattern and N fertigation requirements of drip-irrigated processing tomatoes. Furthermore, current plant tissue diagnostic standards for crop N sufficiency were re-evaluated for applicability with drip-irrigated culture.

Materials and Methods

Three seasonal N rates were compared in field trials conducted at the University of California Davis (UCD) in 2007 and 2008. The field soils were a Reiff loam (2007) or a Yolo clay loam (2008, mixed, nonacid, thermic Typic Xerorthents). The soil pH was 7.4 and 7.3 and organic matter 9 and 16 g·kg^{-1} in 2007 and 2008, respectively. The experimental design in both years was a randomized complete block with a split plot treatment structure. N regime was the main plot and cultivar ('AB2' or 'Heinz 9780', commonly used determinate lines for once-over mechanical harvest) the split plot. There were three main plot replications. Each split plot was three 1.5-m beds wide by 30 m long. Plots were transplanted at a population of 18,500 ha on 9 May and 28 Apr. in 2007 and 2008, respectively. The transplants were established with sprinklers and then irrigated with a buried drip irrigation system. Drip irrigation was applied three times a week for the first month of irrigation and daily thereafter. Irrigation volume was based on reference evapotranspiration (modified Penman) and crop canopy width (visually estimated as the percentage of row width). Seasonal drip application was 390 and 500 mm in 2007 and 2008, respectively; there was no effective precipitation during either growing season.

Nitrogen was applied preplant and in weekly fertigations through the drip system. Low, intermediate, and high N regimes were evaluated in each year with the intent to achieve deficient (fruit yield-limiting), adequate (fruit yield-maximizing), and excessive N regimes. There was minor variation in the N fertilization regimes between years (Table 1), but across years, a mean seasonal total of 103, 210, and 326 kg·ha^{-1} was applied in the low, intermediate, and high treatments, respectively. A 1:1 liquid blend of urea and ammonium nitrate was used for all fertigations. Phosphorus (P) was applied preplant at 34 kg·ha^{-1} in the deficient and adequate N treatments and at 68 kg·ha^{-1} in the excessive N treatment. No potassium (K) was applied as a result of the relatively high exchangeable soil level (0.56 and 0.72 cmol·kg^{-1} in 2007 and 2008, respectively).

Beginning ≈5 weeks posttransplant (early bloom growth stage), the plots were sampled every 2 weeks. In each split plot, four representative whole plants were harvested for determination of total above-ground dry biomass and N content; once fruit began to

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Table 1. Nitrogen application schedule (kg N/ha) in the UCD fertigation trials.

Weeks after transplanting	2007			2008		
	Low	Intermediate	High	Low	Intermediate	High
2	7.9	7.9	7.9			
3	11.2	11.2	16.8			
4	5.6	11.2	16.8	8.4	16.8	25.3
5	5.6	22.5	33.7	8.4	16.8	25.3
6	5.6	22.5	33.7	11.2	22.5	33.7
7	5.6	22.5	33.7	14.0	28.1	42.1
8	5.6	22.5	33.7	14.0	28.1	42.1
9	5.6	22.5	33.7	14.0	28.1	42.1
10	5.6	22.5	33.7	11.2	22.5	33.7
11	5.6	22.5	33.7	8.4	16.8	25.3
Seasonal total[z]	90	213	330	116	206	321

[z]Includes preplant nitrogen (N) at 25.8 kg·ha^{-1} in low and intermediate N, 51.6 kg·ha^{-1} in high N.

develop, plants were segregated into vine and fruit samples. Additional samples of recently matured leaves were collected for analysis of petiole NO_3-N and whole leaf total N. Plant tissue was oven-dried at 65 °C and ground for analysis. Total N was determined by nitrogen gas analyzer (Model FP-528; Leco Corp., St. Joseph, MI). Petiole NO_3-N was measured by flow injection analysis (Lachat Instruments, Milwaukee, WI) after extraction with 2% acetic acid.

Plant sampling was continued until 7 to 10 d before commercial harvest stage, at which point greater than 80% of fruit was ripe. At that point, crop senescence was sufficiently advanced that continued sampling would be confounded by loss of senescent leaf tissue and early-ripening fruit. On the final sampling date (≈15 weeks after transplanting), fruit yield from an additional eight plants per split plot was measured to ensure accuracy. Fruits were graded to determine marketable yield (intact red fruit). Soluble solids concentration was determined by refractometer on composite juice samples of marketable fruit.

In both 2007 and 2008, three commercial drip-irrigated processing tomato fields were also monitored. Soil pH ranged from 6.8 to 7.6 and organic matter from 7 to 15 g·kg^{-1}. Site characteristics, transplant dates, cultivars planted, and seasonal fertility rates are given in Table 2. All cultivars were commonly used in the California industry and similar in maturity to those used in the UCD trials. Three separate areas in each field were monitored with plant sampling performed as outlined for the UCD trials. Sampling was done four times over the season in each field in 2007 and five times in 2008.

Results

The low N treatment at UCD significantly limited above-ground crop biomass and fruit yield, whereas the intermediate N treatment produced biomass and fruit yield equivalent to the high N rate (Table 3); the N treatments will henceforth be referred to as deficient, adequate, and excessive. Crop productivity in 2008 was greater than in 2007, but the adequate and excessive N treatments produced total fruit yields in excess of 125 Mg·ha^{-1} in both years. AB2 was the higher-yielding cultivar. Comparison of leaf P and K concentration to existing sufficiency thresholds (Hartz et al., 1998) indicated that all treatments were adequately supplied with P and K throughout both growing seasons.

The biomass N content at harvest varied widely by N treatment and significantly between years. The majority of biomass N was contained in fruit, with year the only factor affecting N partitioning within the plant. There were no interactions among year, N treatment, and cultivar for any crop productivity parameter.

Biomass development was similar among N treatments through 11 weeks after transplanting, at which point growth slowed in the deficient N treatment compared with the higher N treatments (Fig. 1A); that slower growth coincided with extremely limited N uptake after Week 9 (Fig. 1B). Limited N uptake in the deficient N treatment led to the whole plant N concentration falling below the critical plant N concentration (N_c) for processing tomatoes (Fig. 1C, Tei et al., 2002). Tei et al. validated the N_c curve only for biomass values ranging from 1.2 to 12.4 Mg·ha^{-1}; data from the first and last sampling dates fell outside this range.

Table 2. Cultural detail and fertilization rates for the commercial fields monitored.

Year	Field	Transplant date	Variety	Soil texture	Olsen phosphorus (mg·kg^{-1})	Exchangeable potassium (cmol·kg^{-1})	Seasonal fertilization rate (kg·ha–1)[z]		
							Nitrogen	Phosphorus	Potassium
2007	1	4 Apr.	Heinz 2601	Loam	4	0.29	190	7	22
	2	1 May	AB5	Clay loam	16	0.35	203	7	17
	3	10 May	AB2	Clay loam	11	0.28	209	43	31
2008	4	3 Apr.	AB2	Clay loam	6	0.59	186	15	0
	5	16 Apr.	Heinz 2401	Clay loam	6	0.47	220	32	0
	6	19 Apr.	Heinz 8004	Clay loam	29	1.13	240	26	0

[z]Includes preplant fertilization.

Table 3. Effect of year, cultivar and fertility treatment on crop biomass, N uptake, and fruit yield in the UC Davis trials.

Year	Dry wt (Mg·ha^{-1})			Fruit yield (Mg·ha^{-1})		Fruit soluble solids (%)	Biomass N (kg·ha^{-1})	N in fruit (% of biomass N)
	Vine	Fruit	Total	Total	Marketable			
2007	4.4	7.1	11.5	122	104	5.5	232	72
2008	5.9	8.3	14.2	138	124	5.5	295	65
	**	**	**	**	**	NS	**	*
Cultivar								
AB 2	5.4	8.3	13.7	138	122	5.5	276	69
Heinz 9780	4.9	7.1	12.0	122	105	5.4	253	68
	NS	**	*	*	*	NS	NS	NS
N treatment								
Deficient	4.6 b[z]	6.6 b	11.2 b	108 b	96 b	5.6	197 c	68
Adequate	5.1 ab	8.1 a	13.2 ab	139 a	121 a	5.4	264 b	71
Excessive	5.8 a	8.4 a	14.2 a	143 a	124 a	5.4	331 a	67
						NS		NS

[z]Mean separation by Tukey's test ($P < 0.05$).
NS, *, ** = Differences nonsignificant or significant at $P < 0.05$ or 0.01, respectively; no interactions observed among fertility treatment, cultivar, and year.
N = nitrogen.

The commercial fields varied widely in fruit yield, biomass productivity, and crop N uptake (Table 4). Partitioning of biomass and N between fruit and vine was consistent among the commercial fields; at the final sampling, fruit contained from 60% to 64% of dry biomass and 68% to 73% of biomass N. This was similar to the UCD trials where, across years, the adequate N treatment averaged 61% and 71% of biomass and biomass N, respectively, in fruit. In all commercial fields, like in the adequate N treatment at UCD, crop N uptake substantially exceeded the seasonal fertilizer rate. Comparing the whole plant N concentration with the N_c indicated that Field 4 was the most N-limited (Fig. 2). Comparison of leaf P and K concentration to existing sufficiency thresholds (Hartz et al., 1998) indicated that Field 1 had limited P and K availability, whereas all other fields were adequately supplied.

To evaluate the typical growth pattern of vigorous, high-yield fields, crop biomass in commercial Fields 3 and 6, and in both years of the UCD adequate N treatment, were compared (Fig. 3). A third-order polynomial described the relationship between biomass development and days after transplanting. Across the sampling period from early flowering until greater than 80% ripe fruit, these fields gained an average of 190 kg·ha^{-1} dry mass daily with a maximum daily growth rate of ≈230 kg·ha^{-1} occurring during late fruit setting and early ripening.

Based on this biomass accumulation pattern, the N uptake required to maintain whole plant N above the N_c ($N_{upt} = DM^{-0.673}$; Tei et al., 2002) was compared with the actual crop N uptake (Fig. 4). Total biomass developed in these high-yield fields varied from 10.9 to 16.2 Mg·ha^{-1}. The critical N uptake would have been ≈230 to 290 kg·ha^{-1}, whereas the actual uptake ranged from ≈250 to 380 kg·ha^{-1}. Actual N uptake in these fields peaked at ≈5 kg·ha^{-1}·d^{-1} during fruit setting; meeting the estimated critical N uptake during this period would have required ≈4 kg·ha^{-1}·d^{-1}.

Whole leaf N and petiole NO_3-N from all fields were compared with existing sufficiency thresholds (Hartz et al., 1998; Lorenz and Tyler, 1983; Fig. 5). The data were graphed by posttransplanting growing degree days (GDD, 10 and 30 °C lower and upper temperature thresholds) to match fields by phenological stage; early bloom, full bloom, and early red fruit growth stages corresponded to ≈300, 600, and 900 GDD posttransplant. With the exception of marginally low early-season values, the only samples categorized as N-deficient were from the UCD-deficient N treatment and a midseason date in commercial Field 4. This agreement between diagnosis of N deficiency by leaf N concentration and by the plant critical N concentration approach (Figs. 1 and 2) is the result of the strong correlation between leaf N and whole plant N (Fig. 6). Across all fields and growth stages, the N concentration of recently mature leaves averaged 12% higher than whole plant N.

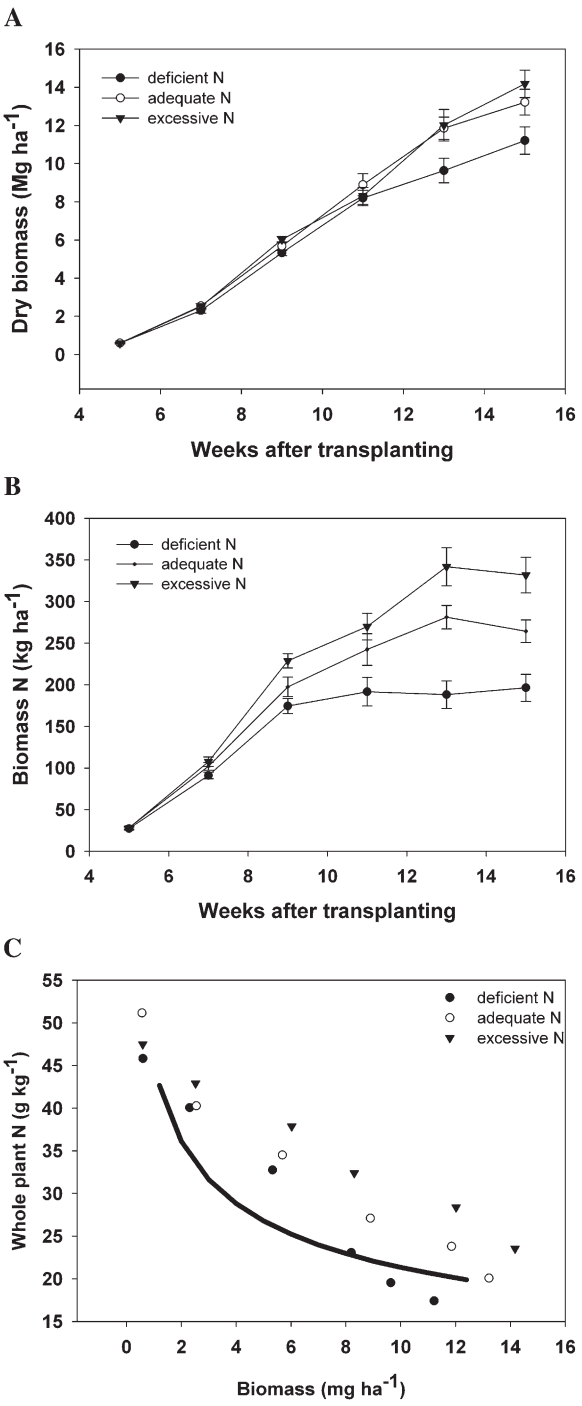

Fig. 1. Effect of nitrogen (N) fertilization on processing tomato growth (**A**), N uptake (**B**), and plant N concentration (**C**) across cultivars and years in the UCD trials. Line in **C**: plant critical %N ($N_c = 45.3$ dry biomass$^{-0.327}$) from Tei et al. (2002).

Table 4. Fruit yield, crop biomass and nitrogen uptake in the commercial fields.

Year	Field	Total fruit yield (Mg·ha^{-1})	Total biomass (Mg·ha^{-1})	Fruit biomass (% of total)	Total biomass N (kg·ha^{-1})	Fruit N (% of total)
2007	1	101	8.1	61	214	71
	2	115	10.1	60	273	70
	3	133	10.9	64	275	73
2008	4	115	11.6	64	206	72
	5	110	10.6	63	257	71
	6	160	16.2	60	382	68

N = nitrogen.

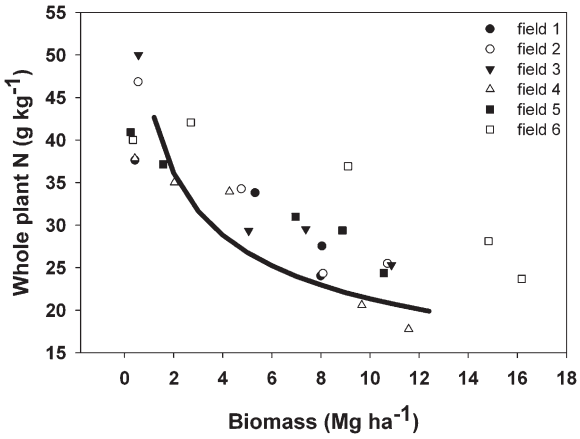

Fig. 2. Seasonal pattern of whole plant nitrogen (N) concentration in the commercial fields. Line: plant critical N concentration (N_c = 45.3 dry biomass$^{-0.327}$) from Tei et al. (2002).

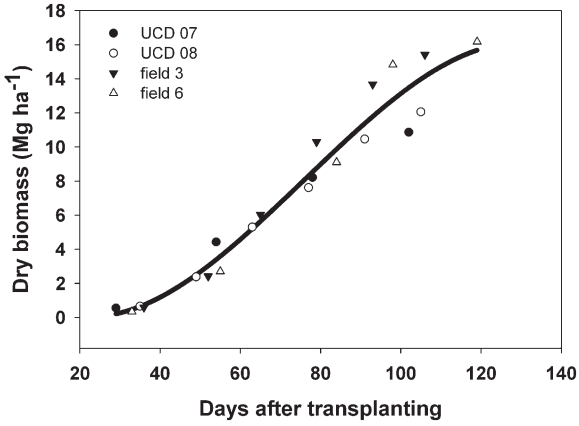

Fig. 3. Crop growth in high-yielding fields as a function of days after transplanting ($y = -0.000026x^3 + 0.006x^2 - 0.23x + 2.53$, $r^2 = 0.95$).

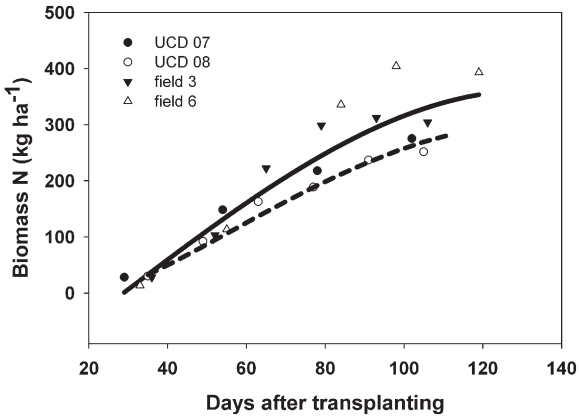

Fig. 4. Crop nitrogen (N) uptake of high-yield fields as a function of days after transplanting ($y = -0.00017x^3 + 0.013x^2 + 4.97x - 150$, $r^2 = 0.88$). Dashed line: critical N uptake (N_{upt} = dry biomass$^{-0.673}$) from Tei et al. (2002).

Conversely, existing petiole sufficiency standards were unrealistic with most commercial fields, and the UCD adequate N treatment, below the standard at all growth stages. The decline in petiole NO_3-N during fruit setting was rapid; by full bloom stage, NO_3-N concentration was less than 3000 mg·kg^{-1} in most fields with little discrimination between adequate and deficient N situations. After full bloom, even adequately supplied plants showed very low petiole NO_3-N concentration.

Discussion

Biomass production, fruit yield, and N uptake in the California processing tomato fields monitored in this study closely matched the results of Tei et al. (2002) in Italy but differ substantially from other recent reports (Blaesing et al., 2006; de C. Carmello and Anti, 2006; Vasquez et al., 2006). We found high-yield fields produced on average 143 Mg of total fruit, 13.4 Mg of above-ground biomass, and 296 kg of biomass N/ha. In a 3-year study Tei et al. (2002) reported that adequately fertilized processing tomatoes produced a mean of 155 Mg total fruit, 12.2 Mg biomass, and 289 kg biomass N/ha. Although achieving fruit yields similar to our study (128 to 158 Mg·ha^{-1}), Blaesing et al. (2006), de C. Carmello and Anti (2006), and Vasquez et al., (2006) reported crop N uptake of 466, 441, and 445 kg·ha^{-1}, respectively. A major portion of the disparity in N uptake related to fruit N content. In the present study, fruit dry matter averaged 57 g·kg^{-1} of fresh weight across fields, similar to the 52 g·kg^{-1} reported by Tei et al. (2002); N concentration in fruit dry mass in both studies averaged 26 g·kg^{-1}, resulting in an N content in fresh fruit of ≈1.4 kg·Mg^{-1} fresh weight. By contrast, the other studies reported fruit N content of 2 to 3.7 kg·Mg^{-1} fresh weight. The higher fruit N content was primarily the result of higher fruit dry mass (80 to 100 g·kg^{-1} fresh weight). Such high DM content would be extraordinarily unusual in processing tomatoes. Dry matter content of tomato fruit generally range from 50 to 75 g·kg^{-1} (Davies and Hobson, 1981). Soluble solids usually account for the vast majority of total solids as was the case in the UCD trials and in the research of Mitchell et al. (1991). Both Blaesing et al. (2006) and de C. Carmello and Anti (2006) found soluble solids averaged less than 50 g·kg^{-1}; the explanation for the much higher DM content they reported was not apparent.

At UCD, a seasonal N rate between 90 and 213 kg·ha^{-1} was sufficient to maximize fruit yield, again corroborating the results of Tei et al. (2002) who reported that seasonal N rates between 100 and 200 kg·ha^{-1} maintained plant N concentration above the N_c. That the commercial fields generally appeared adequately fertilized based on N_c while receiving seasonal N of ≈200 kg·ha^{-1} supported the conclusion that seasonal N application greater than 200 kg·ha^{-1} is seldom required. From an environmental standpoint, a 200 kg·ha^{-1} seasonal N fertilization rate would put this production system in approximate N balance; with a marketable yield goal of 120 to 140 Mg·ha^{-1} of fruit containing 1.4 kg N/Mg, N removal from the field would approach 200 kg N/ha.

Soil contribution to crop N supply, either from residual NO_3-N or in-season mineralization, can be an important factor in processing tomato production. Krueskopf et al. (2002) found that soil residual NO_3-N in the top 60 cm of commercial processing tomato fields in California varied from 4 to 26 mg·kg^{-1}. Tei et al. (2002) reported soil N availability (estimated from the N uptake of unfertilized tomatoes) varied across years from 110 to 203 kg·ha^{-1}. In the present study, the wide disparity in apparent soil N supply (biomass N – fertilizer N) between

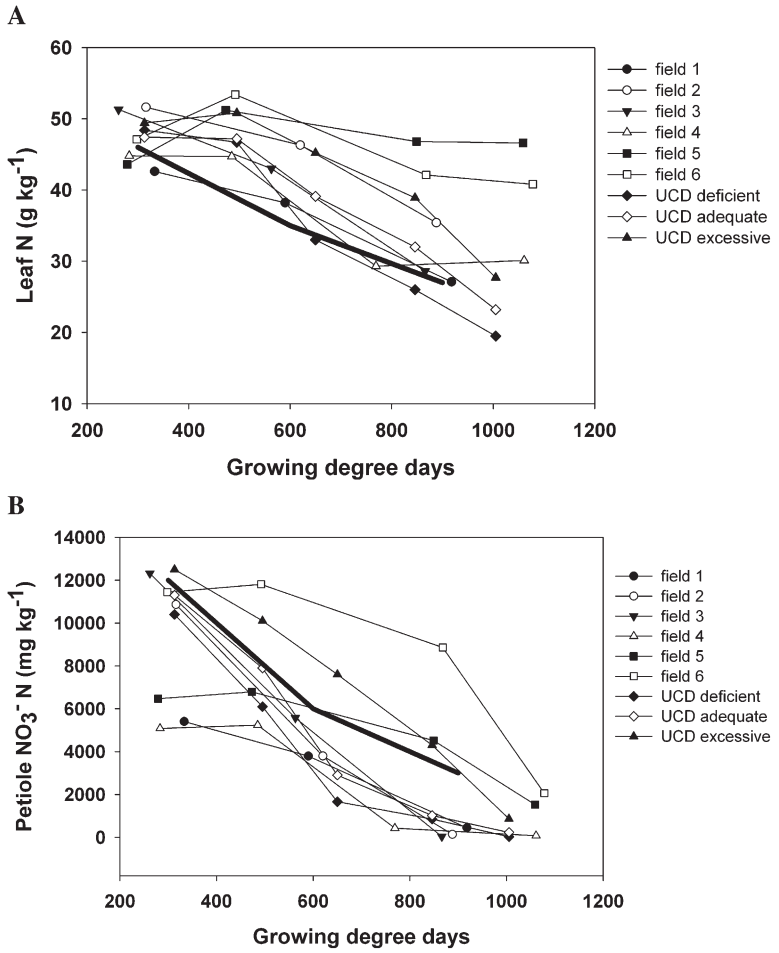

Fig. 5. Comparison of whole leaf nitrogen (N) (**A**) and petiole NO_3-N (**B**) with current tissue sufficiency guidelines (solid lines); leaf N guidelines from Hartz et al. (1998); petiole guidelines from Lorenz and Tyler (1983). GDD = cumulative posttransplanting growing degree days calculated with 10 and 30 °C threshold temperatures.

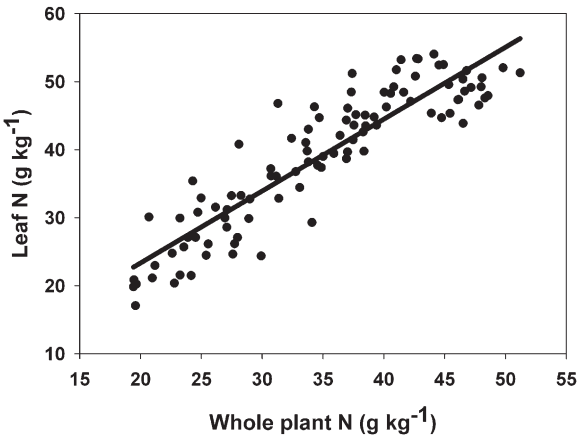

Fig. 6. Relationship between whole plant nitrogen (N) concentration and leaf N concentration (y = 1.12x, r^2 = 0.83); data include all growth stages from all fields.

commercial Fields 4 and 6 (20 versus 142 kg·ha^{-1}) reinforced the potential importance of, and the variability in, the soil contribution to crop N availability.

The timing of biomass development and N uptake was predictable. In the high-yield fields, more than 60% of seasonal growth and N uptake occurred during a 6-week period between early fruit set and the early red fruit stage. This result mirrored the growth pattern reported by Carmello and Anti (2006). For maximum effectiveness, N fertigation should be timed to maintain adequate N supply during this period of peak N demand.

Whole leaf total N appeared to be a useful diagnostic of crop N sufficiency. Support for the broad applicability of leaf N sufficiency standards can be drawn from the applicability of the N_c equation of Tei et al. (2002) to the UCD data; across cultivars and years, the growth rate declined in the deficient N treatment as plant N fell below N_c (Fig. 1). The strong correlation between leaf N and whole plant N (Fig. 6) suggested that leaf N should be a useful surrogate for whole plant N. The leaf N sufficiency thresholds of Hartz et al. (1998) were validated, identifying only Field 4 and the UCD-deficient treatment as N-limited. These thresholds were developed by applying the Diagnosis and Recommendation Integrated System (Beaufils, 1973) approach to data from a large-scale California field survey; the leaf N concentration that was met or exceeded by 80% of nutritionally balanced high-yield fields was considered to be sufficient. Such a standard may be higher than necessary to maximize growth, but it provides a margin of safety for commercial producers.

By contrast, petiole NO_3-N concentration had limited usefulness as a diagnostic of crop N status. Not only were existing sufficiency standards excessively high, but the rapid decline of petiole NO_3-N during the fruit setting phase would make the precise estimation of crop growth stage of paramount importance in interpreting analytical results. After the full bloom stage, petiole NO_3-N quickly fell below 1000 mg·kg^{-1} in most fields and remained low for the rest of the season. This was consistent with the observation of Tei et al. (2002) that NO_3-N as a portion of total plant N declined from 15% to ≈1% at the end of the season. In the current study, maintenance of substantial petiole NO_3-N until the early red fruit stage was limited to the UCD excessive N treatment and commercial Fields 5 and 6; on the basis of whole plant N, Field 6 was far above the N_c throughout the season, suggesting excessive N availability. Maintaining high petiole NO_3-N late in the season may not only be unnecessary, but potentially detrimental; Blaesing et al. (2006) reported that high late-season petiole sap NO_3-N concentration was linked to low fruit soluble solids.

In summary, we concluded that a seasonal N application of ≈200 kg·ha^{-1} is sufficient to maximize processing tomato productivity under most drip-irrigated field conditions. The rate of crop growth and N uptake peak during fruit setting and slow after fruit ripening begins. Whole leaf N concentration is a dependable diagnostic of crop N status throughout the season, whereas petiole NO_3-N is of limited usefulness in documenting N sufficiency.

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