Population Density and Nitrogen Fertility Effects on Tomato Growth and Yield

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Abstract. Greenhouse hydroponics and field experiments were conducted to determine how nitrogen (N) fertilizer treatments affect tomato (*Lycopersicon esculentum* Mill.) growth, yield, and partitioning of N in an effort to develop more sustainable fertilization strategies. In a hydroponics study, after 4 weeks in nitrate treatments, shoot dry weight was five times greater at 10.0 than at 0.2 mM nitrate. An exponential growth model was strongly correlated with tomato root growth at all but 0.2 mM nitrate and shoot growth in 10 mM nitrate. Root dry weight was only 15% of shoot biomass. In field studies with different population densities and N rates, height in the 4.2 plants/m² was similar, but shoot weight was less than in the 3.2 plants/m². At 12 weeks after planting, shoot fresh weight averaged 3.59 and 2.67 kg/plant in treatments with 3.2 and 4.2 plants/m², respectively. In 1998, final tomato yield did not respond to N rate. In 1999, there was a substantial increase in fruit yield when plants were fertilized with 168 kg·ha⁻¹ N but little change in yield with additional N. Nitrogen content of the leaves and the portion of N from applied fertilizer decreased as the plants grew, and as N was remobilized for fruit production. Both studies indicate that decreasing N as a way to reduce N loss to the environment would also reduce tomato growth.

Tomato is one of the most valuable vegetable crops for both fresh market and processing in the United States [U.S. Dept. of Agriculture (USDA), 2001]. Current tomato production systems require high levels of N and irrigation for optimum growth. These systems can pollute surface and groundwater. High levels of N can also encourage pest problems, such as nightshade (*Solanum* sp.) weeds (Gonzalez Ponce and Salas, 1999). A better understanding of tomato utilization of N fertilizer is necessary to develop more sustainable production practices.

An adequate N supply is critical for tomato production. Tomato has continuous N accumulation throughout its growth and development. The percentage of total N in tomato leaves drops steadily from the seedling stage to the start of fruit development. At the seedling stage, ≈80% of the total N in the plant can be found in the leaves. Afterwards there is a shift in N accumulation from the leaves to the developing fruit. At harvest, ≈24% of the total N is in the leaves and ≈69% is in the fruit (Wilcox, 1993).

Most recent research has focused on how N fertilization of tomato transplants impacts crop yield (Garton and Widders, 1990; Liptay and Nicholls, 1993; Melton and Dufault, 1991). Liptay and Nicholls (1993) found that tomato seedlings grown with high N levels had enhanced root growth after transplanting. Also, they found N fertilizer in the range of 100 to 200 mg·L⁻¹ during greenhouse transplant production resulted in maximum survival, growth, and early yield in the field. In another study, applying 25 to 225 mg·L⁻¹ nitrate during transplant production resulted in a significant increase in shoot fresh weight, plant height, stem diameter, leaf number, leaf area, and shoot and root dry weights with increasing nitrate (Melton and Dufault, 1991). Thus, N fertilization of tomato seedlings can affect growth in the greenhouse and have a carryover effect after transplanting.

It may be possible to change fertilization strategies and planting densities to improve the sustainability of tomato production systems (DiTomaso, 1995). Several fertilization approaches could be used to optimize crop growth while reducing nutrient loss into the environment. Nutrients could be deeply banded under the tomato making them readily available to tomato roots and less likely to be lost through soil erosion (Smith et al., 1992). Fertilizing tomato during early growth stages may allow it to capture nutrients before transplanting into the field (DiTomaso, 1995; Dyck and Liebman, 1994; Sainju et al., 2000), reducing the need for fertilizer applications in the field. Increasing population densities of tomato may allow the crop to better utilize applied fertilizer (Smith et al., 1992). In order to develop these strategies

it is necessary to study how tomato utilizes N (Sanchez and Doerge, 1999). The objective of this study was to determine how population density and fertility treatments affect tomato growth, yield, and partitioning of N.

Materials and Methods

Greenhouse hydroponics study. Hydroponic research was conducted to determine the effect of nitrate level on tomato dry weight accumulation. The experiments were conducted in Oct. through Dec. 1996, and Mar. through May 1999. The hydroponic system consisted of plastic vessels ≈7.5 L in volume that held six tomato plants, evenly spaced around the circumference of the lid (Wahle, 2001). ‘Rutgers’ tomato (Totally Tomatoes, Augusta, Ga.) plants were acclimated to the hydroponics system by introducing them to a transplanting solution at the two-leaf stage. The transplanting solution was a mixture of a 1 mM nitrate-N solution with P, K, S, Ca, Mg, and a half-strength micronutrient solution, based on a modified Hoagland’s solution (Resh, 1995; Table 1). Uniform, vigorously growing seedlings were inserted into the plant holes in the lid of the hydroponic container. The solution level and pH were monitored daily in the individual containers. Deionized water was added to maintain the original solution level and the pH was maintained within the range of 5.8 to 6.4 using hydrochloric acid (0.5 N) or sodium hydroxide (1 N).

After 1 week, plants were introduced into four treatment solutions containing 0.2, 1.0, 5.0, or 10.0 mM nitrate-N (Table 1). In fertile soils, nitrate-N is most commonly between 2 and 10 mM (Asher, 1978). Because of the need for counter ions with the nitrate, concentrations of potassium, calcium, magnesium, sulfur, and chlorine varied, but were all sufficient and within the normal range for plants (Table 1). Each nitrate treatment contained the full rate of micronutrients in Hoagland’s solution. The treatments were adjusted to pH 6.0 with sulfuric acid (0.5 N) or potassium hydroxide (1.0 N) before plants were introduced into the solutions. The solution levels and pH range of 5.8 to 6.4 were maintained as described above for the transplant solution.

Because nitrate absorbs UV radiation, spectrophotometric analysis provides a quick and easy method to monitor nitrate concentrations (Mulvaney, 1996; Norman and Stucki, 1981; Norman et al., 1985). Solution samples were monitored daily for nitrate concentration using an ultraviolet spectrophotometer. Individual container solutions were recharged using potassium nitrate (KNO₃) when nitrate levels dropped to half their original concentration. All containers were drained and the solutions were replaced every 7 d.

In 1996, plants were harvested at 0, 2, or 4 weeks after initiation of the nitrate treatments. In 1999, plants were harvested at 1, 3, or 4 weeks after initiation of the nitrate treatments. The experiment was terminated at 4 weeks after initiation of N treatments when tomato started to set fruit. The roots and shoots were separated and dried at 45 °C until a constant

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Table 1. The nutrient solutions used for the greenhouse hydroponic study. The solutions were based on the modified Hoagland's solution used by Crotser and Masiunas (1998).

Nitrate treatment (mM)	Nutrient concentration												
	Na	P	K	Ca	Mg	S	Cl	B	Mo	Cu	Mn	Zn	Fe
	mg·L ⁻¹												
10.0	140	16	180	134	47	47	60	0.50	0.51	0.51	0.497	0.10	5.0
5.0	70	16	159	134	36	84	105	0.50	0.51	0.51	0.497	0.10	5.0
1.0	14	16	159	110	36	104	159	0.50	0.51	0.51	0.497	0.10	5.0
0.2	2.8	16	159	110	36	104	187	0.50	0.51	0.51	0.497	0.10	5.0

^aAll nitrogen was in the form of nitrate.

weight was obtained. The data were analyzed using the general linear model procedure of SAS (SAS, 1998). If the N treatment was significant, means were separated using Fisher's protected least significant difference (LSD) test. In 1999, when plant dry weight was determined at 1, 3, and 4, linear, quadratic, and exponential equations:

$$\begin{aligned}\text{plant dry weight} &= a + bx \\ \text{plant dry weight} &= a + bx + cx^2 \\ \text{plant dry weight} &= a(e^{b(x)})\end{aligned}$$

were fitted to the data. The "x" is days after initiation of N treatments and the "a" parameter represents the y-intercept term and serves as an estimate of the plant weight at initiation of the experiment. The "b" parameter represents the slope or growth rate in the linear regression and for the exponential equation "b" is the relative growth rate (McGiffen and Masiunas, 1992a).

Field study. The objective was to determine how N fertilizer and population density interact to influence tomato growth, yield, and N partitioning. The study was conducted in 1998 and 1999 at the Univ. of Illinois, Cruse Tract Vegetable Research Farm in Champaign. The soil type was a Flanagan silt-loam (fine, montmorillonitic, mesic Aquic Argiudoll; pH 6.2 to 6.3 and organic matter 2.8% to 2.9%). The study was a factorial in a randomized complete-block design with five replications. The factors were tomato plant density and N treatment. Plots were 1.5 × 1.2 m (1.9 m²) and were separated on all sides by a 1.5-m bare ground border.

'Wheeler' rye (*Secale cereale* L.) was planted in mid-October in the experimental area to ensure a uniform previous crop and to immobilize some of the residual soil N. In the spring, the rye was killed with an application of 1.1 kg·ha⁻¹ glyphosate [N-(phosphonomethyl) glycine] and mowed ≈1 week later. After mowing the entire experimental area was treated with triple superphosphate (0–19–0), and potash (0–0–50), at an equivalent rate of 100 kg·ha⁻¹ P and 440 kg·ha⁻¹ K, respectively. Trifluralin, [2,6-dinitro-N,N-dipropyl-4-(trifluoromethyl) benenamine], was applied at 0.8 kg·ha⁻¹ to control grass and some broadleaf weeds. The entire field was then disked to incorporate the rye, trifluralin, triple superphosphate, and potash.

The four N treatments consisted of a bare ground control with no N fertilizer; 0 N plus 22.4 mg·ha⁻¹ sawdust applied to immobilize available soil N; 168 kg·ha⁻¹ N; and 336 kg·ha⁻¹ N in the form of ammonium nitrate (NH₄NO₃). The sawdust, consisting of mixed hardwoods and softwoods, moist from rainfall but still

very friable, was applied by hand on 21 May 1998 and 20 May 1999. To allow N from the fertilizer to be separated from residual N in the soil, NH₄NO₃ enriched with 5 atom percent ¹⁵N was used (Isotech, Miamisburg, Ohio). On 28 May 1998, and 20 May 1999, crystalline NH₄NO₃ was dissolved in water and applied to appropriate plots using a handheld CO₂ sprayer equipped with 8003VS flat fan spray nozzles (TeeJet-Spraying System Co., Wheaton, Ill.) at 30 kPa. The sawdust and N treatments were incorporated immediately following application using a tractor-mounted rotatiller.

'Mountain Supreme' tomato plants were grown in the greenhouse as described in McGiffen et al. (1992b), and after 6 weeks transplanted into the plots. Two tomato populations of 3.2 and 4.2 plants/m² were planted on 1 June 1998 and 20 May 1999. The 4.2 plants/m² treatment consisted of two rows with four plants per row, with 45.7 cm between rows and 30.5 cm between plants within the rows. The 3.2 plants/m² treatment consisted of two rows with three plants per row, with 45.7 cm between rows and 45.7 cm between plants within the rows. Densities for commercial fresh market tomato production are 150 cm or more between rows and 45 to 76 cm between plants within the row giving populations of 7,180 to 14,400 plants/ha (UICES, 2001). Our objective in using high population density in this study was to understand the effect of intraspecific competition among tomato plants on crop growth, yield, and N utilization. Also, previous studies with soybeans have indicated that a square planting scheme that has equal distance between and within rows maximizes competitiveness and yield (Moore, 1991).

No starter fertilizer was applied during transplanting. Weeds were removed by rotatilling, cultivation, and hand-hoeing. In addition, 0.31 kg·ha⁻¹ sethoxydim, 2-[1-(ethoxyimino)butyl-5-[2-(ethylthio)propyl]-3-hydroxy-2 cyclohexen-1-one], a selective postemergence grass-active herbicide was applied on 19 June 1998. Insecticides registered for use on tomato were applied twice in 1998 and three times in 1999 to control insect feeding. Carbaryl (1-naphthyl N-methylcarbamate) was applied at 1.12 kg·ha⁻¹ a.i. on 25 June 1998, and 17 June 1999. Permethrin, (3-phenoxyphenyl)methyl (±)cis-trans 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate, was applied at 0.22 kg·ha⁻¹ a.i. on 24 July 1998, and 11 July and 3 Aug. 1999. Tomatoes were irrigated with 2.5 cm of water on 20 July and 7 Sept. 1998, and 11 June and 7 July 1999.

Plant height was measured at 3, 5, and 7 weeks after planting (WAP). Tomato plant

samples were taken at: flowering (8 WAP); immature-green fruit (10 WAP); mature-green fruit (12 WAP); and full-ripe fruit (15 WAP) stages. Only the most recent, fully mature leaves were sampled at the flowering and immature-green fruit stages. Individual plant fresh weight and both lower and upper leaf and stem samples were collected at the mature-green and full-ripe fruit stages. The tissue samples were air-dried prior to N analysis.

Nitrogen analysis. The air-dried plant samples were ground to a powder using a Wiley mill equipped with a 60-mesh screen. The Kjeldahl digestion followed the procedures outlined in Stevens et al. (2000). A sample weighing 0.050 ± 0.005 g was used in the Kjeldahl digestion. This provided enough tissue for analysis while avoiding excessive foaming. After the Kjeldahl digestion, samples were analyzed for total N using Mason-jar diffusion methodology (Stevens et al., 2000).

The analysis of ¹⁵N was started by adding 1 M H₂SO₄ to the H₃BO₃ solution (0.05 L·g⁻¹ of N) and heating it to dryness on a hot plate. Samples were processed according to the procedure of Stevens et al. (2000). Samples were redissolved in deionized water on microplates, dried, and ¹⁵N content determined using a mass spectrometer (Stevens et al., 2000). The proportion of ¹⁵N in the sample (PL) under analysis was calculated as:

$$PL = (AL - AU) / (AM - AU)$$

where AL is the atom % ¹⁵N in the sample, AU is the natural abundance of atom % ¹⁵N, and AM is the atom % ¹⁵N of the fertilizer applied. The relative abundance of ¹⁵N in unenriched nitrogen (AU), 0.366 atom %, was used for calculations (Hauck et al., 1994).

The data were analyzed using the general linear model procedure of SAS (SAS Institute, Cary, N.C.). If population density was significant, then the means were separated using a *t* test. Secondly, data for the 0, 168, and 336 kg·ha⁻¹ N treatments were analyzed using regression analysis to determine its fit to linear, quadratic, or exponential equations. The appropriate equation was determined based on level of significance and coefficient of determination.

Results and Discussion

Greenhouse hydroponics study. After 4 weeks in the nitrate treatments (WINT), tomato shoot dry weight responded to nitrate rate (Fig. 1). Tomato plant weight was greatest when grown in a 5 or 10 mM nitrate solution. The nitrate concentrations that produced the most tomato shoot growth are toward the high end of the nitrate levels most commonly found in field soils and this supports the findings of other researchers that tomato growth and yields increase with increasing N rates (Hoyt et al., 1994; Mortley et al., 1991; Wyatt et al., 2001).

The response of root dry weight to nitrate differed between the 2 years. In 1996 after 4 WINT, root dry weight did not respond to N rate. In 1999, N rate significantly affected root growth. There was a significant linear increase

in root weight with increasing N rate (Fig. 1). This suggests that none of the nitrate rates in the present study optimized root growth in the hydroponics solution at 4 WINT. Even though the study was conducted in the greenhouse with supplemental lighting, environmental conditions likely varied between the 2 years. The 1996 experiment was conducted during late November and December when the weather was cloudy and the lower temperature set point was difficult to maintain while the 1999 study was conducted in late April and May when the weather was sunny and the upper set point temperature was difficult to maintain. The lower temperatures and irradiance during 1996 than 1999 likely confounded the effect of nitrate treatment.

As was expected, root dry weight was consistently less than shoot dry weight. Resh (1995) reported that roots often account for a small portion of the biomass when plants are grown in hydroponics. Hydroponics culture allowed the tomato roots easy access to water and nutrients. Also, the tomato root system did not have to anchor or support the plants, so it was very branched and composed of fine feeder roots without much weight.

An exponential equation predicted root dry weight accumulation at all nitrate concentrations except 0.2 mM (Fig. 2). At 0.2 mM root dry weight was predicted by a linear equation. There was no plateauing of root dry weight accumulation. The relative growth rate for the roots depended on nitrate concentration, ranging from 0.0738 to 0.116/day. At 10 mM nitrate, the relative growth rate was 0.133 and 0.116/day for the shoot and roots, respectively. The lower relative growth rate for the roots indicates that the tomato plants were maximizing shoot growth at the expense of root growth.

The hydroponics study revealed that tomato growth can be limited when grown in solutions with <5 mM of N. Based on this and companion studies (Wahle and Masiunas, 2003a, 2003b), tomato shoot weight is reduced at low N rates, suggesting that reducing N fertilizer applications would not be a strategy to use for improving the sustainability of tomato cropping systems. Fertilization strategies should aim to optimize tomato growth, so tomatoes will be competitive and produce optimum yields.

Field study. Tomato height was unaffected by population density (data not shown). 'Mountain Supreme' is a determinant type of tomato and may not respond to increased intraspecific competition by elongating. Moreover, the tomato plants may not have been large enough by 7 WAP for intraspecific competitive to have occurred. How tomato responds to competition is important because the plant which overtops others has a competitive advantage (Gonzalez Ponce et al., 1996; McGiffen et al., 1992b).

Plants grown at a greater population density (4.2 plants/m²) had less weight and lower yield per plant. At 15 WAP, shoot fresh weight and fruit yield in plots with 3.2 plants/m² averaged 5.29 and 4.24 kg/plant, respectively while in plots with 4.2 plants/m² they averaged 4.17 and 3.31 kg/plant, respectively. At 15 WAP, the lower shoot fresh weight and fruit yields can probably be attributed to greater intraspecific

Fig. 1. 'Rutgers' tomato shoot dry weight averaged over both years and root dry weight after 4 weeks in hydroponic solutions. Root dry mass in 1996 (□) was not affected by nitrate concentration (x). The equations were: root dry weight (1999) = $1.32 + 0.253x$ ($r^2 = 0.77$) and shoot dry weight (averaged over 1996 and 1999) = $5.09 + 6.22x - 0.392x^2$ ($R^2 = 0.93$). The lines are the equations and the symbols are the actual data points.

Fig. 2. The increase in (A) tomato shoot and (B) root dry weight as a function of days (x) growing in four different nitrate solutions. All coefficients of determination were >0.90. The equations for tomato shoots growing in 1 and 10 mM nitrate were: shoot weight = $0.582 + 0.00969x^2$; and shoot weight = $0.748^{[0.133(x)]}$, respectively. The effect of days on shoot dry weight for plants grown in 0.2 and 5 mM, although significant, could not be predicted with a linear, quadratic, or hyperbolic model. The equations for tomato roots growing in 0.2, 1, 5, and 10 mM nitrate were: root weight = $0.0744 + 0.0223x$; root weight = $0.253^{[0.0738(x)]}$; root weight = $0.159^{[0.102(x)]}$; and root weight = $0.136^{[0.116(x)]}$, respectively.

competition at the higher population density. Smith et al. (1992) also found that increasing tomato density reduced yield/plant. There were no differences between densities when shoot fresh weight and fruit yields of tomato were considered on an area basis. The shoot weight/ha averaged 30.4 and 92.2 Mg·ha⁻¹ at 12 and 15 WAP, respectively. This indicates that at the population range used in the present study, individual tomato plant weight changes so tomato produces a constant weight per unit area.

In a greenhouse replacement series experiment, Perez and Masiunas (1990) found that intraspecific competition resulted in smaller tomato plants than did competition with eastern black nightshade (*Solanum ptycanthum* Dun.). Our results also suggest that increasing the high density of tomatoes we used will not be an effective strategy either to maximize crop growth, improve sustainability, or to increase competitiveness with weeds because the higher densities will adversely impact growth per tomato plant. Since there is a cost associated with using additional tomato plants, using high population levels would not be economical if competitiveness or yield are not increased.

Tomato height, growth rate, fresh weight, and yield increased with N fertilizer rate (Table 2). At 3 WAP, plants in plots with either no N or with sawdust were shorter than plants in plots with N fertilizer (Fig. 3A). We expected the sawdust to immobilize residual soil N, resulting in the least amount of tomato growth, but at 3 WAP, there were no differences in height between plants in the sawdust and no fertilizer treatments. This was probably because tomato was recently established and the plants were able to use residual N from fertilization in the greenhouse for initial growth in the field. Other researchers have also found that N fertilization of greenhouse tomato transplants affects subsequent growth in the field (Garton and Widders, 1990; Liptay and Nicholls, 1993; Melton and Dufault, 1991).

At 5 and 7 WAP, plants in the sawdust treatment were shorter than those in any other treatment, including the no fertilizer (Fig. 3A). For example, at 5 WAP the plants in the sawdust treatment were 43 cm in height while those in the 168 kg·ha⁻¹ N treatment were 63 cm. This was probably because the sawdust promoted immobilization of N. Later in the season, unfertilized plants and plants receiving sawdust had similar weight (Table 3) and N in their tissues (Table 4). In the fertile soil (Wahle, 2001) in the present study, sawdust applied may have been inadequate to immobilize N throughout the entire season.

The effect of N treatment on shoot weight and fruit yield differed from its effect on height (Table 2). The optimum N treatment for production of shoot weight and fruit yield varied between years and measurement times, which means that our research cannot provide an overall N recommendation to maximize tomato growth and yield. Shoot fresh weight and yield responded to increased N rates (Table 3, Fig. 3B). Yields were greatest with 336 kg·ha⁻¹ N, and lowest with sawdust added (Fig. 3B). At 15 WAP, fresh weight per plant was smaller

with no fertilization compared to either rate of fertilizer (Table 3). Final yield per plant (15 WAP) in 1998 did not respond to N treatments, but in 1999, plots with added N produced the greatest yield (Fig. 3B). Similar yields (1999) on the plots with no N and no N with sawdust indicates that at least in some years the Flanagan silt-loam soil used in the present study could release adequate levels of mineralized N to provide exceptional tomato yields. Yaffa et al. (2000) found that N release from cover crop residues was synchronized with the N need of tomato during its early growth. These differences between years were most likely due to differences in the two sections of the field we used and to environmental differences. In 1998, the greater early season moisture and slightly warmer temperatures probably caused more rapid degradation of the rye residues and release of mineralized N.

This study illustrates the difficulty with current preplant N fertilization recommendations for tomato which in some years will be greater than what is needed for optimum growth and yield on the rich prairie soils of the Midwest. Dufault et al. (2000), in the southeastern United States also found environmental effects on the optimum N fertilizer rate for tomato. This study also illustrates the difficulty in trying to reduce N rates and develop more sustainable cropping systems.

Nitrogen analysis. During vegetative growth, the upper leaves were developing and were the strongest sink for N. At 12 WAP, the upper leaf N content averaged 39 g·kg⁻¹, while N content of the lower leaves averaged 22 g·kg⁻¹ (Table 4). The N content of the lower leaves was less than that of the upper leaves because the lower leaves were no longer growing and may have served as one source of N that was translocated to the upper leaves. The N levels observed for upper leaves in our study at 15 WAP were similar to the 36.1 g·kg⁻¹ for tomato

shoots reported by Qasem (1992).

The N content of tomato plants decreased from 8 to 15 WAP (Table 4). This was probably because N was being remobilized from the leaves and stem to the developing tomato fruit, and due to dilution caused by plant growth (Gonzalez Pounce and Salas, 1999; Smith et al., 1992). Also the amount of N available in the soil from the preplant fertilizer application was decreasing. For example, at 8 WAP, 49% of the N in the upper leaves was from fertilizer, but at 15 WAP only 10% of the N was from fertilizer and the remainder was from mineralized N. Gonzalez Ponce and Salas (1999) also reported high N concentrations in tomato tissue during initial growth stages and a decline later in the season.

The only effects of N treatment were on the N concentration of the upper leaves and on the percentage of N from fertilizer in the upper leaves and stem. At 8 WAP, population and N treatment interacted to determine the N content of the upper leaves (Table 4). With 3.2 plants/m², N concentration of the upper leaves was greatest with 336 kg·ha⁻¹ N. With 4.2 plants/m², the only difference in N concentration in the upper leaves was between plants without added N and those in the 336 kg·ha⁻¹ N treatment. At 12 WAP, the N content was higher in plants in the sawdust and 0 N plots than in plots treated with fertilizer. This result is unexpected and only occurred for the upper leaves at 12 WAP. It might indicate a later shift to reproductive growth or less dilution for the smaller plants in the 0 N and sawdust treatments causing them to maintain higher N levels in the upper leaves later into the season. The higher N content may also represent differences in mineralization of N between the treatments.

There were also differences in the percentage of N in the upper leaves that originated from fertilizer (data not shown). At 8 WAP, plants in plots with 336 kg·ha⁻¹ N acquired 59%

Table 2. The regression equations predicting the effect of nitrogen rate on tomato plant height and yield. The data are averaged over years except for yield at 15 weeks after planting (WAP) when in 1998, yield was not affected by N treatment.

Time (WAP)	Y ^z	Equation ^y	Coefficient of determination
3	Height	27.7 + 0.0233x	0.71
5	Height	49.3 + 0.124x - 0.000225x ²	0.85
7	Height	66.5 + 0.0952x - 0.000155x ²	0.83
12	Yield	1.82 + 0.00364x	0.65
15	Yield	2.74 + 0.00461x	0.50

^zHeight is in cm and yield is in kg/plant.

^yThe independent variable (x) is nitrogen at kg·ha⁻¹.

Table 3. Tomato shoot (foliage and fruit) fresh weight at 12 and 15 weeks after planting (WAP) relative to nitrogen treatments.

Nitrogen treatment (kg·ha ⁻¹) N	Fresh wt/plant		Fresh wt/ha		
			12 WAP ^z		
	12 WAP	15 WAP	1998	1999	15 WAP
	kg/plant	Mg·ha ⁻¹			
0 + sawdust ^y	2.18 c ^x	4.10 b	24.8	17.6	79.8
0	2.72 c	4.21 b	31.3	21.6	81.9
168	3.43 b	5.18 a	36.1	30.7	101
336	4.17 a	5.42 a	39.4	41.8	106

^zAt 12 weeks after planting, the year × rate interaction was significant for shoot fresh weight per hectare.

^ySawdust was applied to the plots at 22 Mg·ha⁻¹ to immobilize nitrogen.

^xMean separation in columns using Fisher's protected least significant test, P = 0.05.

Table 4. The effect of four fertility treatments on the total nitrogen concentration in tomato tissues ($\text{g}\cdot\text{kg}^{-1}$) at 8, 12, or 15 weeks after treatment.

Nitrogen treatment ($\text{kg}\cdot\text{ha}^{-1}$) N	Upper leaves				Lower leaves		Upper stems		Lower stems	
	8 WAP ²									
	3.2	4.2	12	15	12	15	12	15	12	15
0 + sawdust ³	35.0 b ^a	41.4 ab	41.5 a	36.6	23.2	18.9	19.6	13.5	12.4	11.5
0	38.8 b	36.3 b	42.3 a	36.6	24.2	18.8	17.1	14.8	13.6	10.2
168	39.9 b	39.9 ab	35.5 b	34.6	21.4	18.2	14.9	17.1	12.4	11.0
336	51.0 a	45.3 a	35.8 b	36.8	20.8	19.4	16.0	15.0	12.9	12.2

^aThe population $\times$ rate interaction affected N concentration of the upper leaves, therefore the total nitrogen content of leaves in the 3.2 and 4.2 plants/m² are shown separately.

³Sawdust was applied to the plots at 22 Mg $\cdot\text{ha}^{-1}$ to immobilize nitrogen.

^aMean separation within column using Fisher's protected least significant test, $P = 0.05$. Means in columns without letters were not significantly different.

of their total N from applied N, compared to 39% in plots treated with 168 $\text{kg}\cdot\text{ha}^{-1}$ N, but by 10 WAP, these percentages were only 23% and 11%, respectively. This could be due to N fertilizer loss in the soil, increased available N due to mineralization, and remobilization

of N to other plant parts such as fruit, and a "dilution effect" due to growth.

This study does eliminate some production strategies that could be used for optimizing tomato growth and yield while increasing the sustainability of the cropping system. Both the

greenhouse hydroponic and the field studies indicate that tomato growth is improved with high levels of N and indicates that reducing N would reduce tomato growth. With higher N concentrations, tomato plants grew more rapidly and were larger, which would make them able to support greater fruit loads. Thus, the best fertilizer strategy is to apply adequate N to allow optimum tomato growth. The problem with this strategy is that the optimum N rate for tomato varies even on the same soil type, depending on the environmental conditions and time of measurement. Because of this variation, there will be years when N applications will exceed the needs of the tomatoes, and result in environmental contamination.

Placing N fertilizer in the transplant row where it is readily available to tomato or applying high rates of N to greenhouse seedlings might be ways to manipulate fertilization to increase tomato growth and yield while minimizing N loss into the environment. Wyatt et al. (2001) reported that the highest tomato yields were from banding potassium nitrate over the row before transplanting. Other researchers have found that tomato seedlings grown with high N levels had enhanced growth and survival after transplanting (Liptay and Nicholls, 1993; Melton and Dufault, 1991). Further research is needed to test these strategies.

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Fig. 3. (A) Tomato plant height and (B) yield in response to nitrogen treatment. Tomato height was measured at 3, 5, and 7 weeks after planting (WAP) in 0 N + 22 Mg $\cdot\text{ha}^{-1}$ sawdust (dots), 0 N (downward hatched), 168 $\text{kg}\cdot\text{ha}^{-1}$ N (upward hatched) and 336 $\text{kg}\cdot\text{ha}^{-1}$ N (open). Fruit yield was measured at 12 (averaged over 1998 and 1999) and 15 (1998 and 1999 separately) the bar hatching is the same as for height. Bars within date with the same letter are not significantly different using Fisher's protected least significant test, $P = 0.05$.

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