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Responses of Greenhouse Tomato and Pepper Yields and Nitrogen Dynamics to Applied Compound Fertilizers*1

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ABSTRACT

Yield and N uptake of tomato (Lycopersicum esculentum Mill.) and pepper (Capsicum annuum L.) crops in five successive rotations receiving two compound fertilizers (12-12-17 and 21-8-11 N-P2O5-K2O) were studied to determine 1) crop responses, 2) dynamics of NO3-N and NH4-N in different soil layers, 3) N balance and 4) system-level N efficiencies. Five treatments (2 fertilizers, 2 fertilizer rates and a control), each with three replicates, were arranged in the study. The higher N fertilizer rate, 300 kg N ha\(^{-1}\) (versus 150 kg N ha\(^{-1}\)), returned higher vegetable fruit yields and total aboveground N uptake with the largest crop responses occurring for the low-N fertilizer (12-12-17) applied at 300 kg N ha\(^{-1}\) rather than with the high-N fertilizer (21-8-11). Ammonium-N in the top 90 cm of the soil profile declined during the experiment, while nitrate-N remained at a similar level throughout the experiment with the lower rate of fertilizer N. At the highest rate of N fertilizer there was a continuous NO3-N accumulation of over 800 kg N ha\(^{-1}\). About 200 kg N ha\(^{-1}\) was applied with irrigation to each crop using NO3-contaminated groundwater. In general, about 50% of the total N input was recovered from all treatments. Pepper, relative to tomato, used N more efficiently with smaller N losses, but the crops utilized less than 20% of the fertilizer N over the two and a half-year period. Local agricultural practices maintained high residual soil nutrient status. Thus, optimization of irrigation is required to minimize nitrate leaching and maximize crop N recovery.

Key Words: greenhouse vegetables, N dynamics, N efficiency, N uptake, N utilization

INTRODUCTION

Vegetable production in greenhouses has increased dramatically during the last two decades in Northeast China and has become economically important in some locations (Zhu et al., 2002; Li et al., 2001). When compared with cereal cropping, vegetable cropping systems often require a greater degree of management and involve larger inputs of N and irrigation (Power and Schepers, 1989). Because of low N recovery with vegetable crops most of the N applied to crops as fertilizer N is mineralized from the soil and cannot be effectively utilized (Lowrance and Smittle, 1988). This may lead to N accumulation in the soil and increase the potential for nitrate leaching losses (Tripathi et al., 1997). Zhu et al. (2002) and Li et al. (2001) reported that high N inputs from fertilization and irrigation caused negative effects on soil environmental quality. According to Biernbaum (1992), the key to reducing nitrate groundwater contamination due to leaching or runoff was to clearly define the plants’ water and nutrient requirements. Since the recommended rates of N for maximum yield of vegetables vary greatly according to soil fertility and vegetable varieties (McPharlin et al., 1995), in order to maintain sustainability and enhance environmental quality, information on N dynamics and N balance are essential when making fertilizer recommendations to reduce nutrient losses.

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Several studies have examined soil mineral N measurements to understand the crop response to N fertilizer in open fields (Tripathi et al., 1997; Everaarts and De Moel, 1995; Everaarts et al., 1996; Rahn et al., 1998). Varrina et al. (1988) recommended N fertilization of tomato transplants in greenhouses under solution culture conditions. However, there is little published information on N fertilization for field vegetable production in greenhouses. In order to use nutrients (especially N fertilizer) efficiently and to sustain the productivity of intensively cultivated vegetable systems, it is essential to obtain information on N balance. The objectives of the present study involved utilizing five successive tomato and pepper vegetable crops with different fertilizer formulations, intensive fertilization and irrigation to quantify 1) crop responses to fertilizer N, 2) dynamics of NO$_3$-N and NH$_4$-N in different soil layers in relation to two fertilizer N rates, 3) N balance and 4) system-level N efficiencies.

MATERIALS AND METHODS

The field experiment on irrigated vegetable crops was conducted in a 60 × 7.5 m plastic greenhouse from August 1999 to January 2002 in Shouguang, Shandong Province, where there was a large intensive greenhouse vegetable production region. Local farmers had managed the greenhouse for more than 7 years, and the field was used for open cereal production before that. Selected soil properties at the experimental site are presented in Table I. The sampling site in the middle of the greenhouse was divided into fifteen 7 × 2.4 m plots, and plastic film was installed from the soil surface down to 90 cm depth to prevent water or nutrients from diffusing between adjacent plots. The mean annual maximum and minimum temperatures were 42.5 and 13.8 °C, respectively, in the greenhouse and 28.7 and −3.6 °C, in that order, outside. The irrigation water source was pumped groundwater.

<table>
<thead>
<tr>
<th>Soil depth</th>
<th>pH (H$_2$O)</th>
<th>Total N (mg g$^{-1}$)</th>
<th>Total OM (%)</th>
<th>Inorganic N (mg kg$^{-1}$)</th>
<th>Available P (mg kg$^{-1}$)</th>
<th>Available K (mg kg$^{-1}$)</th>
<th>Bulk density (g cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–30</td>
<td>6.76</td>
<td>0.18</td>
<td>1.52</td>
<td>63</td>
<td>116</td>
<td>246</td>
<td>1.38</td>
</tr>
<tr>
<td>30–60</td>
<td>6.81</td>
<td>0.12</td>
<td>0.78</td>
<td>58</td>
<td>38</td>
<td>156</td>
<td>1.42</td>
</tr>
<tr>
<td>60–90</td>
<td>6.82</td>
<td>0.09</td>
<td>0.44</td>
<td>39</td>
<td>23</td>
<td>98</td>
<td>1.55</td>
</tr>
</tbody>
</table>

The experiment consisted of five treatments with three replicates and was laid out in a completely random design. The five treatments were: CK, a control receiving no fertilizer; AL and AH, a low-N compound fertilizer (12–12–17) at 150 and 300 kg N ha$^{-1}$ crop$^{-1}$, respectively; and BL and BH, a high-N compound fertilizer (21–8–11) at 150 and 300 kg N ha$^{-1}$ crop$^{-1}$, correspondingly. The two compound fertilizers commonly used in the region, were composed of N-P$_2$O$_5$-K$_2$O. Five cropping patterns were established using tomato (Lycopersicum esculentum Mill.) and pepper (Capsicum annuum L.) in successive rotations. Forty percent of the fertilizer was applied as a basal dressing, and the remaining 60% was applied as two top dressings during the cropping season. Additionally, during 2000 and 2001 the total NH$_4$-N in the top 90 cm of the soil profile for the high N rate in both types of fertilizer was maintained at about 60 kg N ha$^{-1}$, while at the low N rate it was maintained at about 40 kg N ha$^{-1}$. The plots were irrigated immediately after the fertilizers were broadcast, and at later times for a total of 8–12 irrigation episodes providing a total of about 800–1100 mm water per crop.

Soil was sampled before transplanting, before each top dressing, and at the end of each cropping season. Six soil cores (3.5 cm diameter) per plot were taken to 90 cm depth and partitioned into 0–30, 30–60 and 60–90 cm depth increments. Soil samples were mixed in the field to furnish composite samples, stored on ice, transported to the laboratory and refrigerated. A 10-g sub-sample was weighed in a plastic bottle and extracted with 100 mL CaCl$_2$ (0.01 mol L$^{-1}$) for 1 h to determine mineral N. Simultaneously, another sub-sample was weighed in a pre-weighed aluminum can for gravimetric determination of the soil water content. All the analyses were initiated within 24 h of sampling. Concentrations of mineral
N were determined using a TRAACS 800 Autoanalyzer. Soil bulk density in different profiles was also ascertained before the experiment in order to compute mineral N at different soil depths.

Vegetable fruits were sampled from each plot on every harvest date to calculate fresh and dry weight. Following the farmers’ conventional practices, stems and leaves were removed at the end of the harvesting period while roots were left in the soil. Plant samples were taken from each plot after harvesting; divided into leaves, petioles and stems; chopped; mixed and then weighed before and after drying at 80 °C for 48 h. Dried plant samples from the same plot were also milled and mixed for Kjeldahl N determination. In addition, fresh weights of vegetable fruits (total and marketable portions) along with total stems and leaves removed from the field were recorded.

Fertilizer N use efficiency (FUE) as defined by Parr (1973) is “the percentage recovery of fertilizer N by the crop.” Crop fertilizer N recovery was calculated as follows:

\[
\text{FUE} \, (\%) = \frac{(N_{\text{fr}} - N_{\text{nc}})}{N_{\text{fr}}} \times 100 \times N_{\text{fr}}^{-1}
\]

where \(N_{\text{fr}}\) = crop (fruit + leaf + stem) N uptake under one of the four fertilizer application rates, \(N_{\text{nc}}\) = crop N uptake in the control without N application, and \(N_{\text{fr}}\) = N supplied by the fertilizer treatment.

System-level N efficiencies (NE) of different fertilizer treatments were calculated using the following equation (after Tripathi et al., 1997):

\[
\text{NE} \, (\%) = \frac{(N_{\text{uptake}} + N_{\text{left}})}{N_{\text{fertilizer}} + N_{\text{irrigation}} + N_{\text{planting}}} \times 100 \times (N_{\text{fertilizer}} + N_{\text{irrigation}} + N_{\text{planting}})^{-1}
\]

where \(N_{\text{uptake}}\) is the crop N uptake, \(N_{\text{left}}\) is the soil mineral N left at harvest, \(N_{\text{fertilizer}}\) is the fertilizer N, \(N_{\text{irrigation}}\) is the N input from irrigation, and \(N_{\text{planting}}\) is the soil mineral N at planting. Soil mineral N is the total mineral N in the top 0–90 cm of the soil profile.

The SAS statistical package was used to test data with analysis of variance (ANOVA) and to compare mean values using Duncan’s multiple range test. All tests were conducted at the 0.05 and 0.01 probability levels.

RESULTS AND DISCUSSION

**Crop yield and N utilization**

High soil nutrient status in the experimental field was observed (Table I) at the start, mainly due to large fertilizer inputs during the seven years preceding the experiment. About 689 kg N, 749 kg P and 2139 kg K ha\(^{-1}\) were measured in the 0–90 cm soil layers at the beginning of the experiment.

Table II shows the aboveground dry matter yield under the different fertilizer treatments. In the first cropping season in 1999, no significant differences were found between the two fertilizers or between the two fertilizer N rates. However, dry matter yields of fruit for the next four cropping seasons were all significantly different from the control with some differences among treatments. The highest aboveground dry matter yields were often observed in treatment AH with a total of 15.35 tons of fruit dry matter yield after five cropping seasons. Treatment BH gave the second highest fruit dry matter yield at the end of the experiment, but differed significantly when compared to treatment AH, perhaps because of its lower P and K application rate. Increasing the application rate of each fertilizer sometimes significantly increased fruit yields but seldom increased yields of stems and leaves. In addition, only one significant difference (treatments AH and BH for tomato crop in 2000) in dry matter yield of total stems and leaves was found between the two fertilizers with identical rates. The low-N fertilizer (12-12-17) at the higher rate application (300 kg N ha\(^{-1}\)) (treatment AH) could be regarded as the most effective treatment in the experiment because of its higher fruit yield, which was important in high-value crops such as pepper and tomato.

Additional N did not significantly increase crop N utilization in the first season because of the high content of soil mineral N before planting, but differences occurred during the subsequent four seasons.


### TABLE II

<table>
<thead>
<tr>
<th>Treatment(^a)</th>
<th>1999-T(^b)</th>
<th>2000-HP(^c)</th>
<th>2000-T</th>
<th>2001-HP</th>
<th>2001-T</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK (control)</td>
<td>2.18a(^d)</td>
<td>1.12c</td>
<td>1.91d</td>
<td>0.70c</td>
<td>1.63b</td>
<td>7.54d</td>
</tr>
<tr>
<td>AL</td>
<td>2.48a</td>
<td>1.92b</td>
<td>2.72c</td>
<td>2.14b</td>
<td>2.66a</td>
<td>11.92bc</td>
</tr>
<tr>
<td>AH</td>
<td>2.59a</td>
<td>2.43a</td>
<td>4.05a</td>
<td>3.36a</td>
<td>2.92a</td>
<td>15.35a</td>
</tr>
<tr>
<td>BL</td>
<td>2.46a</td>
<td>1.73b</td>
<td>2.49c</td>
<td>1.92b</td>
<td>2.47a</td>
<td>11.08c</td>
</tr>
<tr>
<td>BH</td>
<td>2.50a</td>
<td>1.99a</td>
<td>3.31b</td>
<td>2.15b</td>
<td>2.72a</td>
<td>12.66b</td>
</tr>
</tbody>
</table>

*Fruit*

| CK (control)    | 1.69a        | 3.05b        | 2.13d  | 1.35b   | 1.48c  | 9.70c |
| AL              | 2.15a        | 3.81ab       | 2.75c  | 2.81a   | 2.00ab | 13.52ab |
| AH              | 2.45a        | 4.35a        | 2.83b  | 3.11a   | 2.35a  | 15.11a |
| BL              | 2.35a        | 3.82ab       | 2.59c  | 2.69a   | 1.84bc | 13.29b |
| BH              | 2.25a        | 3.80ab       | 3.28a  | 2.94a   | 1.94abc| 14.21b |

*Stems and leaves*

| CK (control)    | 101.2a       | 111.6c       | 98.1d  | 63.9c   | 75.5b  | 450.3d |
| AL              | 106.9a       | 180.8b       | 110.8cd| 139.8b  | 92.2ab | 630.5c |
| AH              | 120.0a       | 225.2a       | 133.5ab| 185.5a  | 101.9a | 766.6a |
| BL              | 114.6a       | 188.5b       | 119.7bc| 139.2b  | 102.4a | 664.4bc |
| BH              | 113.2a       | 191.4b       | 146.6a | 150.1b  | 101.9a | 703.1b |

\(^a\)AL and AH—treatments applied with low-N compound fertilizer (12-12-17, N-P₂O₅-K₂O) at 150 and 300 kg N ha\(^{-1}\) crop\(^{-1}\), respectively; BL and BH—treatments applied with high-N compound fertilizer (21-8-11, N-P₂O₅-K₂O) at 150 and 300 kg N ha\(^{-1}\) crop\(^{-1}\), respectively.

\(^b\)1999-T—tomato crop in 1999.

\(^c\)2000-HP—pepper crop in 2000.

\(^d\)Values followed by the same letter within a column for a particular crop season are not significantly different at \(P < 0.05\) by Duncan’s multiple range test.

Nonetheless, in the two pepper rotations, aboveground N utilization differed significantly between treatments AH and BH, with removal of 410.7 and 341.5 kg N ha\(^{-1}\), respectively, while 320.6 and 327.7 kg N ha\(^{-1}\) were removed from treatments AL and BL, respectively. These were significantly lower than treatment AH but not treatment BH. Also, pepper, with higher uptakes, utilized N more effectively than tomato. After five cropping seasons comparison to the control’s total uptake was utilized to calculate the crops apparent fertilizer N recovery (Eq. 1). The result was recovery of about 24\% and 21\% of the N fertilizer from the low- and high-N application rates with the low N fertilizers, respectively, and 28\% and 17\% from the low- and high-N application rates with the high N fertilizers.

**Ammonium nitrogen**

Farmers often applied relatively large amounts of organic manure (mainly chicken manure) as a basal dressing to the soil in greenhouses for vegetable production, and high NH₄-N concentrations were observed before the experiment, mainly as a result of manure-N mineralization. No organic manure was applied during the experiment, therefore the total NH₄-N in the top 90 cm of the soil profile declined in all treatments from > 120 kg N ha\(^{-1}\) at the start of the tomato crop in August, 1999 to 60 kg N ha\(^{-1}\) before planting the pepper crop in February 2000 (Fig. 1). Crop uptake, nitrification and volatilization would have decreased soil NH₄-N.

Over the last four cropping seasons, additional N used to maintain NH₄-N at about 60 kg N ha\(^{-1}\) or about 40 kg N ha\(^{-1}\) as described above exerted some effect, but soil NH₄-N varied little throughout the entire experimental period and no differences were found between the two fertilizer types. There was also a peak of soil NH₄-N that occurred for all treatments in May 2001 when a pepper crop was grown (Fig. 1). Root rot on pepper in its later growth stages, which meant the aboveground parts were
harvested earlier than the local commercial practice, was the probable cause. This resulted in a decrease in the crop’s NH₄-N uptake and increased NH₄-N accumulation in the top 90 cm of the soil profile.

![Graphs showing soil NH₄-N and NO₃-N levels](image)

**Fig. 1** Soil NH₄-N in the 0-90 cm depth for 5 treatments from August 1999 to January 2002. CK is the control; AL and AH are the treatments applied with low-N compound fertilizers (12-12-17, N-P₂O₅-K₂O) at 150 and 300 kg N ha⁻¹ crop⁻¹, respectively; and BL and BH are the treatments applied with high-N compound fertilizer (21-8-11, N-P₂O₅-K₂O) at 150 and 300 kg N ha⁻¹ crop⁻¹, correspondingly. Bars represent standard errors of means for three replicates per treatment averaged over five crop cycles.

**Fig. 2** Soil NO₃-N accumulation for five treatments in three soil layers (0-30, 30-60 and 60-90 cm) from August 1999 to January 2002 at the experimental site. CK is the control; AL and AH are the treatments applied with low-N compound fertilizers (12-12-17, N-P₂O₅-K₂O) at 150 and 300 kg N ha⁻¹ crop⁻¹, respectively; and BL and BH are the treatments applied with high-N compound fertilizer (21-8-11, N-P₂O₅-K₂O) at 150 and 300 kg N ha⁻¹ crop⁻¹, correspondingly; NS is not significant; *, ** Statistically significant at P ≤ 0.05 and ≤ 0.01, respectively.

**Nitrate nitrogen**

Sixty-five percent of the N applied for the two fertilizers was NH₄-N and 35% was NO₃-N. Although NH₄-N was relatively immobile in the soil, the biologically mediated process of nitrification rapidly converted it to NO₃-N. The dynamics of NO₃-N, which was consistently the major form of N for all treatments, in the top 90 cm of the soil profile, were monitored over the whole experimental period...
(Fig. 2). Fertilizer application led to most of the NO$_3$-N accumulation that occurred in the top 30 cm of the soil profile, and NO$_3$-N also increased in the deeper soil layers. During the first cropping season additional fertilizer had no effect on NO$_3$-N in the top 90 cm of the soil profile as compared to the control, however a decline occurred from 580 kg ha$^{-1}$ at the start of the experiment to about 400 kg ha$^{-1}$ at the end. This may be attributed to both crop uptake as well as N losses via nitrate leaching and denitrification. In the next four cropping seasons, NO$_3$-N in the soil profile differed significantly between the control and the treatments. Total soil NO$_3$-N in the top 90 cm of the control declined from 580 kg ha$^{-1}$ at the start of the experiment to 217 kg ha$^{-1}$ after five crop harvests. When both fertilizers were applied at the low N rate (treatments AL and BL), which was equivalent to a total application of 750 kg N ha$^{-1}$ during the five cropping seasons, soil NO$_3$-N varied little during the total experimental period, with 575 and 618 kg ha$^{-1}$ NO$_3$-N being observed at the end of the experiment for treatments AL and BL, respectively. These were similar to the amount at the start of the experiment.

Increasing the N rate (treatments AH and BH) increased soil NO$_3$-N accumulation in the top 90 cm of the soil profile. At the high N rate (equivalent to a total application of 1500 kg ha$^{-1}$ over the whole experimental period), there was a constant accumulation of NO$_3$-N in the 0-90 cm soil layer. Totals of 879 and 862 kg ha$^{-1}$ NO$_3$-N in the top 90 cm were found in treatments AH and BH at the end of the experiment, which was significantly higher than the low N application rate. High soil NO$_3$-N values were also observed during the second pepper cropping season (from Feb. to Jun. 2001) due to root rot on pepper that resulted in a decreased crop uptake and increased N accumulation in the top soil layer. Heavy irrigation using groundwater with high N concentrations (about 20 mg N L$^{-1}$) may also have contributed to higher soil N levels. About 800 to 1100 mm irrigation water and an average of 213.8 kg N ha$^{-1}$ were applied to each crop (Table III). In addition, high irrigation inputs and evaporation in the greenhouse led to frequent alternating periods of soil drying and wetting. Such cycles were normally associated with increased NO$_3$-N in aerobic soil (Vavrina et al., 1998; Linn and Doran, 1984; Radford et al., 1992; George et al., 1993).

$N$ balance

The apparent N loss was also calculated for all treatments from the start to the end of the experiment (Table III). After the tomato harvest in January 2000, the total apparent N loss was the highest in treatment AH followed by treatment BH, with the lowest loss in the control plots. In the first season about 172 kg mineral N ha$^{-1}$ were added from the irrigation water, and the large N losses could be mainly attributed to NO$_3$$^{-}$ leaching. Compared with the three tomato cropping seasons, N losses in the two pepper cropping seasons were relatively low. The more intensive fruit harvests with pepper may have led to greater N utilization compared to tomato (Table II), thus the N losses correspondingly decreased. The root rot on pepper from January to June 2001 caused soil residue N to increase sharply, as mentioned earlier, due to decreasing crop N uptake and increasing N accumulation. Thus, high residual mineral N at the planting stage of tomato crop in 2001 led to N losses after harvest of the tomato crop in 2001. After five cropping seasons, therefore, the total apparent N losses across all treatments was high. An increasing N rate increased both residual N in the soil and apparent N losses from the system, but no significant differences were found between the two fertilizers for the same rate. Table III also revealed that about 1065 kg N ha$^{-1}$ were applied via irrigation water during the two-and-a-half-year study. The concentration of NO$_3$$^{-}$ in the groundwater used for irrigation was about 20 mg N L$^{-1}$, which was above the maximum contaminant level of 10 mg L$^{-1}$, and by regulatory standards could be considered unsuitable for drinking (Williams et al., 1998). Since NO$_3$-N was highly soluble and mobile, most of the N losses may have been due to NO$_3$$^{-}$ leaching.
**TABLE III**

<table>
<thead>
<tr>
<th>Treatment&lt;sup&gt;a,b&lt;/sup&gt;</th>
<th>Fertilizer</th>
<th>Soil mineral N input from irrigation</th>
<th>N removed by aboveground harvests</th>
<th>Soil mineral N after harvest</th>
<th>Apparent N loss of N balance in the 0–90 cm soil depth after each crop harvest and final total N balance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N applied</td>
<td>planting</td>
<td>NH₄-N (B)</td>
<td>NO₃-N (C)</td>
<td>Fruit (E)</td>
</tr>
<tr>
<td>CK</td>
<td>0</td>
<td>126.2</td>
<td>539.4</td>
<td>17.2</td>
<td>63.4&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>AL</td>
<td>150</td>
<td>126.2</td>
<td>539.4</td>
<td>17.2</td>
<td>61.7a</td>
</tr>
<tr>
<td>AH</td>
<td>300</td>
<td>126.2</td>
<td>539.4</td>
<td>17.2</td>
<td>72.4a</td>
</tr>
<tr>
<td>BL</td>
<td>150</td>
<td>126.2</td>
<td>539.4</td>
<td>17.2</td>
<td>66.2a</td>
</tr>
<tr>
<td>BH</td>
<td>300</td>
<td>126.2</td>
<td>539.4</td>
<td>17.2</td>
<td>67.7a</td>
</tr>
</tbody>
</table>

<sup>a</sup>AL and AH—treatments applied with low-N compound fertilizer (12-12-17, N-P₂O₅-K₂O) at 150 and 300 kg N ha⁻¹ crop⁻¹, respectively; BL and BH—treatments applied with high-N compound fertilizer (21-8-11, N-P₂O₅-K₂O) at 150 and 300 kg N ha⁻¹ crop⁻¹, correspondingly.

<sup>b</sup>1999-T—tomato crop in 1999.

<sup>c</sup>Values followed by the same letter within a column for a particular crop season are not significantly different at P < 0.05 by Duncan’s multiple range test.

<sup>d</sup>2000-HP—pepper in 2000.

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**System-level nitrogen efficiencies**

Apparent system-level N efficiencies for the different treatments in the five crops are shown in Table IV. The N recovery efficiencies were generally higher in the seasons when peppers were grown from spring to summer than in those when tomatoes were grown from autumn to winter. In autumn and
winter, evapotranspiration was lower and water input often exceeded the water holding capacity of the soil. These conditions would have increased nitrate-leaching losses in autumn and winter (Meisinger et al., 1991; Liang and MacKenzie, 1994; Liang et al., 1991). Over the total experimental period, apparent system-level N efficiencies were relatively low, with only about 50% of the applied N recovered in the fertilizer treatments and less than 40% in the control plots. Thus, 50% of the N inputs to the system were lost during the two and a half years of the study. In similar studies for N applied in one year, rice (Oryza sativa L.)-tomato rotations made use of 40% to 60%, rice-sweet pepper (Capsicum spp.) cropping used 25% and rice-tobacco (Nicotiana tabacum L.) rotations utilized 65% to 84% (Tripathi et al., 1997). Some researchers reported that potato's (Solanum tuberosum L.) N recovery ranges from 25% to 40% (Errebhi et al., 1998), and rape recovers 38% to 44% of the applied N (Cai et al., 1995). Because of low N recovery by vegetable crops (Lowrance and Smittle, 1988; Chen et al., 2002), most of the N applied to crops as fertilizer and mineralized from soil may remain unutilized.

### Table IV
System-level nitrogen efficiencies of tomato and pepper crops for five treatments

<table>
<thead>
<tr>
<th>Treatment (a)</th>
<th>1999-T (b)</th>
<th>2000-HP (c)</th>
<th>2001-T</th>
<th>2001-HP</th>
<th>2001-T</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK (control)</td>
<td>57.5</td>
<td>70.3</td>
<td>72.0</td>
<td>89.0</td>
<td>51.9</td>
<td>39.8</td>
</tr>
<tr>
<td>AL</td>
<td>54.9</td>
<td>91.9</td>
<td>73.6</td>
<td>95.5</td>
<td>61.0</td>
<td>49.6</td>
</tr>
<tr>
<td>AH</td>
<td>52.6</td>
<td>93.3</td>
<td>76.6</td>
<td>95.2</td>
<td>62.6</td>
<td>51.3</td>
</tr>
<tr>
<td>BL</td>
<td>58.8</td>
<td>93.6</td>
<td>94.6</td>
<td>89.3</td>
<td>58.2</td>
<td>52.7</td>
</tr>
<tr>
<td>BH</td>
<td>55.5</td>
<td>90.3</td>
<td>84.7</td>
<td>86.4</td>
<td>61.3</td>
<td>49.3</td>
</tr>
</tbody>
</table>

(a) AL and AH—treatments applied with low-N compound fertilizers (12-12-17, N-P$_2$O$_5$-K$_2$O) at 150 and 300 kg N ha$^{-1}$ crop$^{-1}$, correspondingly; BL and BH—treatments applied with high-N compound fertilizers (21-8-11, N-P$_2$O$_5$-K$_2$O) at 150 and 300 kg N ha$^{-1}$ crop$^{-1}$, respectively.

(b) 1999-T—tomato crop in 1999.

(c) 2000-HP—pepper in 2000.

### Applications

Concerning the agronomic value of these two compound fertilizers, neither significantly increased dry matter yields during the first season mainly because of the abundant residual nutrients in the soil at the start of the experiment. However, this experiment indicated that the low-N fertilizer (12-12-17) applied at a rate of 300 kg N ha$^{-1}$ gave overall higher vegetable fruit yields than the high-N fertilizer (21-8-11) applied at the same N rate over the five cropping seasons. There was a high soil available P and K status at the beginning of the experiment, and this, combined with the increasing P and K from fertilizer application, may have contributed to increased fruit yields. Also in the surface soil layers for the last 4 harvests, the increasing N rate significantly increased crop N uptake 50% of the time and NO$_3$-N accumulation 75% of the time, however in different soil profiles crop responses and the soil mineral N dynamics were poorly related to N fertilizer rate during the experiment. This could be due to the experimental conditions where many other factors affected soil mineral N concentrations. The increasing N rate also increased apparent N losses at the system level. Since only about 50% of the total N input to the system could be recovered after the experiment, and fertilizer N use efficiencies were always lower than 29% for all treatments, the crop N requirement for a given yield potential should be examined carefully and appropriate fertilizer recommendations should be developed.

There may also be serious implications for environmental safety in protected vegetable production systems. Several studies have indicated that soil saturation as a result of rain or irrigation may have promoted NO$_3$-N losses through denitrification (Aulakh et al., 1991; Buresh et al., 1993; Ladha et al., 1996). Heavy irrigation and high NO$_3$-N accumulation in the upper soil layers may also have increased the potential for NO$_3$$^{-1}$ leaching and denitrification losses in the experimental greenhouse. Although N losses due to denitrification cannot be accurately estimated, most of the N losses appear
to be due to NO$_3^-$ leaching. In this region, after about twenty years of greenhouse vegetable growth following local commercial practices, groundwater had nitrate contamination due to heavy fertilizer N and irrigation inputs. A survey conducted in this region in 2001 verified this, showing that nitrate nitrogen concentrations in about 50% of the wells used for irrigation and drinking water exceeded 10 mg NO$_3^-$ N L$^{-1}$ (Zhu, 2002). In the experiment where in one cropping season about 200 kg N ha$^{-1}$ was applied with about 1000 mm irrigation water, this could pose a serious health risk.

Thus, irrigation could be one of the most important factors controlling nitrate-leaching losses in this type of intensive vegetable production system. Under local practices, farmers often applied three to four times the amount of N to vegetable crops in greenhouses compared to what was applied in this experiment. Therefore fertilizer N recovery under local practices would be much lower than the experiment. Thus, there is an urgent need to identify the factors contributing to poor N efficiencies in these greenhouse vegetable production systems. Optimum irrigation management practices need to be developed to limit water inputs without decreasing vegetable yields.

REFERENCES


