

Responses of Agronomic Benefit and Soil Quality to Better Management of Nitrogen Fertilizer Application in Greenhouse Vegetable Land^{*1}

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ABSTRACT

As a result of intensive greenhouse vegetable production in northern China, the potential risk of nitrogen (N) fertilizer over-applied is increasingly apparent and is threatening ecosystem and the sustainability of food production. An experiment was carried out in Shouguang, Shandong Province, China to evaluate agronomic benefit and soil quality under different N applications, including the conventional chemical N rate (1 000 kg N ha⁻¹ season⁻¹, N1), 70% of N1 (N2), 70% of N1 + maize straw (N3), 50% of N1 + maize straw + drip irrigation (N4), and 0% of N1 (N0), during two successive growing seasons of autumn-winter (AW) and winter-spring (WS). The maximum yields for N4 were 1.1 and 1.0 times greater than those for N1 in the AW and WS seasons, respectively. N agronomic efficiency (AE_N) and apparent N recovery efficiency (RE_N) were greatest with the N4. A significant relationship was found between soil NO₃⁻-N content and electrical conductivity (EC) ($R^2 = 0.61$ in the AW season and $R^2 = 0.29$ in the WS season). Reducing N fertilizer decreased soil NO₃⁻-N accumulation (20.9%–37.8% reduction in the AW season and 11.7%–20.1% reduction in the WS season) relative to the accumulation observed for N1 within the 0–100 cm soil layer. Soil urease and invertase activities were not significantly different among N treatments. The N4 treatment would be practical for reducing excess N input and maintaining the sustainability of greenhouse-based intensive vegetable systems in Shouguang.

Key Words: maize straw, N use efficiency, soil enzyme, soil NO₃⁻-N accumulation, tomato yields

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INTRODUCTION

Rapid economic development and increasing living standards in China since the 1980s have contributed to the rapid development of vegetable production, especially in greenhouse systems (Zhu *et al.*, 2002). Shandong, in northern China, is the primary vegetable-growing province with 72.6×10^4 ha of greenhouse cultivation, which accounts for nearly 50% of the total greenhouse area coverage in the country (Gao, 2010). Within Shandong Province, Shouguang is the major region of intensive greenhouse vegetable production by 2003. In Shouguang, greenhouse vegetable cultivation covered 50 000 ha, accounting for more than 80% of total vegetable cultivation (Tang, 2004). The planting of greenhouse vegetables has become the prin-

cipal source of revenue for local farmers.

Nitrogen (N) fertilization in mineral forms is the most important nutrient input for the greenhouse vegetable system. Farmers use very large amounts of N fertilizer and irrigation water with the goal of maximizing yields (Ju *et al.*, 2007). Consequently, continuous and excessive N input in greenhouses has become a major problem in Shouguang, and it has led to reduced product quality, a high risk of nitrate leaching, soil salinity and low fertilization profit. Several systematic investigations showed that greenhouse vegetables received very high N and water inputs, typically totaling 2 388 kg N ha⁻¹ (Liu, 2000), of which more than 1 200 kg N ha⁻¹ was N fertilizer. The water applied was 1 000 mm per irrigation during the two or three crop cycles each year (Zhu *et al.*, 2005). These high inputs

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and the extremely low crop recoveries of N fertilizer nutrients, usually less than 10% in the case of N, lead to a marked deterioration in soil and groundwater quality; as such, the systems are clearly unsustainable (Zhang *et al.*, 1996). Similar observations for N use efficiency have been reported by Wu *et al.* (2000) and He *et al.* (2007). Zhu (2002) reported that the conventional nutrient input in protected vegetable fields in Shouguang was 2063 kg N ha⁻¹ for a single cropping season and greatly exceeded the amount required for vegetables. High application rates of N fertilizer led to soil pH decrease with the age of greenhouse and led to high level of NO₃⁻-N in soil layers. High irrigation rates allow NO₃⁻-N to leach into deeper soil layers, resulting in pollution of shallow groundwater (Zhang *et al.*, 1996; Ju *et al.*, 2007). The seasonal average N input through chemical fertilizer application increased from 817 kg N ha⁻¹ in 1994 to 1178 kg N ha⁻¹ in 2004. Over time, the proportion of NO₃⁻-N content in groundwater above the limit for drinking water standards increased from 18% in 1996 to 81% in 2005 within the surveyed regions (He, 2006). Excessive N input in greenhouse vegetables also impacts soil enzyme activity (Yang *et al.*, 2008); for instance, chemical N fertilizer was found to inhibit soil enzymatic activity (Yang *et al.*, 2008). Improved N management for intensive greenhouse vegetable production is therefore urgently required in Shouguang.

To achieve sustainable vegetable production and environmentally safe agriculture, many management practices have been proposed to increase vegetable yields and N use efficiency and to improve soil quality. In China, agricultural straw resources are abundant; in 2000, the straw yield was 7×10^{12} kg and the highest worldwide (Weng *et al.*, 2004). Furthermore, straw resources have been increasing at an annual rate of $1.251.2 \times 10^7$ kg (Zhong *et al.*, 2003). However, the utilization ratio and efficiency are quite low, as large amounts of straw are burned or discharged indiscriminately, and little is utilized. Several studies have shown that straw reapplication on grain crops can improve crop yield, soil aggregation and soil structure (Seo *et al.*, 2007). Despite the fact that maize or wheat straw could help mitigate the problem of imbalances in the C/N ratio, which is caused by high N levels in greenhouses, there have been only a few studies assessing the use of agricultural straw in greenhouse vegetable cultivation. Drip irrigation (above-ground tape) combined with fertigation is used on many farms (Pérez-Parra and Céspedes, 2001) and is highly recommended as the most efficient irrigation method (Munir, 2004) in enhancing N fertilizer use efficiency and crop production

(Papadopoulos, 2000). However, in the greenhouse vegetable production systems in China, there is very little published information describing or evaluating drip irrigation and N management practices combined with C/N adjustment.

The objectives of the present study were to improve N use efficiency and soil quality for greenhouse tomato crops and to reduce the risk of excessive N fertilizer application. Different N fertilizer management strategies were incorporated into the study and compared with the local farmers' conventional management of N fertilizer application. The results of this study outline improved N fertilizer management strategies, which are proposed for use by farmers in greenhouse production.

MATERIALS AND METHODS

Field site

The field experiment was conducted during the successive autumn-winter (AW) and winter-spring (WS) seasons from September 2008 to July 2009 in Daotian, a town in Shouguang, Shandong Province, China (36° 49' 57.7" N, 118° 54' 58.9" E), which lies in the representative region of intensive greenhouse production. The mean annual evapotranspiration is 1345.7 mm and the annual precipitation is 550 mm. The frost-free period is 200 d. The internal temperature of greenhouses used for vegetable production ranges from 12 to 45 °C annually, with a mean of 25 °C (Song *et al.*, 2009). The greenhouse used in the present study had been used for vegetable cultivation for three years before the field experiment site was established. The soil texture is 36% sand (2–0.05 mm), 61% silt (0.05–0.002 mm) and 3% clay (< 0.002 mm) (Song *et al.*, 2009). The region is characterized as coastal alluvial plain, and the elevation does not exceed 50 m. There is no obvious acidification and the average soil pH value in Shouguang was previously reported as 7.16 (Gan *et al.*, 2008). For mixed soil samples at a depth of 0–20 cm, the values for several parameters are as follows: a pH value (H₂O) of 7.7; an electrical conductivity (EC) of 0.4 dS m⁻¹; organic matter of 14.6 g kg⁻¹; and available N, phosphorus (P), and potassium (K) values of 63.0, 54.7, and 122.1 mg kg⁻¹, respectively.

Crop and fertilization

The planting pattern in the greenhouse vegetable cropping system involved an initial transplantation of tomato (*Solanum lycopersicum* cv. Hao wei si te, one of the primary cultivars in the local area) in September and a final harvest in February of the following year

(AW season). For the winter-spring (WS) season, transplanting occurred in March and the final harvest occurred in July of the same year. The distance between rows was 70 cm, and the distance between plants was 40 cm.

The areas used during the AW and WS seasons were divided into 15 plots, each covering an area of 11 m × 2.8 m. There were five treatments, with three replicates each, laid out in a completely randomized design for both seasons. The five treatments were as follows: a control receiving no chemical N fertilizer (N0), 100% of the conventional chemical N rate (N1, 1 000 kg N ha⁻¹), 70% of N1 (N2), 70% of N1 + maize straw (N3), and 50% of N1 + maize straw + drip irrigation (N4) (Table I).

Urea was used as the N chemical fertilizer in the basal dressing before transplanting and also for supplementary fertilization. Calcium superphosphate (800 kg P₂O₅ ha⁻¹), potassium sulfate (1 000 kg K₂O ha⁻¹) and organic manure (chicken manure with 47.2 Mg ha⁻¹, containing 50.3 g kg⁻¹ of organic carbon, 25.4 g kg⁻¹ of total N, 20.7 g kg⁻¹ of total P₂O₅, and 21.2 g kg⁻¹ of total K₂O) were equally applied for each treatment before transplanting. All of the calcium superphosphate and organic manure was applied as a basal dressing. For the urea and potassium sulfate fertilizers, 40% was used for the basal dressing, and the remaining 60% was applied as top-dressing. Dry maize straw (N: 9.8 g kg⁻¹; P₂O₅: 6.2 g kg⁻¹; K₂O: 10.5 g kg⁻¹; C/N ratio: 49; water content: 600 g kg⁻¹) was cut to a length of 1.5 cm and applied at 7 500 kg ha⁻¹ as a basal dressing in the N3 and N4 treatments. Pumped groundwater was used for irrigation and applied 7 and 9 times during the growth stages in the AW and WS seasons, respectively. A total of 47 mm water was applied to N0, N1, N2, and N3, respectively, in AW season and 67 mm water in WS season. A total of 21 mm water was applied to N4 in AW season and 27 mm water in WS season. A tensiometer was used to measure

soil water tension in the N4 treatment. The plots were irrigated immediately after the fertilizers were broadcast as a basal dressing. For the top-dressing application, fertilizers were dissolved in water. The NO₃⁻-N concentrations of irrigation water were uniformly higher than 10 mg L⁻¹, the acceptable standard level for drinking water. The average value of NO₃⁻-N concentration was 29.6 mg L⁻¹. The N fertilizer of 120.4 kg ha⁻¹ was input to soil followed by irrigation water. Plastic films were installed vertically from the soil surface to a 50-cm depth to prevent water or nutrient diffusion between adjacent plots. Other aspects of crop management followed conventional practices.

Soil and plant samples

After crop harvesting, five soil cores 100 cm in depth were taken from each plot and each then sectioned into portions of the following depths: 0–20, 20–40, 40–60, 60–80 and 80–100 cm. Portions corresponding to the same depth were mixed as one composite sample to determine soil NO₃⁻-N and soil moisture contents. Other soils were air-dried and sieved (< 2 mm) for chemical analysis. Tomato fruits were harvested several times during the growth period, and plants were sub-sampled from each plot at every harvest date to calculate fresh weight. Each plant was separated into shoot and fruit; belowground residues were not considered. Straw samples were oven-dried at 70 °C and weighed to obtain the dry matter weight. Samples were ground and filtered through a 2-mm sieve for nutrient analysis.

Chemical analysis and methods

Soil and water were mixed at a ratio of 1:2.5 and a glass electrode was used to measure soil pH. The soil EC was measured with an electrolytic conductivity meter and a soil:water ratio of 1:5. Soil NO₃⁻-N was extracted from fresh soil samples with 1 mol L⁻¹ KCl

TABLE I

Fertilization rates^{a)} in the field plots during the autumn-winter (AW) and winter-spring (WS) seasons

Code	Treatment	Chemical fertilization			Organic fertilization			Total fertilization		
		N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O
		kg ha ⁻¹ season ⁻¹			kg ha ⁻¹ year ⁻¹					
N0	0% of N1	0	800	1 000	1 200	976	1 001	1 200	2 576	3 001
N1	100% of conventional chemical N rate	1 000	800	1 000	1 200	976	1 001	3 200	2 576	3 001
N2	70% of N1	700	800	1 000	1 200	976	1 001	2 600	2 576	3 001
N3	70% of N1 + maize straw	700	800	1 000	1 200	976	1 001	2 600	2 576	3 001
N4	50% of N1 + maize straw + drip irrigation	500	800	1 000	1 200	976	1 001	2 200	2 576	3 001

^{a)} Chemical fertilization was applied in both AW and WS seasons and organic fertilization was only in the WS season.

solution and determined by an auto-analyzer (TRA-CCS 2000 Continuous Flow Analysis, Bran Luebbe, Hamburg, Germany) after shaking for 30 min (Ju *et al.*, 2002). Analyses of available nutrients in the soil included measurements for soil available N (Jenkinson, 1968), P (Olsen *et al.*, 1954), and K (Pratt, 1951). Soil enzyme activities were assayed in triplicate using air-dried samples as described by Guan (1986). Briefly, urease activity was determined using urea as substrate, and the soil mixture was incubated at 37 °C for 24 h. The $\text{NH}_3\text{-N}$ produced was determined using the colorimetric method, and urease activity was expressed as $\text{mg NH}_3\text{-N g}^{-1} \text{ d}^{-1}$. Invertase activity was determined using sucrose as a substrate and incubation at 37 °C for 24 h. The glucose produced was measured with the colorimetric method, and invertase activity was expressed as $\text{mg glucose g}^{-1} \text{ d}^{-1}$. Fruit and shoot tissues were digested in an $\text{H}_2\text{SO}_4\text{-H}_2\text{O}_2$ solution, and the Kjeldahl method (Lu, 2000) was used for determination of the N concentration.

Calculation method

The calculation of N use efficiency was performed using the parameters N agronomic efficiency (AE_N) and apparent N recovery efficiency (RE_N), which are widely used because they are easy to use and inexpensive to measure in any experiment (Ladha *et al.*, 2005).

The ratio of yield to N supply is commonly referred to as N agronomic efficiency (AE_N , kg kg^{-1}):

$$\text{AE}_\text{N} = (Y_\text{T} - Y_0)/F_\text{N} \quad (1)$$

where Y_T is the fruit yield in a treatment with N fertilizer application (kg ha^{-1}), Y_0 is the fruit yield measured in a control treatment with no N fertilizer application (kg ha^{-1}), and F_N is the N supplied by fertilizer treatment (kg ha^{-1}).

The ratio of plant N to N supply is referred to as the apparent N recovery efficiency (RE_N , %):

$$\text{RE}_\text{N} = (U_\text{T} - U_0)/F_\text{N} \times 100 \quad (2)$$

where U_T is the plant N uptake measured from above-ground biomass in a plot that received N at the rate of F_N (kg ha^{-1}), and U_0 is the total N uptake from above-ground biomass in the treatment without N fertilizer addition (kg ha^{-1}).

Statistical analysis

The results were subjected to analysis of variance (ANOVA) to determine whether the differences

among data were significant (means $\pm$ standard errors, $n = 3$). The analysis was performed using SAS 8.0 for Windows software package (SAS Inc., 1999). The least significant difference (LSD) was conducted to determine the differences between the individual treatments. All tests were conducted at a significance level of $P < 0.05$.

RESULTS

Local farmers' conventional fertilizer rates

A survey to N management practices in the greenhouse-based vegetable production system of Shouguang was conducted in 127 farms in July 2007. The survey consisted of some components related to general aspects of each farm: (i) completion of a questionnaire that characterized general features of each greenhouse, and farm management practices associated with irrigation and N management and (ii) calculation of the total amounts of fertilizer N applied. Fertilization rate of greenhouse vegetable was more than its uptake according to investigation. The median chemical fertilizer rate for tomato was 1065 kg N ha^{-1} , 808 $\text{kg P}_2\text{O}_5 \text{ ha}^{-1}$, and 1174 $\text{kg K}_2\text{O ha}^{-1}$; the median organic fertilizer rate for tomato was 1221 kg N ha^{-1} , 946 $\text{kg P}_2\text{O}_5 \text{ ha}^{-1}$, and 1112 $\text{kg K}_2\text{O ha}^{-1}$ (Fig. 1). The fertilizer ratio of N, P_2O_5 and K_2O was unreasonable. Most of chemical N and P_2O_5 were used as basal fertilizer and most of K_2O was used as top-dressing fertilizer. The N fertilizer was being extremely over-applied to greenhouses. Based on the results of the survey, local farmers' conventional fertilizer rates were established (Table I).

Tomato yields

Use of N fertilizer promoted tomato yields compared to the N0 treatment (Fig. 2), with increases of 7.3%–17.6% and 7.8%–18.1% in the AW and WS seasons, respectively. For all N fertilization treatments in the AW season, the average fruit yields were 87.8–96.3 Mg ha^{-1} . The highest chemical N fertilizer rate (N1) did not produce the highest fruit yields; instead, the maximum yields were observed when 50% chemical N fertilizer was combined with maize straw and drip irrigation (N4). This treatment produced a total of 96.3 Mg ha^{-1} , which was 9.7% higher compared to the N1 treatment. In the WS season, the average fruit yields were 77.5–84.9 Mg ha^{-1} . The largest yields were also obtained with the N4 treatment, and again, the conventional N management (N1) did not have the highest yields. Between the two seasons, tomato yields differed

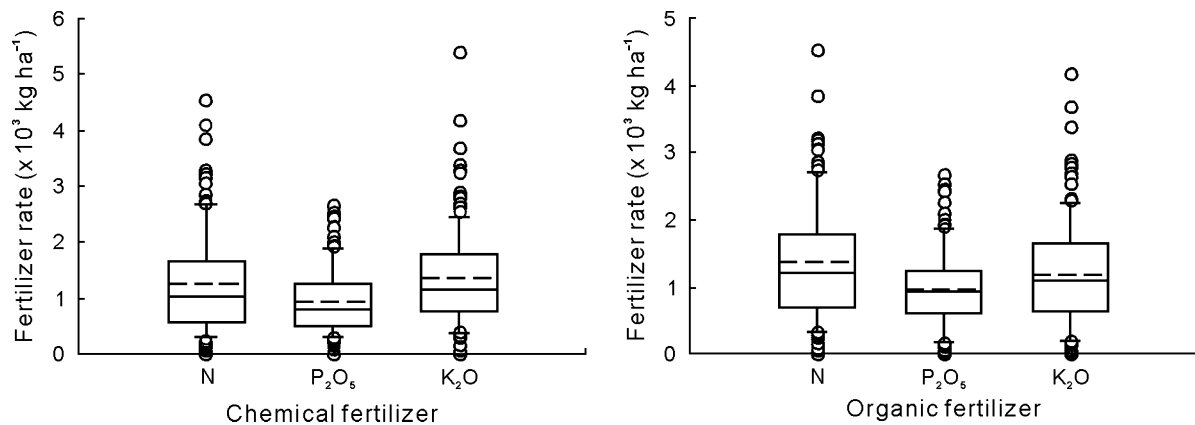


Fig. 1 Variability of local farmers' conventional application rates of chemical fertilizer and organic fertilizer. The boundary of the box closest to zero indicates the 25th percentile; the solid line within the box indicates the median; the broken line indicates the mean; the boundary of the box farthest from zero indicates the 75th percentile; error bars above and below the box indicate the 90th and 10th percentiles, respectively; and bullet points indicate the outliers.

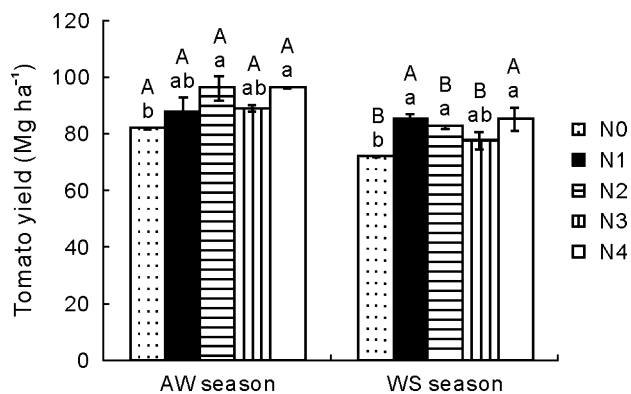


Fig. 2 Effects of N fertilization rates on tomato yields in the autumn-winter (AW) and winter-spring (WS) seasons. Bars with the same uppercase letter(s) within a given N rate are not significantly different among seasons at $P < 0.05$. Bars with the same lowercase letter(s) within a given season are not significantly different among N rates at $P < 0.05$. Vertical bars indicate standard errors of the means ($n = 3$). See Table I for the descriptions of treatments N0–N4.

significantly for the N0, N2 and N3 treatments, with lower yields observed in the WS season compared to the AW season, but no differences were observed for the N1 and N4 treatments.

N use efficiency

The effects of different N fertilizer management on AE_N during the two seasons are summarized in Fig. 3. Additional N did not significantly increase N utilization in crops. On the contrary, N4 produced a significantly greater AE_N in both seasons, compared to other treatments, with AE_N values of 28.9 and 26.1 kg kg⁻¹ in the AW and WS seasons, respectively. Compared to N1, the AE_N for the N4 treatment was 194.9% and 102.3% higher in the AW and WS seasons, respectively. There were no significant differences in AE_N between the two seasons for the four different treatments. The

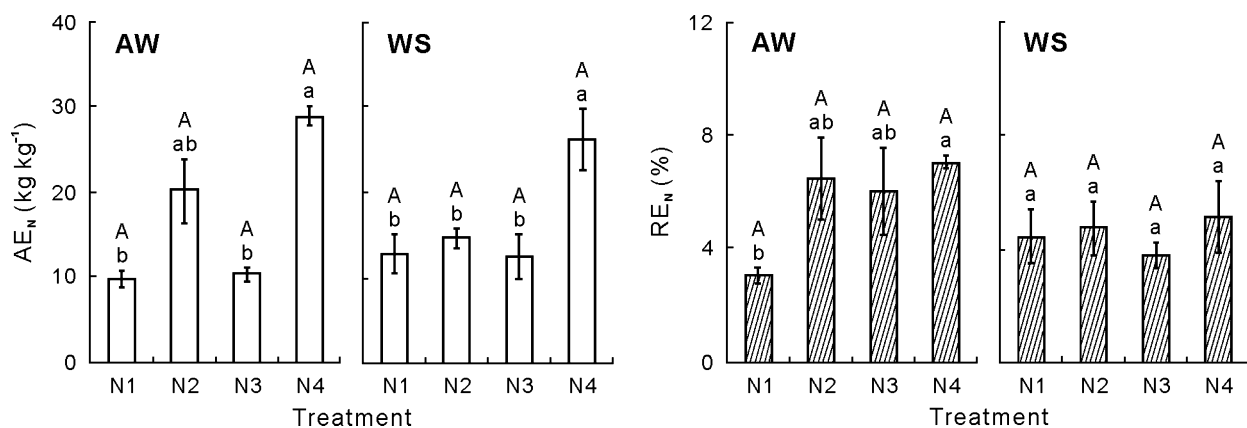


Fig. 3 Effects of N fertilization rates on N agronomic efficiency (AE_N) and apparent N recovery efficiency (RE_N) in the autumn-winter (AW) and winter-spring (WS) seasons. Bars with the same uppercase letter(s) within a given N rate are not significantly different among seasons at $P < 0.05$. Bars with the same lowercase letter(s) within a given season are not significantly different among different N rates at $P < 0.05$. Vertical bars indicate standard errors of the means ($n = 3$). See Table I for the descriptions of treatments N1–N4.

RE_N decreased with the increasing N application rates in the AW season (Fig. 3). The RE_N for the N1 treatment was significantly lower ($P < 0.05$) than that for the N4 treatment. There were no significant differences, however, among the reduced N fertilizer treatments (N2, N3 and N4). RE_N was not significantly affected by the different N fertilizer rates during the WS season, but the highest value was observed in the N4 treatment. The crop utilized less than 10% of the N fertilizer in both seasons, and N use efficiency was higher in the AW season than in the WS season.

Soil electrical conductivity

N fertilizer application rates increased soil EC values in the surface soil relative to the N0 treatment in both the AW and WS seasons. A significantly higher ($P < 0.05$) soil EC was observed for the N1 treatment (Fig. 4). Among the five N fertilization rates, soil EC was greatest under the N1 treatment, with 1.3 dS m^{-1} in the AW season and 0.8 dS m^{-1} in the WS season, indicating that salts readily accumulated with increased application of N fertilizer in the greenhouse. For the N treatments, soil EC values were observed in the orders of $N4 < N2 < N3 < N1$ in the AW season and $N3 < N4 < N2 < N1$ in the WS season. However, the differences in soil EC values between the different treatments were not significant. Between the two seasons, significant differences in soil EC were not observed for any of the treatments.

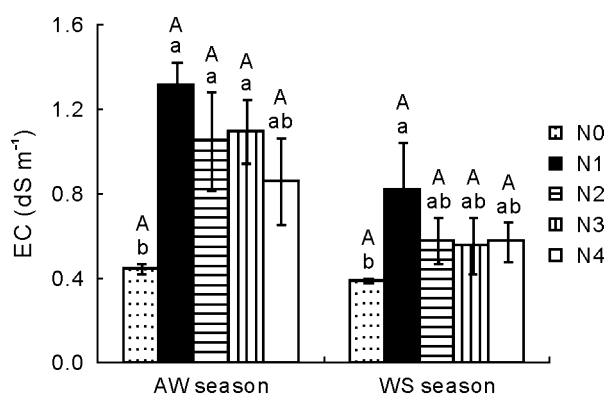


Fig. 4 Soil electrical conductivity (EC) in the autumn-winter (AW) and winter-spring (WS) seasons under different N fertilization rates. Bars with the same uppercase letter(s) within a given N rate are not significantly different among different seasons at $P < 0.05$. Bars with the same lowercase letter(s) within a given season are not significantly different among different N rates at $P < 0.05$. Vertical bars indicate standard errors of the means ($n = 3$). See Table I for the descriptions of treatments N0–N4.

Soil EC values showed a highly significant and positive correlation with NO_3^- -N content in the topsoil ($R^2 = 0.61$ in the AW season and $R^2 = 0.29$ in the WS

season), indicating that high NO_3^- -N content was an important factor contributing to soil salinity (Fig. 5). Thus, soil EC may be used as an index of NO_3^- -N accumulation.

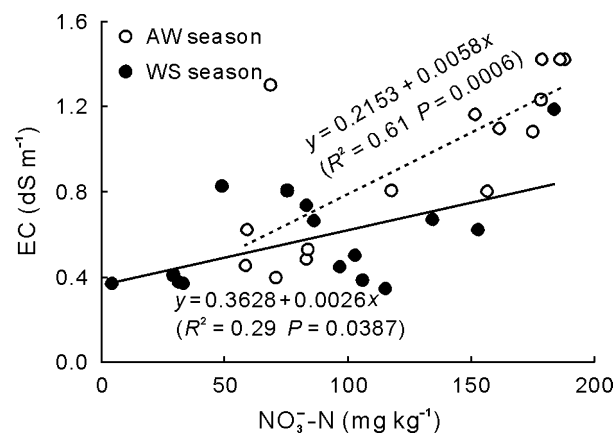


Fig. 5 Relationships between soil electrical conductivity (EC) and soil NO_3^- -N content in the autumn-winter (AW) and winter-spring (WS) seasons.

Soil NO_3^- -N accumulation

NO_3^- -N accumulation in the 0–100 cm soil profile varied greatly among different treatments (Fig. 6). NO_3^- -N accumulation for the N0 treatment in the 0–100 cm soil layer declined from $287.4 \text{ kg N ha}^{-1}$ in the AW season to $280.1 \text{ kg N ha}^{-1}$ in the WS season. N fertilizer application significantly increased NO_3^- -N accumulation in the top 100 cm of the soil profile. The ranges were 696.9 – $1119.3 \text{ kg N ha}^{-1}$ (an average of $874.4 \text{ kg N ha}^{-1}$) in the AW season and 782.6 – $979.6 \text{ kg N ha}^{-1}$ (an average of $879.3 \text{ kg N ha}^{-1}$) in the WS season. Application of large amounts of N fertilizer (N1 treatment) caused greater accumulation of NO_3^- -N in the 0–100 cm soil layer. For the N1 treatment, the NO_3^- -N contents were 1119.3 and $979.6 \text{ kg N ha}^{-1}$ in the AW and WS seasons, respectively. These values indicated significantly greater NO_3^- -N accumulation in the N1 treatment compared to the other treatments. When N fertilizer was applied at the lower rate and combined with maize straw and drip irrigation (*i.e.*, N4 treatment), there was less accumulation of soil NO_3^- -N in both seasons. For the various N fertilizer treatments, NO_3^- -N accumulation was higher in the WS season than in the AW season. This was due to the large amounts of irrigation water used in the summer, which could cause NO_3^- -N leaching and thus reduce soil NO_3^- -N accumulation in the 0–100 cm soil layer. NO_3^- -N accumulation was mainly distributed throughout the 0–40 cm depth of the soil profile. The average percentages of NO_3^- -N accumulated in the 0–40 cm depth were 48.0%–65.2% in the AW season and

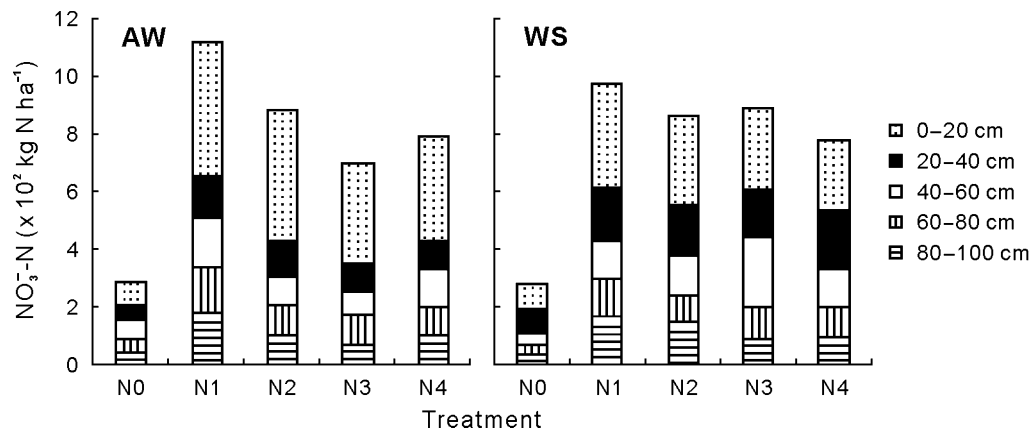


Fig. 6 Soil NO_3^- -N accumulation in the 0–100 cm depth for different fertilization treatments in the autumn-winter (AW) and winter-spring (WS) seasons. See Table I for the descriptions of treatments N0–N4.

49.9%–59.2% in the WS season. However, the observed accumulation of more than 40% NO_3^- -N in the 40–100 cm depth of the soil profile, a level where accumulated NO_3^- -N cannot be utilized by plant roots, could lead to NO_3^- pollution of groundwater.

Soil enzyme activities

Soil invertase activity was not significantly affected by any of the treatments. As shown in Fig. 7, the average soil invertase activity ranged in 6.0–7.0 $\text{mg glucose g}^{-1} \text{d}^{-1}$ in the AW season and 6.1–7.9 $\text{mg glucose g}^{-1} \text{d}^{-1}$ in the WS season. In both seasons, soil invertase activity increased with the increasing N fertilizer application rates, but the activity declined at the highest application rates (N1). The highest values, 7.0 and 7.9 $\text{mg glucose g}^{-1} \text{d}^{-1}$, were observed with N3 treatment in the AW season and with N2 treatment in the WS season, respectively. No differences of invertase activity were observed for the different N fertilization rates between the two seasons.

Soil urease activity was affected by fertilization (Fig. 7). The ranges of average soil urease activity were 1.2–2.1 $\text{mg NH}_3\text{-N g}^{-1} \text{d}^{-1}$ in the AW season and 1.7–2.2 $\text{mg NH}_3\text{-N g}^{-1} \text{d}^{-1}$ in the WS season. Soil urease activity increased significantly when N fertilizer was applied in the AW season. There were no significant differences in soil urease activity for the lower N fertilization treatments in both seasons. The soil urease activity was in the order of $\text{N4} > \text{N2} > \text{N3} > \text{N1} > \text{N0}$ in the AW season and $\text{N4} > \text{N1} > \text{N3} > \text{N2} > \text{N0}$ in the WS season. Soil enzyme activity was also affected by the season. For all treatments except N2, soil urease activity was lower in the AW season than in the WS season.

DISCUSSION

Responses of agronomic benefit to better management of N fertilizer

Tomato is one of the most important vegetables growing in greenhouse. It is out of question that ferti-

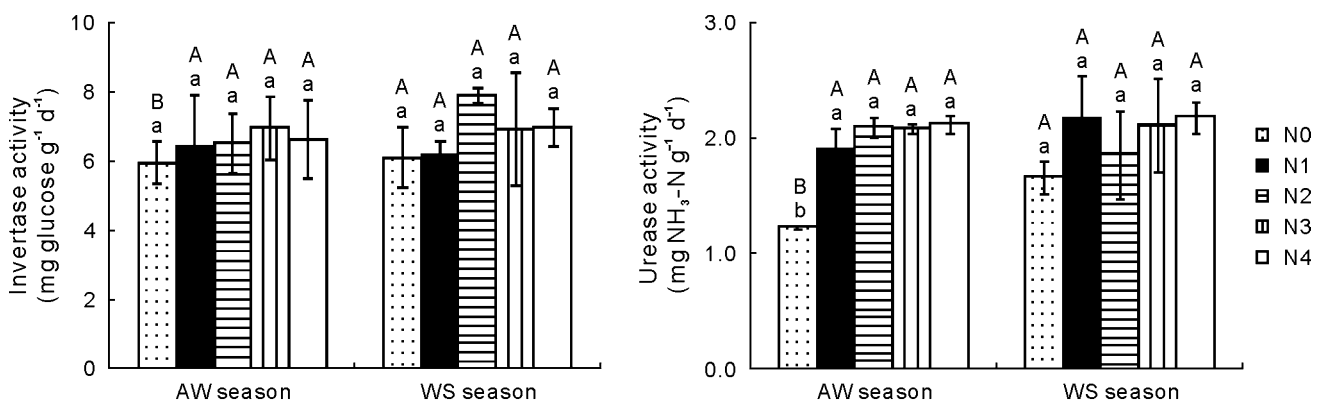


Fig. 7 Effects of different N fertilizer management levels on soil invertase and urease activities in the autumn-winter (AW) and winter-spring (WS) seasons. Bars with the same uppercase letter(s) within a given N rate are not significantly different among different seasons at $P < 0.05$. Bars with the same lowercase letter(s) within a given season are not significantly different among different N rates at $P < 0.05$. Vertical bars indicate standard errors of the means ($n = 3$). See Table I for the descriptions of treatments N0–N4.

lizer can increase crop yield, but in recent years, crop yield was not increasing with the increasing amount of fertilizer application. This is in agreement with the results in our study. Although N fertilizer greatly improved tomato yields compared with no N fertilizer application (N0) during the AW and WS seasons (Fig. 2), tomato yields did not increase significantly when the N fertilizer application rate exceeded crop requirements (*e.g.*, N1 treatment) in both seasons. The highest yields were observed in the N4 treatment (50% of N1 combined with maize straw and drip irrigation), with 96.3 and 84.9 Mg ha⁻¹ in the AW and WS seasons, respectively. For the two seasons, the fruit yields for the N4 treatment were 1.1 and 1.0 times greater than the yields observed for N1. This was in agreement with the results of Zhu *et al.* (2005), who reported that the increasing N fertilizer application rates increased the total N uptake of crops, but did not increase the fruit yield. The highest N fertilizer application rate tested (1800 kg N ha⁻¹, the highest rate used in commercial practice in Shouguang) should be regarded as excessive, and even the second-highest rate (1200 kg N ha⁻¹, the average local commercial rate) was excessive in terms of fruit yield response. Other reports have indicated no yield loss when N application is based on site-specific N management (He *et al.*, 2007). The application of straw is one possible explanation for the increased crop yields observed in the present study, which is consistent with the observations of other researchers (Brady and Weil, 2002). When maize residues with high C/N ratios (C/N = 49) are applied to soils, there is intense competition between microorganisms and plants for inorganic N, which may reduce the available N for crops. Seo *et al.* (2007) also reported that rice straw application could increase tomato yields.

N use efficiency is a complex parameter with many components. The two regularly used efficiency parameters (AE_N and RE_N) are commonly calculated by the N difference method, also referred to as the N balance or the apparent N efficiency of applied-fertilizer-N methods (Ladha *et al.*, 2005). AE_N has been determined from many trials as the grain yield per unit applied N, a parameter representing the ability of plants to increase yield in response to N applied (Muchow, 1998). N management of greenhouse tomato was studied by Gao *et al.* (2009), and the result showed that AE_N in the conventional N treatment and optimum N treatment in the whole year is 0 and 0.3 kg FW kg⁻¹ N, respectively. Our results showed that AE_N tended to decrease with the increasing rates of N fertilizer, implying progressively higher N losses with the increasing

N rates (Fig. 3). Similar results were obtained by other researchers (Pandey *et al.*, 2001; Sharmasarkar *et al.*, 2001). The AE_N was highest under the N4 treatment and was 2.9 and 2.0 times greater than the AE_N values observed for the N1 treatment in the AW and WS seasons, respectively. In addition to excessive N fertilization, excessive irrigation might have produced a lower AE_N. Similar conclusions were made by Chen *et al.* (2002), who showed that the AE_N of vegetable crops was low when associated with excessive irrigation. The rate and time of N fertilizer application can be better controlled with fertigation (Papadopoulos, 2000), which also improves N fertilizer utilization (Muchow and Sinclair 1994; Mohammad *et al.*, 1999). The results of the present study showed that the highest N fertilizer rate and irrigation not only lowered AE_N, but also failed to improve tomato yields, thus reducing income for farmers and wasting N fertilizer.

Increasing RE_N assumes great significance as N fertilizer use is increasing to meet the food and fiber needs of an expanding global population (Rao *et al.*, 1992). Due to irrational application of N fertilizer, however, the RE_N measured in greenhouses used for vegetable production was usually less than 10% (Han *et al.*, 2010). Li *et al.* (2001) studied the N utilization in Shouguang and the result indicated that RE_N was so low that nearly 90% of applied N could not be used by tomato. Yang *et al.* (2007) studied the effects of conventional N treatment (2100 kg ha⁻¹) and optimum N treatment (900 kg ha⁻¹) on RE_N during the cucumber growth period in greenhouse and the results showed that RE_N of the conventional N treatment was lower than that of the optimum N treatment, 4.91% and 10.59%, respectively. Similar RE_N values were obtained in this study for the four treatments. Although N fertilizer was applied at higher rates under the N1 treatment, the low N recovery of the crops resulted in a lower RE_N. The highest values were observed under the N4 treatment, with 7% in the AW season and 5.2% in the WS season. One possible reason for this trend is the combination of reduced N fertilizer application and drip irrigation measurement. With drip irrigation, both the time and rate of N fertilizer application can be controlled and adjusted to meet the specific requirements of crops at each physiological growth stage (Mohammad *et al.*, 1999). In contrast, conventional fertilization may cause huge losses of N fertilizer by leaching and volatilization especially in greenhouse soils. Drip irrigation reduces leaching and volatilization losses, improves the N use efficiency and minimizes ground water contamination (Papadopoulos, 1985). Therefore, a rational reduction of N input is a practical approach for

sustaining vegetable production and soil quality.

Responses of soil quality to better management of N fertilizer

Another consequence of long-term high fertilizer application rates in greenhouse vegetable production is soil salinization due to excessively high nutrient accumulation in soils. Soil EC can be used as an index of salinization. Most crops have an EC tolerance limit of 0.4 dS m^{-1} (Kingery *et al.*, 1994). Wu *et al.* (2000) found soil EC values up to 0.4 dS m^{-1} in greenhouses after 8 years of intensive vegetable cropping. Our results showed that N fertilizer application led to the increase of soil EC in the surface soil. The soil EC in all four N fertilizer treatments exceeded 0.4 dS m^{-1} . The N1 treatment produced the highest soil EC values, which were 1.3 and 0.8 dS m^{-1} in the AW and WS seasons, respectively, and these levels may have had some negative effects on crop growth. Among the four N fertilization rates, soil EC was lowest under the N4 treatment, being 0.9 and 0.6 dS m^{-1} in the AW and WS seasons, respectively. In fact, the soil EC had probably been harmful to plant growth because large amounts of N fertilizers had been applied in the preceding years, resulting in an increased background level of soil EC.

In the soil of Liaoning Province in China, the main anion present is NO_3^- , comprising 67%–76% of total anions. NO_3^- content was found to be significantly correlated with the total soil salinity (Liang *et al.*, 1997). This is in agreement with our results that showed a very close relationship between soil EC and soil NO_3^- -N content, suggesting that substantial accumulation of NO_3^- -N may have been an important factor contributing to soil salinity under the experimental conditions. The low RE_N values observed prompts the following question: where is the rest of the fertilizer going? High application rates of N fertilizer and large amounts of irrigation water would increase N accumulation in deep soil layers, and consequently, NO_3^- -N accumulation in large quantities in the soil would pose an environmental risk. In this study, N fertilizer application increased soil NO_3^- -N accumulation in the 0–100 cm of the soil profile. At the highest N rate (N1 treatment) there was greater accumulation of NO_3^- -N (1119.3 and 979.6 kg N ha^{-1} in the AW and WS seasons, respectively). High NO_3^- -N accumulation and the free flow of water in the soil profile are conditions that will lead to NO_3^- leaching into the subsoil or groundwater. A survey of groundwater NO_3^- -N concentrations, conducted by the Chinese Academy of Agricultural Science, in Beijing, Tianjin, Hebei, Shandong and Shanxi

showed that approximately 45% of 600 groundwater samples exceeded the WHO and European Union (EU) limits for NO_3^- in drinking water, set at $11.3 \text{ mg NO}_3^- \text{ N L}^{-1}$ ($50 \text{ mg NO}_3^- \text{ L}^{-1}$), with the highest concentration of $113 \text{ mg NO}_3^- \text{ L}^{-1}$ (Zhang *et al.*, 2004). A survey of 258 groundwater samples in Shandong, by the Soil and Fertilizer Institute, Shandong Academy of Agricultural Sciences, found an average NO_3^- concentration of $89.11 \text{ mg NO}_3^- \text{ L}^{-1}$; furthermore, the concentration was much higher in the regions with intensive vegetable farming than in other cropping areas (unpublished data). Because vegetable crops have shallow root systems and are sensitive to water and nutrient supplies, farmers readily apply large amounts of fertilizer and frequently irrigate the fields, leading to NO_3^- -N leaching out of the root zone and into the subsoil or shallow groundwater (Ju *et al.*, 2006). In the present study, the long-term application with excess N fertilizer and heavy irrigation raised the average NO_3^- concentration of irrigation water to $95.64 \text{ mg NO}_3^- \text{ L}^{-1}$ in Daotian, exceeding the WHO and EU limits for drinking water. In addition, heavy irrigation using groundwater with high N concentrations may have further increased soil N levels. In this study, reduced N fertilizer application combined with C/N adjustment and drip irrigation significantly decreased soil NO_3^- -N accumulation, and this combination may be an optimal application and management approach. These data support the findings of Zhang *et al.* (2009) that the addition of straw and the use of drip irrigation were the most feasible measures for controlling the leaching of soil NO_3^- -N. On one hand, straw application played an important role in improving soil quality by increasing the soil C/N ratio and utilizing microbes to consume excess inorganic N; on the other hand, drip irrigation increased nutrient supply in the root zone and enabled control of water and fertilizer application.

Soil enzymatic activity is an indicator of the soil ecosystem function. It reflects the intensity and direction of various biochemical processes within the soil and also correlates closely with soil quality (He *et al.*, 2002). Our results demonstrated that, relative to the N0 treatment, applied N fertilizer could greatly increase soil enzyme activity in both seasons, probably owing to the higher vegetable production under such fertilization conditions. The activity of soil invertase, which provides glucose and fructose for plants, declined under higher rates of N fertilization. The activity of soil urease, which catalyzes the degradation of urea into CO_2 and NH_3 and is widely used in the evaluation of soil quality, was not greatest under the highest N application rate. Reduced N fertilizer application co-

mbined with other methods resulted in higher soil enzyme activities. Verstraete (1977) indicated that a positive correlation existed between crop yield and soil urease activity. This finding was confirmed in our study and the correlation coefficients were 0.86 and 0.76 in the AW and WS seasons, respectively.

CONCLUSIONS

The N fertilizer application rate used for greenhouse vegetable production is often several times higher than the required level. Combined with excessive irrigation, this practice has led to higher soil EC levels, increased salinity in surface soils, and a substantial accumulation and leaching of soil NO_3^- -N into shallow groundwater. Low N fertilizer efficiency, with crop recoveries of less than 10% of N fertilizer, also increases soil nutrient accumulation and gaseous losses. This situation has become so serious that soil and groundwater quality are deteriorating. The present study showed that environmental protection and high crop yields could be achieved with a 50% reduction of the conventional N chemical fertilizer input combined with adjustment of the C/N ratio and water-fertilizer coupling. These combined approaches represent a practical means for reducing excess N input while maintaining the sustainability of greenhouse-based intensive vegetable systems.

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REFERENCES

- Brady, N. C. and Weil, R. R. 2002. The Nature and Properties of Soils. 13th Edition. Prentice-Hall, Upper Saddle River, NJ, USA.
- Chen, Q., Zhang, H. Y., Tang, L. L., Li, X. L. and Liebig, H. P. 2002. Effects of water and nitrogen supply on spinach (*Spinacia oleracea* L.) growth and soil mineral N residues. *Pedosphere*. **12**: 171–178.
- Gan, Y. D., Li, J. L., Chen, Y. Z., Ding, G. G. and Wang, H. B. 2008. Analysis on the topsoil nutrients status in Shouguang. *Chin. Agr. Sci. Bull.* (in Chinese). **24**: 260–264.
- Gao, B., Li, J. L., Chen, Q., Liu, Q. H. and Wang, J. 2009. Study on nitrogen management and irrigation methods of greenhouse tomato. *Sci. Agr. Sin.* **42**: 2034–2042.
- Gao, Z. Q. 2010. Analysis on the current situation, problems and countermeasure of protected plant industry in Shandong. *China Fruit Veg.* (in Chinese). **2**: 12–14, 20.
- Guan, S. Y. 1986. Method for Determination of Soil Enzyme Activity (in Chinese). Agricultural Press, Beijing, China.
- Han, P. Y., Jiao, X. Y., Wang, L. G., Dong, E. W. and Wang, J. S. 2010. Use efficiency and fate of applied nitrogen in long-term tomato districts of Taiyuan. *Chin. J. Eco-Agr.* (in Chinese). **18**: 482–485.
- He, F. F. 2006. Studies on optimizing nitrogen management and environmental implication in greenhouse tomato cropping system (in Chinese). Ph.D. Dissertation. China Agricultural University, Beijing.
- He, F. F., Chen, Q., Jiang, R., Chen, X. and Zhang, F. S. 2007. Yield and nitrogen balance of greenhouse tomato (*Lycopersicon esculentum* Mill.) with conventional and site-specific nitrogen management in Northern China. *Nutr. Cycl. Agroecosys.* **77**: 1–14.
- He, W. X., Jiang, X., Bian, Y. R. and Wang, F. 2002. Study on soil enzyme activity affected by dimehyppo. *J. Northwest A&F Univ.* **30**: 13–17.
- Jenkinson, D. S. 1968. Chemical tests for potentially available nitrogen in soil. *J. Sci. Food Agr.* **19**: 160–168.
- Ju, X. T., Kou, C. L., Christie, P., Dou, Z. X. and Zhang, F. S. 2007. Changes in the soil environment from excessive application of fertilizers and manures to two contrasting intensive cropping systems on the North China Plain. *Environ. Pollut.* **145**: 497–506.
- Ju, X. T., Kou, C. L., Zhang, F. S. and Christie, P. 2006. Nitrogen balance and groundwater nitrate contamination: comparison among three intensive cropping systems on the North China Plain. *Environ. Pollut.* **143**: 117–125.
- Ju, X. T., Liu, X. J. and Zhang, F. S. 2002. Dynamics of various nitrogen forms in soils and nitrogen utilization under application urea and different organic materials. *J. China Agr. Univ.* (in Chinese). **7**: 52–56.
- Kingery, W. L., Wood, C. W., Delaney, D. P., Williams, J. C. and Mullins, G. L. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. *J. Environ. Qual.* **23**: 139–147.
- Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J. and van Kessel, C. 2005. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. *Adv. Agron.* **87**: 85–156.
- Li, J. L., Zhu, J. H., Zhang, X. S., Meng, X. X., Chen, Q., Li, X. L. and Zhang, F. S. 2001. Nitrate leaching loss from soil and nutrient utilization by tomato in protected field. *Chin. J. Appl. Environ. Biol.* (in Chinese). **7**: 126–129.
- Liang, C. H., Tang, Y., Xu, X. C. and Hui, C. Z. 1997. Dynamics of soil salt in protected vegetable fields in Shenyang, China. In Xie, J. C. and Chen, D. X. (eds.) Soil Fertility and Fertilizer Recommendation in Vegetable Fields (in Chinese). Hohai University Publisher, Nanjing. pp. 283–288.
- Liu, Z. H. 2000. Characteristics of greenhouse vegetable soil and reasonable fertilization in Shandong Province (in Chinese). Ph.D. Dissertation, Chinese Academy of Agricultural Sciences, Beijing.
- Lu, R. K. 2000. Analytical Methods of Soil Agrochemistry (in Chinese). China Agricultural Science and Technology Press, Beijing.
- Mohammad, M. J., Zuraiqi, S., Quasmeh, W. and Papadopoulos, I. 1999. Yield response and nitrogen utilization efficiency by drip-irrigated potato. *Nutr. Cycl. Agroecosys.* **54**: 243–249.
- Muchow, R. C. 1998. Nitrogen utilization efficiency in maize and grain sorghum. *Field Crop. Res.* **56**: 209–216.
- Muchow, R. C. and Sinclair, T. R. 1994. Nitrogen response of leaf photosynthesis and canopy radiation use efficiency in field grown maize and sorghum. *Crop Sci.* **34**: 721–727.
- Munir, J. M. 2004. Utilization of applied fertilizer nitrogen and irrigation water by drip-fertigated squash as determined by nuclear and traditional techniques. *Nutr. Cycl. Agroecosys.* **68**: 1–11.

- Olsen, S. R., Cole, C. V., Watanabe, F. S. and Dean, L. A. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Circular of United States Department of Agriculture. No. 939. USDA, Washington, D.C.
- Pandey, R. K., Maranville, J. W. and Bako, Y. 2001. Nitrogen fertilizer response and use efficiency for three cereal crops in Niger. *Commun. Soil Sci. Plant Anal.* **32**: 1465–1482.
- Papadopoulos, I. 1985. Constant feeding of field-grown tomatoes irrigated with sulphate water. *Plant Soil*. **88**: 231–236.
- Papadopoulos, I. 2000. Fertigation: present situation and future prospects. In Ryan, J. (ed.) Plant Nutrient Management under Pressurized Irrigation Systems in the Mediterranean Region. Proceedings of the IMPHOS International Fertigation Workshop. ICARDA, Aleppo, Syria. pp. 232–245.
- Pérez-Parra, J. J. and Céspedes, A. 2001. Análisis de la demanda de inputs para la producción en el sector de cultivos protegidos de Almería. In Cuadrado, I. M. (ed.) Estudio de la Demanda de Inputs Auxiliares. Producción y Manipulación en el Sistema Productivo Hortícola Almeriense (in French). FIAPA, Almería, Spain. pp. 1–102.
- Pratt, P. F. 1951. Potassium removal from Iowa soils by greenhouse and laboratory procedures. *Soil Sci.* **72**: 107–118.
- Rao, A. C. S., Smith, J. L., Parr, J. F. and Papendick, R. I. 1992. Consideration in estimating nitrogen recovery efficiency by the difference and isotopic dilution methods. *Fert. Res.* **33**: 209–217.
- SAS Inc. 1999. SAS 8.0 for Windows. SAS Inc., Cary, NC, USA.
- Seo, Y. H., Lim, S. J., Kim, S. K. and Jung, Y. S. 2007. Effect of rice straw and woodchip application on greenhouse soil properties and vegetable crops productivity. *Korean J. Soil Fert.* **40**: 4–11.
- Sharmasarkar, F. C., Sharmasarkar, S., Miller, S. D., Vance, G. F. and Zhang, R. 2001. Assessment of drip and flood irrigation on water and fertilizer use efficiencies for sugarbeets. *Agr. Water Manage.* **46**: 241–251.
- Song, X. Z., Zhao, C. X., Wang, X. L. and Li, J. 2009. Study of nitrate leaching and nitrogen fate under intensive vegetable production pattern in northern China. *C. R. Biol.* **332**: 385–392.
- Tang, L. L. 2004. Studies on nitrogen topdressing techniques and profitable evaluation for greenhouse tomato production (in Chinese). Ph.D. Dissertation, China Agricultural University, Beijing.
- Verstraete, W. 1977. Soil microbial and biochemical characteristics in relation to soil management and fertilizer. *Soil Biol. Biochem.* **9**: 253–258.
- Weng, W., Yang, J. T., Zhao, Q. L. and Zhang, B. L. 2004. Current situation and developing direction of straw utilization technology in China. *China Resour. Compr. Util.* (in Chinese). **7**: 18–21.
- Wu, F. Z., Zhao, F. Y. and Liu, Y. Y. 2000. Analysis of the problems in continuous cropping system of protective vegetable and the controlling ways. In Li, X. L., Zhang, F. S. and Mi, G. H. (eds.) Fertilizing for Sustainable Production of High Quality Vegetables (in Chinese). China Agricultural University Publisher, Beijing. pp. 157–163.
- Yang, L. J., Li, T. L., Li, F. S., Lemcoff, J. H. and Cohen, S. 2008. Fertilization regulates soil enzymatic activity and fertility dynamics in a cucumber field. *Sci. Horti.* **116**: 21–26.
- Yang, Z. P., Chen, M. C., Zhang, Q. and Zhang, J. J. 2007. Effect of different fertilizer measurement on nutrient utilization in cucumber and nitrate leaching loss from soil in greenhouse. *J. Soil Water Conserv.* (in Chinese). **21**: 57–60.
- Zhang, N. M. and Dong, Y. 2004. Effects of fertilization and protected soil planting on soil microflora. *Ecol. Environ.* (in Chinese). **13**: 61–62.
- Zhang, W. L., Tian, Z. X., Zhang, N. and Li, X. Q. 1996. Nitrate pollution of groundwater in Northern China. *Agr. Ecosyst. Environ.* **59**: 223–231.
- Zhang, X. S., Liu, Z. H., Jiang, L. H., Feng, Y. and Sui, F. G. 2009. Study on the technology of soil nitrate nitrogen leaching preventive and control in mushroom house. *J. Qingdao Agr. Univ.* (in Chinese). **26**: 207–211.
- Zhong, H. P., Yue, Y. Z. and Fan, J. W. 2003. Characteristics of crop straw resources in China and its utilization. *Resour. Sci.* **25**: 62–67.
- Zhu, J. H. 2002. Study on fate and utilization of nitrogen in protected vegetable fields (in Chinese). Ph.D. Dissertation, China Agricultural University, Beijing.
- Zhu, J. H., Li, J. L., Li, X. L. and Zhang, F. S. 2002. Effects of compound fertilizers utilized on soil environmental quality in protected vegetable field. *Agro-Environ. Protect.* (in Chinese). **21**: 5–8.
- Zhu, J. H., Li, X. L., Christie, P. and Li, J. L. 2005. Environmental implications of low nitrogen use efficiency in excessively fertilized hot pepper (*Capsicum frutescens* L.) cropping systems. *Agr. Ecosyst. Environ.* **111**: 70–80.