Reducing Nutrient and Irrigation Rates in Solar Greenhouse without Compromising Tomato Yield

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Additional index words. formula fertilizer, irrigation, nutrient accumulation, solar greenhouse

Abstract. Overapplication of nutrients and water is common in intensive greenhouse systems. A 2-year experiment (2011–13) was conducted to study the effect of different nutrient and water treatments on the growth and yield of tomato (*Lycopersicon esculentum* Mill.) and on soil nutrient accumulations in solar greenhouses in South Loess Plateau, China. The treatments included 1) current fertilizer and water practices (FW), 2) formula fertilizer and water 1 (FW1), 3) formula fertilizer and water 2 (FW2), and 4) farmer's practice (FP). Compared with FW, FW1 and FW2 had yields not significantly different from grower control treatments; however, they saved 35% to 46% of the nitrogen (N) fertilizer, 40% to 54% of the phosphorus (P_2O_5) fertilizer, 19% to 35% of the potassium (K_2O) fertilizer, and 15% to 21% of irrigation water. The economic profits of FW1 and FW2 were greater than those of the FW and FP treatments. The two formula treatments also reduced soil electrical conductivity (EC) and the accumulation of nitrate, available P, and available K in soil. However, the soil nutrients are still above optimal levels. Obvious N surplus in the greenhouse was observed in different treatments, mainly because of high N input from manures. This study revealed there is great potential to reduce nutrient and water use while maintaining the same yield in a greenhouse system.

Vegetable production in protected production systems has developed rapidly since the 1980s in China. By 2011, the area of protected production in China reached 4 million ha (Li et al., 2013). Solar greenhouses are rectangular greenhouses 50 to 100 m long and 7 to 8 m wide, with one side wall (≈ 3.6 m high) and two end walls constructed from soil, brick, or concrete (Zhou et al., 2010). This is a common practice in protected production in northern China, which makes possible growing vegetables such as tomato, cucumber, and eggplant in the cold winter weather. Although solar greenhouses only account for 20% of the production area of protected agriculture in China, they produce nearly 40% of vegetables in north China (Zhang et al., 2011).

Solar greenhouses are a very intensive production system; growers make a good income compared with open-field production. However, growers usually add high amounts of organic and inorganic nutrients mainly because of 1) their traditional concept (the more fertilizers, the more crop yield) and

2) poor services of rational fertilizer recommendations for small-hold farmers in China. Therefore, overuse of nutrients and water in the greenhouses is a common practice (Gao et al., 2012; Ren et al., 2014). Consequently, accumulations of nutrients in solar greenhouses are significant (Huang, 2011; Ju et al., 2006). Our recent study in the southern Loess Plateau of China showed that, even for the newly built solar greenhouses, where the topsoil was removed to build the walls of the greenhouse, the accumulation of nutrients was very fast as a result of the addition of manures and inorganic fertilizers (Gao et al., 2012).

The overaccumulation of nutrients in soil profiles results in a series of problems, including low nutrient use efficiency, poor product quality, and groundwater contamination (Chen et al., 2004; Shi et al., 2009). The apparent recovery rate of N fertilizer is usually less than 20% in greenhouses (Liu et al., 2008; Zhu et al., 2005). Nutrient imbalances in greenhouse soil resulting from high accumulation of N, phosphorus (P), and potassium (K) also result in deficiencies in other nutrients, such as magnesium, and micronutrients (Chen et al., 2011). Overaccumulation of nitrate in the soil profile of greenhouses leads to nitrate leaching during the summer fallow period, when rainfall is high, which ultimately leads to nitrate concentration in groundwater (Ju et al., 2006; Zhou et al., 2010). Therefore, nutrient use efficiency in greenhouses is a concern, not only for crop production but also for the environment.

Overirrigation is another problem in solar greenhouses. The irrigation rates in some

greenhouses ranged from 5000 to 9000 $m^3 \cdot ha^{-1}$ in a growing season, which was several times greater than necessary to produce the crop being grown (Fan et al., 2014; Ren et al., 2010). Chen et al. (2013) found that deficit irrigation during the early stage of tomato crop production had no significant influence on crop yield and quality. Luo et al. (2014) reported that, compared with farmers' current water practices in the study region, reducing 40% of irrigation water got the same yield of mini watermelons. Overirrigation increases the leaching risk of nutrients from greenhouses (Fan et al., 2014). However, there are limited studies on the combined effects of nutrients and water on crop yields and soil nutrient contents in the solar greenhouse system.

Nutrient additions to cereal crops in China far exceed those in the United States and northern Europe, and much of the excess fertilizer is lost to the environment, degrading both air and water quality (Chen et al., 2014; Vitousek et al., 2009). Compared with cereals, overfertilization is more common in solar greenhouse production in China (Shi et al., 2009; Zhou et al., 2010). Therefore, we hypothesized there is the potential to optimize nutrient and water inputs in this system. To test our hypotheses, we compared the effects of different nutrient and water management practices on tomato yield and nutrient accumulation in the soil in solar greenhouses.

Materials and Methods

Site description

The study site was located in the southern edge of the Loess Plateau, Yangling, Shaanxi, China. It has a continental monsoon climate, with 630 mm average annual precipitation, and 12.9 °C average annual air temperature.

The experiment was conducted in a farmer's greenhouse in Dazhai, Yangling, Shaanxi (lat. 34°17'N, long. 108°2'E), which is 90 m long and 6.5 m wide, and was built in 2010. The soil at the study site was an Anthrosol (World Reference Base for Soil Resources, WRB system). The soil has 10.7 $g \cdot kg^{-1}$ organic matter, 20.2 $mg \cdot kg^{-1}$ inorganic N ($NH_4^+-N + NO_3^--N$), 70.3 $mg \cdot kg^{-1}$ Olsen-P, and 198 $mg \cdot kg^{-1}$ available K. The average air temperature in the greenhouse during crop season was 19.2 °C.

Experimental design

The experiment was conducted over two growing seasons (Nov. 2011–Aug. 2012 and Nov. 2012–July 2013) in the same greenhouse mentioned previously. Three different fertilization and irrigation treatments were established in the greenhouse, including FW, FW1, and FW2. For the FW treatment, the irrigation and fertilization rates represented the average levels of the study region, which were from a survey we did in the region (Gao et al., 2012; Wang et al., 2015). The fertilization rates of the formula treatments were based on theoretical requirements of nutrients on desired tomato yield and initial soil nutrient content, and our research experience in the region (Gao et al., 2012; Luo et al., 2015). The experimental design was a randomized complete block with three replications. The plot area was 6.5 × 5.5 m

Received for publication 24 Aug. 2018. Accepted for publication 10 Dec. 2018.

This work was supported by the National Key Research and Development Program of China (2017YFD0200106), the National Natural Science Foundation of China (41201238), and the 111 Project (No.B12007).

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and each plot had six ridges, with a ridge distance of 70 cm and a row distance of 50 cm. Tomato (cv. Jingpeng11) was planted in a single row on a ridge. Distance between plants was 30 cm.

Our experimental plots covered half the area of the greenhouse. We also recorded the application rates of fertilizers and irrigation in the other half of the same greenhouse, where the farmer added water and fertilizer according to his experience (FP). The irrigation rate and fertilizer inputs for the different treatments for 2 years are given in Table 1.

For the whole greenhouse, chicken manure was applied at the same rate, 112.5 t·ha⁻¹ (N = 1.19%) in 2011 and 120 t·ha⁻¹ in 2012. The basic physicochemical properties of manure were 280.3 g·kg⁻¹ organic C, 11.9 g·kg⁻¹ total N, 2.6 g·kg⁻¹ total P, and 18.0 g·kg⁻¹ total K; pH was 7.40. All manure and P fertilizer (in superphosphate) were broadcast uniformly as a basal fertilizer on the surface, and then plowed into a 0- to 20-cm soil layer before transplanting tomatoes each year. The forms of N and K fertilizers used were urea and potassium sulfate.

About one-fourth of the total N inputs and one-third of the total K inputs for the current fertilizer and water practice, and one-sixth of the total N and K inputs for the formula treatments were applied as base fertilizer. A topdressing of N and K fertilizer was applied using the drip irrigation system (fertigation) five to seven times equally at 10- to 15-d intervals when the first fruit began expansion.

All plots were irrigated after transplanting with the same amount water: 25 mm in the 2011–12 season and 23 mm in the 2012–13 season. At 5 to 10 d after transplanting (DAT), the drip line was installed in each crop row in the greenhouse and the entire soil surface was covered with polyethylene film (0.005 mm thick) to reduce soil evaporation and to increase the soil temperature. The drip switches were set up within drip lines to control the amount of irrigation and fertilizer received by each plot. A water flowmeter was set up on the main drip tape to record the irrigation amount for each cycle. The irrigation was five times during the whole tomato growing season. For all treatments, irrigation timing was done following local practice, which is irrigating

Table 1. Irrigation rates and chemical fertilizer inputs from 2011 to 2013.

Treatment	Irrigation rate (m ³ ·ha ⁻¹)	Chemical fertilizer inputs N-P ₂ O ₅ -K ₂ O (kg·ha ⁻¹)
2011–12		
Current practice	3,045	542–622–580
Formula 1	2,600	353–376–467
Formula 2	2,400	291–285–375
Farmer' practice	3,600	623–382–952
2012–13		
Current practice	2,797	383–222–493
Formula 1	2,391	354–213–455
Formula 2	2,200	305–198–390
Farmer' practice	3,300	336–214–681

Fig. 1. Effect of different fertilization and water treatments on plant height, stem diameter, and chlorophyll content of tomato. Bars represent the SD of the mean (n = 3). BP = before planting, FW = current fertilizer and water practice used by local farmers (FW), FW1 = formula fertilizer and water-1, FW2 = formula fertilizer and water-2, and FP = farmer's practice.

every 10 to 15 d after fruit expansion, depending on the climate and soil water content. There was no irrigation in January and December each year because of low temperatures.

During the experimental period, except for fertilizer and irrigation, other management practices such as pollination, pruning branches and stems, and pest control were the same for all treatments as local growers. Tomato seedlings were transplanted 7 Nov. 2011 and harvested on 8 Aug. 2012 in the first season, and transplanted 12 Nov. 2012 and harvested 25 July 2013 in the second season.

Sampling and measurements

Soil sampling and analytical methods. In 2011, before transplanting, topsoil samples (0–20 cm) were taken from 10 soil cores in each plot. They were then mixed them to form one composite sample. After harvest, soil samples from two sites in each plot were collected from the top 200 cm of soil in 20-cm increments.

Fresh soil samples were extracted with 1 mol·L⁻¹ KCl (soil:solution ratio, 1:10), then analyzed with an autoanalyzer (Bran Luebbe A3; SPW FLOW, Norderstedt, Germany) to determine the nitrate and ammonium N contents in the filtrate. Air-dried soil samples were ground and passed through 1-mm and 0.25-mm

sieves for organic matter, total N, available P, available K, and EC analyses. Soil organic matter (SOM) was determined using the Walkley-Black method (Nelson and Sommers, 1996). Total N was determined using the micro-Kjeldahl digestion, distillation, and titration method (Page et al., 1982). Soil-available P was measured using the method of Olsen et al. (1954). Available K content of the extract was determined by flame photometry. EC was determined in a 1:5 soil–water paste mixture with a conductivity meter (DDS-307A; Shanghai, China).

Sampling and measurement of plant sample. Six plants were chosen randomly

Table 2. Tomato yield and profit of different treatments in 2 years.

Growing season	Tomato yield (t·ha ⁻¹)				Economic profit (×10 ³ yuan/ha) ²			
	FW	FW1	FW2	FP	FW	FW1	FW2	FP
2011–12	214 ± 16	219 ± 7	232 ± 4	210 ± 7	233	238	257	230
2012–13	223 ± 7	225 ± 11	226 ± 14	196 ± 12	242	245	247	216

²Economic profit = Tomato fruit income – Fertilizer costs.

FW = current fertilizer and water practice used by local farmers; FW1 = formula 1, fertilizer and water; FW2 = formula 2, fertilizer and water; FP = farmer's practice.

Fig. 2. Changes in soil organic matter and total N content at the 0- to 100-cm depth in the solar greenhouse during the two growing seasons. Bars represent the SD of the mean (n = 3). The lowercase letters mean significant differences between treatments at $P < 0.05$. BP = before planting, FW = current fertilizer and water practice used by local farmers (FW), FW1 = formula fertilizer and water-1, FW2 = formula fertilizer and water-2, and FP = farmer's practice.

Fig. 3. Changes in soil NO_3^- -N content at the 0- to 200-cm depth in the solar greenhouse after harvesting the second crop. Bars represent the SD of the mean ($n = 3$). BP = before planting, FW = current fertilizer and water practice used by local farmers (FW), FW1 = formula fertilizer and water-1, FW2 = formula fertilizer and water-2, and FP = farmer's practice.

Table 3. Change in soil nitrate-N accumulation in the 0- to 200-cm soil depth in a greenhouse over 2 consecutive years.

Soil depth (cm)	Sampling time	Treatments	NO_3^- -N accumulation ($\text{kg}\cdot\text{ha}^{-1}$)	
			Accumulation $\pm$ SD	Mean
0-100	After harvesting the second season	BP	105.8 ± 19.6	105.8 ± 19.6 B
		FW	619.2 ± 129.1 a	523.5 ± 68.8 A
		FW1	489.7 ± 43.5 a	
		FW2	461.6 ± 56.1 a	
		FP	515.2 ± 121.1	
0-200	After harvesting the second season	BP	174.6 ± 7.2	174.6 ± 7.2 B
		FW	$1,486.3 \pm 226.3$ a	$1,164.5 \pm 230.9$ A
		FW1	$1,007.1 \pm 127.5$ a	
		FW2	999.9 ± 129.1 a	
		FP	$1,242.0 \pm 25.7$ a	

The mean is the average of nitrate-N in three irrigation and fertilizer treatments. The lowercase letters mean there was a significant difference between treatments at $P < 0.05$.

BP = before planting; FW = current fertilizer and water practice used by local farmers; FW1 = formula 1, fertilizer and water; FW2 = formula 2, fertilizer and water; FP = farmer's practice.

from each plot to measure plant height, stem diameter, and chlorophyll content in leaves [using a soil-plant analyses development (SPAD) chlorophyll meter (SPAD-502Plus; Minolta, Japan)] once every 10 d 25 DAT. Nine tomato leaves were chosen from the top, middle, and bottom of the plant to measure chlorophyll content. Plant height was measured in both years. Only SPAD of leaves and diameters of stems were measured the second year. Fresh yield, individual fruit weight, and fruit number in each plot were measured at each harvest during both seasons. The fruit harvesting period in the first season was from 18 Mar. 2011 to 1 Aug. 2012, and from 24 Feb. 2012 to 23 July 2013 in the second season. The total marketable yield of each plot was calculated.

Subsamples of tomato fruit were oven-dried at 65°C for at least 72 h after harvest-

ing. After harvesting, five plants from each plot were taken and divided into leaves, stems, and roots; weighed before and after drying at 65°C for 48 h; and then sieved through a 0.5-mm mesh. Total N in the fruit, leaves, stems, and roots was determined using the Kjeldahl method.

Calculation of N balances and economic profit

Apparent N balance. The N balance of each treatment was calculated by subtracting the gross N inputs from the gross N outputs. The gross inputs consisted of N derived from manure and inorganic fertilizers, irrigation, and soil inorganic N in the 0- to 60-cm soil layer at the beginning of the experiment. N input from inorganic N fertilizer and manure was calculated by multiplying the fertilizer or manure application

rates by their N contents. N input from irrigation water was estimated by multiplying the irrigation rates by N content (He et al., 2007; Zhou et al., 2006).

Gross N output refers to the N removal by the crop and inorganic N in the 0- to 60-cm soil layer after harvesting the second crop. N uptake by crop was calculated based on multiplying the economic yield of tomato by its N uptake parameter (Huang, 2011). It included the total N in the aboveground of crop (including fruits). Nutrient losses resulting from leaching were not included in the calculation of gross output because of less water infiltration in the greenhouse soil under the relatively closed environment.

Economic profit. The economic profit of each treatment was calculated by subtracting the gross income from the gross expense. The gross income was calculated by multiplying the economic fruit yield of each plot and market prices at different harvest times. The gross expense only considered fertilizer and manure costs, and was calculated by multiplying the applied fertilizer rates with their prices.

Statistical analysis. Analyses of variance (ANOVA) for all data was performed using the SAS statistical program (SAS version 8.1). Whenever ANOVA detected significant differences between treatments, mean separation was conducted using the least significant difference test at $P < 0.05$. All figures were plotted using Sigmaplot version 12.0.

Results

Tomato growth and fruit yield. Treatments had no significant effects on tomato plant height, stem diameter, and SPAD values during the different growing seasons (Fig. 1). Fruit yields also did not show significant differences resulting from treatments in both seasons (Table 2). The economic profits of FW1 and FW2 were greater than those of the FW and FP treatments.

SOM and total N. There were no significant differences in SOM content in the topsoil (0-20 cm) between treatments in either growing season. The SOM content of the subsoil (20-60 cm) was relatively stable. Compared with SOM content before planting, the average SOM content in the first and second seasons was increased by 22% and 45%, respectively (Fig. 2A and B).

Total N content in the topsoil after the first or second growing season (0.76 and $1.08 \text{ g}\cdot\text{kg}^{-1}$) was significantly greater than before planting ($0.59 \text{ g}\cdot\text{kg}^{-1}$) (Fig. 2C and D), equivalent to an increase of 29%, up to 83%. Total N in subsoil (20-100 cm) was less than in topsoil; it increased continually over two seasons. Total soil N increased during the second season compared with the first season; however, it did not change significantly for different treatments.

Soil nitrate. The soil nitrate content at the end of the second season was consistently greater in the FW treatment compared with the other treatments (FW1, FW2, and FP), except at a soil depth of 160 to 200 (Fig. 3). Nitrate content at a soil depth of 0 to 40 cm was greater for FW1 and FW2 compared with

Fig. 4. Changes in soil-available P and available K content at the 0- to 100-cm depth in the solar greenhouse during the two growing seasons. Bars represent the sd of the mean ($n = 3$). The lowercase letters mean significant differences between treatments at $P < 0.05$. BP = before planting, FW = current fertilizer and water practice used by local farmers (FW), FW1 = formula fertilizer and water-1, FW2 = formula fertilizer and water-2, and FP = farmer's practice.

FP, but was significantly less at the 60- to 200-cm depth (Fig. 3).

Compared with FW, soil nitrate-N accumulation at the 0- to 200-cm soil depth was less by 32.4% and 32.8% in FW1 and FW2, respectively. The average nitrate-N accumulation at depths of 0 to 100 cm ($523.5 \text{ kg} \cdot \text{ha}^{-1}$) and 0 to 200 cm ($1164.4 \text{ kg} \cdot \text{ha}^{-1}$) after harvesting the second crop were significantly greater compared with the nitrate-N accumulation before planting (Table 3).

Soil-available P and K. At the end of the first growing season, available P in the topsoil (0–20 cm) was significantly greater in the FW treatment compared with the available P at the start of the study and the FW1, FW2, and FP treatments (Fig. 4A). Available P in the FW2 treatment was less than the FW1 and FP treatments both in the first and second seasons (Fig. 4A and B). The average available P in the topsoil of the second season was greater than that in the first season (Fig. 4B).

In the first season, there was no significant difference between treatments in available K

content across all soil depths (Fig. 4C). In the second season, there were significant differences between treatments in available K content in the topsoil only (Fig. 4D). Compared to the first season, the increasing available K content in the second season ranged from 26.8% to 27.5%.

Electrical conductivity. In the first season, EC in the topsoil differed significantly between treatments; FW had the greatest EC compared with the EC before planting (Fig. 5Fig.). EC in the FW treatment was 134% greater than the EC before planting. The EC in the FW1 and FW2 treatments was 70% and 47% greater, respectively, than the EC before planting. After the second season of the experiment, there were no significant differences in EC in the different treatments in the topsoil. With the exception of the soil EC at a depth of 60 to 80 cm, soil EC in subsoil of FP was significantly greater than that of FW1 and FW2 (Fig. 5B).

Apparent N balance in two seasons. N from manure contributed more than two-thirds of the total N input in the different treatments (Table 4). Total N inputs for the

treatments were greater than N removal in crops; therefore, an obvious N surplus was observed in the different treatments. Apparent N surpluses were 3238, 3028, 2901, and 3281 $\text{kg} \cdot \text{ha}^{-1}$ for the FW, FW1, FW2, and FP treatments, respectively.

Discussion

Effects of reducing nutrient and irrigation rate on tomato yield. The FW1 and FW2 treatments had yields not significantly different from grower control treatments; however, they saved 35% to 46% of the N fertilizer, 40% to 54% of the P fertilizer, and 19% to 35% of the K fertilizer. Economic profits with FW1 and FW2 treatments were high because of the reduction in the fertilizer input. Other studies also reported that high N input for vegetables grown in greenhouses did not increase yield significantly. However, it decreased farmers' returns as a result of high fertilizer inputs (Zhang et al., 2012; Zhou et al., 2006). Fertilizer consumption in China has increased strongly in past decades, and growth is mainly

Fig. 5. Changes in soil electrical conductivity (EC) of the 0- to 100-cm depth in solar greenhouse during the two growing seasons. Bars represent the SD of the mean (n=3). The lowercase letters mean significant differences between treatments at $P < 0.05$. BP = before planting, FW = current fertilizer and water practice used by local farmers (FW), FW1 = formula fertilizer and water-1, FW2 = formula fertilizer and water-2, and FP = farmer's practice.

Table 4. Nitrogen balance (measured in kilograms per hectare) in the solar greenhouse across the two growing seasons.

Inputs and outputs	FW	FW1	FW2	FP
N input				
(1) Manure-N	2,778.4	2,778.4	2,778.4	2,778.4
(2) Fertilizer-N	925	707	596	959
(3) Soil N (0–60 cm) before sowing	18.8	18.8	18.8	18.8
(4) Irrigation	5.6	4.8	4.4	6.6
Total input = [(1)+(2)+(3)+(4)]	3,727.8	3,509.0	3,397.6	3,762.8
N output				
(5) N removal in crop	394.8	403.9	424.1	410.8
(6) Soil N (0–60 cm) after harvesting the second crop	95.2	77.3	72.7	71.4
Apparent balance = [(1)+(2)+(3)+(4)–(5)–(6)]	3,237.8	3,027.8	2,900.8	3,280.6

FW = current fertilizer and water practice used by local farmers; FW1 = formula 1, fertilizer and water; FW2 = formula 2, fertilizer and water; FP = farmer's practice.

attributable to fertilizer consumption in horticultural crops, including vegetables and fruit trees (Xin et al., 2012). Therefore, our study indicates that there is a great potential to reduce nutrient inputs in solar greenhouse in China while maintaining the same yield as the current production system. An intensive study showed that when advanced crop and nutrient management was used, it increased average cereal yields without any increase in N fertilizer at different agroecological areas in China (Chen et al., 2014). Further study is needed to compare different nutrient management practices on vegetable production in different areas in China.

Compared with FW, the FW1 and FW2 treatments also saved 15% to 21% of irrigation water. And they save more water comparing with FP (Table 1). Another study by our group at a different site found that reducing 40% of irrigation water from FW did not reduce tomato yield, and it increased use efficiency of irrigation water by 50.9% (Luo et al., 2015). Other studies showed that when water inputs were decreased, tomato yield increased (Chen et al., 2013; Fan et al., 2014). This indicates there is also a potential to save irrigation water in greenhouse production.

Effects of reducing nutrient and water rates on nutrients in greenhouse soils. Compared with FW, the two formula treatments

reduced the accumulations of available nutrients in the soil. This result is in agreement with previous reports by other researchers (Zhao et al., 2011; Zhou et al., 2006). However, soil nutrient contents are still at a relatively high level. The average soil-available P content is within the medium category, according to Gao et al. (2012); the average available K content is within the high category, according to Huang (2011).

Although we decreased inputs of chemical fertilizers during the second season, soil-available P and K contents were still increased (Fig. 4). This was attributed to the high addition of manure in the greenhouse. Compared with the arable land, the application of different manures is very common in greenhouses (Zhou et al., 2010). However, farmers in China usually do not consider the nutrients from manures in their practice. One reason is that it is very complex for them to estimate the available nutrients from the different manures. Therefore, developing an easy method to evaluate the nutrient release from manures is needed to make optimal fertilizer recommendation for this system.

N balance in greenhouse soil. In our study, there were no significant differences in total N uptake between the different

treatments. Furthermore, high N application decreased N uptake by the vegetables (Table 4). This confirms the overapplication of N in the greenhouse system. Nutrient balance analysis showed an N surplus in the different treatments (Table 4). Although we reduced inorganic N fertilizer inputs in our two formula treatments, the N surplus was still very high as a result of the high proportion of N input from manure. Other studies also reported that manure accounted for more than 50% of the N applied to greenhouse soils in greenhouses in other regions (Chen et al., 2004; Yu et al., 2010). If one-third of total N in manure is available for crops during the first season (Defra, 2010), it seems that available N from manure could meet the plant demand. Therefore, ignoring N from manures also explains the N surplus in the greenhouse.

Compared with P and K in soil, N has different loss pathways from soil. N saturation in an ecosystem increases its losses to the environment (Chen et al., 2014). Our two formula treatments reduced nitrate-N in the 0- to 200-cm soil layers by 5% to 32%. Similar results have been reported by others (Min et al., 2012; Sun et al., 2013; Zhang et al., 2007). Compared with open fields, solar greenhouses have high temperatures, and organic matter in soil is also high. Therefore, N

surplus in greenhouse soil could also increase its gaseous loss. More research is needed to estimate the loss by different pathways.

Conclusions

Current results indicate that, compared with the FW, the two formula treatments gave similar tomato yields; however, they conserved nutrients and water. And although they reduced the accumulation of available nutrients in the soil, the nutrient levels in the soil were still above optimal levels. This confirms that the overapplication of fertilizer and irrigation is very severe in the greenhouse production system considered here. Our results reveal the potential to reduce the current overapplication of nutrients and water in the greenhouse production system. We recommend that growers in the study region reduce nutrient and water inputs in their greenhouses.

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