Effect of Large Inputs of Manure and Fertilizer on Nitrogen Mineralization in the Newly Built Solar Greenhouse Soils

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Abstract. In China, greenhouse soils often receive large rates of different manures and have a high content of soil organic matter (SOM). Understanding changes in nitrogen (N) mineralization in soils of newly built greenhouses after their construction is important for managing N. Soil samples were obtained from solar greenhouses of different ages (0, 1, 2, and 3 years) located in the south edge of the Loess Plateau, China, at 0- to 20- and 20- to 40-cm depth. N mineralization in the soils was measured with the Stanford and Smith long-term aerobic incubation method over 30 weeks. SOM, total N, and the mineralized N in the 0- to 20-cm and 20- to 40-cm soil layers were significantly increased in the older greenhouses. The cumulative mineralized N in the 0- to 20-cm soil layer in different cultivation years was increased in each year since the greenhouses were established. For the greenhouses with the same age, the cumulative mineralized N in the 0- to 20-cm soil layer was greater than that in the 20- to 40-cm layer. The potentially mineralizable N (N_0) both in the 0- to 20-cm and the 20- to 40-cm soil layers increased with the greenhouses' age. Regression analysis indicated that when SOM increased $1 \text{ g} \cdot \text{kg}^{-1}$, N_0 in the 0- to 20-cm and 20- to 40-cm depth increased 22.6 and $8.4 \text{ mg} \cdot \text{kg}^{-1}$, respectively. Therefore, as the N supply in soil increases with the age of the solar greenhouse, we suggest that the application rates of manure and synthetic fertilizer be reduced.

The production of vegetable crops and fruit trees in China has increased rapidly since the 1980s, especially vegetables produced in different protected systems, and accounted for about 80% of the global protected horticultural areas in 2010 (Yu, 2011). Compared with grain crops, nutrient addition in this intensive horticultural crop production system is very high in China (Dai et al., 2011; Ma et al., 2000; Shi et al., 2009). Thus, the percentage of fertilizer consumption of horticultural crops grew from 17.8% in 1998% to 30.8% in 2008 in China, whereas the fertilizer consumption of grain crops dropped from 71.0% in 1998% to 57.8% in 2008 (Xin et al., 2012; Zhang et al., 2011).

Solar greenhouses, unique greenhouses developed by Chinese farmers and scientists in the early 1980s, make it possible to produce vegetables during the winter without additional heating and lighting in large parts of northern China (Chen, 2001). As a result, areas with solar greenhouses in China grew rapidly in past decades and became the main income for farmers (Gao et al., 2012; Yu, 2011). Overapplication of N in this system is

more common and severe than in open-field vegetable crops and fruit trees (Ju et al., 2006). A survey in Shouguang, Shandong Province found an N application surplus of $3210 \text{ kg N/ha/year}$ (Yu et al., 2010). In recent years, the amount of applied chemical fertilizer in solar greenhouses has declined in some regions; however, the amount of organic fertilizer is still very high (Li et al., 2017; Shi et al., 2018). Therefore, excessive inputs of nutrients are still widely observed in vegetable production in China (Cai et al., 2016; Liu et al., 2017; Zhao et al., 2017; Zhou, 2017). Such overuse of fertilizers leads to a series of problems, including low nutrient use efficiency, nitrate pollution, soil degradation, serious plant diseases, and pests (Ju et al., 2007; Min et al., 2011; Zhu et al., 2005). Therefore, how to apply N efficiently is important for the sustainable development of this system.

Nitrogen input to solar greenhouses includes manures and synthetic N fertilizers. The amount of manure N addition in greenhouses can rival that from inorganic N sources (Gao et al., 2012; Yu et al., 2010). The long-term use of manures and fertilizers in the system results in a large accumulation of N both in organic and inorganic forms in the soil (Min et al., 2011). Many researchers have studied nitrate accumulation and leaching in solar greenhouses soils (Ju et al., 2007). The high application rate of different manures significantly increases the organic matter contents in the greenhouse soil (Shi et al.,

2009; Zhou et al., 2010). High temperature and optimum soil moisture in the greenhouse during the vegetable-growing season favors N mineralization from SOM. However, few researchers have studied the N mineralization from the greenhouse soils (Ji et al., 2014; Jin et al., 2004).

Nitrogen mineralization from soils is a biological process and is affected by chemical composition and soil environment. Thus, it is difficult to predict the pattern and amount of available N release from SOM (Agehara and Warncke, 2005; Benbi and Richter, 2002). Although chemical methods are used, incubation assays remain the preferred way of estimating mineralizable N from soil (Carter and Gregorich, 2008; Gianello and Bremner, 1986). Among the incubation methods, the Stanford and Smith (1972) aerobic incubation method is regarded as the standard reference method to estimate soil N mineralization. Thus, in present study, we used soil samples collected from solar greenhouses of different ages and determined N mineralization with this incubation method. We hypothesized that the large application of manures and fertilizers in a newly built solar greenhouse system would increase the soil's capacity to supply N in solar greenhouses. The aim of this research was to quantify N-supplying capacity in solar greenhouses of different ages.

Materials and Methods

Site description. The study site was located in Yangling, Shaanxi, China ($108^{\circ}2'E$, $34^{\circ}17'N$), which is the south edge of the Loess Plateau. The region has a continental monsoon climate. The average attitude is about 520 m above the sea level. Average annual precipitation is 630 mm, with most of the rainfall occurring from July to September. The average annual air temperature is 12.9°C .

The solar greenhouses in the study region were built in 2009 and 2010. The greenhouse is of a typical design, with a loess back and side walls and a quadrant metal frame supporting a removable polyethylene cover facing south. The area of each greenhouse ranges from 350 to 700 m^2 . The average air temperature in the solar greenhouses during vegetable season is 19°C . The soil at the study region is an Anthrosol. The original topsoil was removed to build the walls of the greenhouses. Therefore, the soil fertility of the new greenhouse was quite low (Table 1).

The main vegetable crop in the greenhouses is tomato, which is usually transplanted in October and harvested the following June. Chicken and cattle manures are commonly applied, and some greenhouses also receive sheep, swine manures, and anaerobic fermentation residues. Manures at rate of $140 \text{ t} \cdot \text{ha}^{-1}$ are broadcasted onto the soil surface each year, then incorporated into soil before plowing the field. Chemical fertilizers applied include urea, $\text{Ca}(\text{H}_2\text{PO}_4)_4$, K_2SO_4 , and a range of compound fertilizers. The average application rates of N, P_2O_5 , and K_2O fertilizers in the region are $690 \text{ kg} \cdot \text{ha}^{-1}$, $720 \text{ kg} \cdot \text{ha}^{-1}$, and 760

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Table 1. Physical and chemical properties of solar greenhouse soils used.

Soil layer (cm)	Yr	Organic matter (g·kg ⁻¹)	Total N (g·kg ⁻¹)	Mineral N (mg·kg ⁻¹)	Olsen-P (mg·kg ⁻¹)	Available K (mg·kg ⁻¹)
0~20	Before planting	8.7 ± 0.6 C ^z	0.70 ± 0.01 B	29.00 ± 7.0 A	9.0 ± 2.3 C	147 ± 6.4 C
	First year	9.9 ± 1.8 BC	0.68 ± 0.12 B	52.82 ± 34.97 A	84.6 ± 30.38 B	202 ± 55 BC
	Second year	14.1 ± 3.0 B	1.05 ± 0.10 A	55.54 ± 34.72 A	101.2 ± 22.25 AB	286 ± 65 AB
	Third year	20.1 ± 5.3 A	1.27 ± 0.26 A	95.39 ± 88.01 A	139.1 ± 46.99 A	363 ± 103 A
20~40	Before planting	9.0 ± 0.6 B	0.60 ± 0.1 B	19.90 ± 2.2 A	8.7 ± 1.4 A	147 ± 9.0 A
	First year	7.2 ± 0.8 B	0.55 ± 0.08 B	36.56 ± 15.28 A	21.1 ± 21.37 A	123 ± 39 AB
	Second year	7.9 ± 2.1 B	0.59 ± 0.08 B	35.84 ± 36.68 A	16.9 ± 4.41 A	136 ± 24 A
	Third year	12.1 ± 3.1 A	0.82 ± 0.18 A	41.02 ± 17.54 A	26.5 ± 10.57 A	179 ± 79 A

^zDifferent letters in the table indicate significant differences at the 1% level (Duncan's multiple comparison test).

Table 2. Nutrient inputs from manure and inorganic fertilizer in solar greenhouses (kg·ha⁻¹).

Yr	Manure			Chemical fertilizer		
	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O
First year	1332 ± 194 ^z	1022 ± 44	1003 ± 190	621 ± 205	738 ± 176	834 ± 164
Second year	886 ± 256	688 ± 228	707 ± 207	933 ± 293	959 ± 523	1145 ± 343
Third year	769 ± 223	590 ± 170	705 ± 186	766 ± 265	790 ± 288	1106 ± 369

^zValues are means ± SD.

kg·ha⁻¹, respectively (Bai et al., 2013; Gao et al., 2012). All organic manure, phosphorus (P) fertilizer, and about one-fourth of N, potassium (K) fertilizers are basally applied and plowed into the soil. The remaining N, K fertilizers are dressed equally with a fertigation system five to seven times since the first fruit expansion period. Detailed information on nutrient addition in the three successive growing seasons is shown in Table 2.

Soil samples. Soil samples of two depths (i.e., 0- to 20-cm and 20- to 40-cm layers) were collected from five newly built solar greenhouse at the different times, i.e., before planting (i.e., after construction the greenhouse and before addition of manures and fertilizers) and the first, second, and third year after construction the greenhouse. Three cores were collected from the different locations in each greenhouse each year after harvesting the crops in June and then mixed into a composite sample. A portion of fresh soil sample was extracted with 1 mol·L⁻¹ KCL (soil:solution rate, 1:10) to determine mineral N in soil. The remaining soils were air-dried and sieved to 1 mm for subsequent incubation experiment. The basic properties of soils were determined with conventional methods (ISSAS, 1995). To summarize, SOM was measured with the dilution heat K₂Cr₂O₇ oxidation volumetric method. Total N was measured with the Kjeldahl method. Available P was determined according to the method of Olsen et al. (1954). Available K was extracted with 1 mol·L⁻¹ CH₃COONH₄ (soil:solution ratio, 1:10) and determined using flame photometry.

Nitrogen mineralization incubation method. The aerobic incubation method of Stanford and Smith (1972) was used to estimate the mineralizable N from the different soils. To summarize, a sand soil mixture including 15-g samples of soil and equal weights of 20-mesh quartz sand were moistened using a fine spray of distilled water and mixed thoroughly. This mixture was placed into a 50-mL leaching tube. A 6-mm glass wool board was put at the bottom of the tubes and a 3-mm glass wool was put on the top,

then 10 g of quartz sand was added. Soil samples were leached four times with 100 mL of 0.01 M CaCl₂ to remove the originally mineral N in soil. Then, 25 mL of N-free nutrient solution was added into the tube and a vacuum was applied to remove excess water. The tubes were covered with a plastic sheet with several small holes and incubated at 35 °C. There were three replicates for each soil.

After incubation for periods of 0, 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, and 30 weeks, the tubes were leached with 100 mL of 0.01 M CaCl₂ and leachate was collected. The leachate tubes were then leached with 25 mL of an N-free nutrient solution composed of 0.002 mol·L⁻¹ CaSO₄·2H₂O, 0.002 mol·L⁻¹ MgSO₄, 0.005 mol·L⁻¹ Ca (H₂PO₄)₂·2H₂O, and 0.0025 K₂SO₄ in succession. The tubes were pumped down to -80 k Pa before continuing the incubation. Leachates were analyzed with a Bran+Luebbe A3 auto-analyzer (SPW FLOW, Norderstedt, Germany) to determine NO₃⁻-N and NH₄⁺-N content.

Data analysis. Differences in soil nutrient contents over time were analyzed by analysis of variance and Duncan's multiple comparison test using SAS, version 8.0 (SAS Institute, Cary, NC). The first-order kinetic model was used to fit the pattern of N mineralization during the incubation period:

$$N_t = N_0(1 - e^{-kt})$$

where N_t is the cumulative mineralized N in time t , N_0 is potentially mineralizable N, and k is the mineralization rate constant. The nonlinear least-square regression was used to estimate N_0 and k in the model. Linear regression analyses were used to investigate the relationship between potentially mineralizable N (N_0) and organic matter, total N in different soil layers. All figures were plotted using Sigmaplot (Version 12.0; Systat Software, Inc., San Jose, CA).

Results

Organic matter and total N content. The average contents of SOM and total N in 0- to

20- and 20- to 40-cm soil layers were significantly increased through time after the greenhouses were constructed (Table 1). Compared with the newly built greenhouse before planting, the SOM and total N contents of the 0- to 20-cm depth at the end of the second and third planting years increased significantly ($P < 0.01$). In addition, SOM and total N contents in the 20- to 40-cm soil depth at the end of the third year also increased significantly ($P < 0.01$). The rapid increase of SOM and total N is related to the high application rates of manures each year in the greenhouses.

Cumulative mineralized N. The cumulative mineralized N in the 0- to 20-cm soil layer increased linearly with duration of incubation (Fig. 1). The mineralized N in the second and third years of the greenhouse's life in the 0- to 20-cm soil layer was significantly greater than those at the beginning and first year of the greenhouses. The mineralized N at the end of the first year was significantly greater than that before the greenhouses were constructed.

The cumulative mineralized N in the 20- to 40-cm soil layer was significantly lower than in the 0- to 20-cm soil layer. After 30 weeks of incubation, the average cumulative mineralized N during the life of the greenhouse in the 0- to 20-cm soil layer was 86.2 mg·kg⁻¹ and was only 47.2 mg·kg⁻¹ in the 20- to 40-cm soil layer. There were no significant differences in the mineralized N between the first year and the beginning of the study.

Potentially mineralizable N (N_0). The first-order kinetic model fitted the curves of cumulative mineralized N from the greenhouse soils with the different well. Potentially mineralizable N (N_0) and the mineralization rate constant increased through time after the greenhouses were constructed (Table 2). This could be explained by the increase of SOM and total N in the older greenhouses (Table 1). Potentially mineralizable N_0 of the 0- to 20-cm soil layer of the third year was 290 mg·kg⁻¹, which was 2.04, 1.42, and 1.16 times greater than that before construction, in the first year and the second year, respectively.

Fig. 1 The cumulative mineralized nitrogen from (A) 0- to 20-cm and (B) 20- to 40-cm layers of the different soils of the solar greenhouses with different ages during the incubation.

Table 3. Potentially mineralizable N (N_0) and its constant fitted with the single model over the life of the solar greenhouse.

Soil layer (cm)	Yr	N_0 (mg·kg ⁻¹)	k	R
0-20	Before planting	142.06 ± 27.42 b ^z	0.0037 ± 0.0021 ab	0.9975 ^y
	First year	204.22 ± 62.64 b	0.0049 ± 0.0021 b	0.9990 ^y
	Second year	250.71 ± 71.83 ab	0.0059 ± 0.0033 ab	0.9980 ^y
	Third year	290.03 ± 107.04 a	0.0065 ± 0.0041 a	0.9995 ^y
20-40	Before planting	80.62 ± 37.08 b	0.0034 ± 0.0023 a	0.9961 ^y
	First year	72.19 ± 38.78 b	0.0032 ± 0.0025 a	0.8869 ^y
	Second year	107.62 ± 10.71 ab	0.0035 ± 0.0028 a	0.9961 ^y
	Third year	163.88 ± 45.09 a	0.0038 ± 0.0005 a	0.9949 ^y

^zDifferent letters in the table indicate significant differences at the 5% level (Duncan's multiple comparison test).

^yIndicates 1% significant correlation.

The k value of the third year in the 0- to 20-cm soil layer was significantly greater than the end of the first year.

Potentially mineralizable N_0 of the 20- to 40-cm soil layers was significantly lower than those of 0- to 20-cm soil depth. This indicates that as the greenhouse aged, the mineralized N in both the 0- to 20-cm and 20- to 40-cm soil layer increased. The mineralization rate constant (k) of the 20- to 40-cm depth of soil showed no significant differences over time (Table 3).

The relationship between potentially mineralizable N (N_0) and SOM and total N. Potentially mineralizable N_0 was positively and linearly correlated with SOM and total N (Fig. 2). Regression analysis indicated that when SOM increased 1 g·kg⁻¹, N_0 in the 0- to 20-cm and 20- to 40-cm depth increased by 22.63 and 8.41 mg·kg⁻¹, respectively. When the soil total N increased 1 g·kg⁻¹, N_0 in the 0- to 20-cm and 20- to 40-cm depth increased by 324.84 and 131.27 mg·kg⁻¹, respectively.

The ratio of potentially mineralizable N (N_0) to soil total N also was increased with cultivation years. In the 0- to 20-cm soil layer, the ratios of potentially mineralizable N (N_0) to soil total N before construction, first year, second year, and third year were 0.77%, 1.17%, 1.47%, and 1.95%, respectively. In the 20- to 40-cm soil layer, the ratios of potentially mineralizable N (N_0) of total N were greatest at the end of the third year, which was about 3.09 times greater than that

before construction of the greenhouse. The first year and second year were 1.23 and 2.48 times greater than at the beginning of monitoring.

Discussion

Changes of mineralizable N in the newly built solar greenhouse soils. Many researchers have reported that application of manures or straws in arable fields significantly increases the content of the mineralized N (Bruun et al., 2006; Singh et al., 2007). However, there are only a few researchers who have evaluated N mineralization from the intensive horticultural soils, especially soils with history of many years of cultivation. Our study found that the potentially mineralizable N (N_0) in 0- to 20-cm soil layer increased significantly with time. Potentially mineralizable N_0 at the end of the third year was more than double that at the start of the greenhouse cultivation. Wang et al. (2010) reported that it took 19 years for soil N_0 in manure and inorganic fertilizer treatments to double that in no fertilizer treatment in an arable crop field. The increasing rate of soil mineralizable N in the greenhouse is faster than that in arable soils in the study region. The rapid and significant increase in potentially mineralizable N_0 in our study is related to the fast increase of SOM in this system due to the large application of manures every year (Chen et al., 2004; Gao et al., 2012). According to our survey in the study region, the

application rate of manure in solar greenhouses was in the range of 36 to 360 t·ha⁻¹ (Bai et al., 2013). Manures contributed 71% of the total N input, 66% of the total P input, and 64% of the total K input in the newly built greenhouses (Gao et al., 2012). Other studies in Beijing, Shandong Provinces also found that manures have contributed more than one-half of total nutrient inputs in greenhouses (Chen et al., 2004; Ju et al., 2006). The original fertile topsoil was removed to build the walls of the new greenhouses in Loess Plateau; therefore, adding high rate of manures is a quick way to improve the N supply ability of soils in newly built greenhouses.

Studies on N mineralization from the different soils focus mainly on topsoil (He et al., 2005; Li, 2008). Recent studies indicate that the subsoil contributes more than two-thirds of the plant requirements for N, P, and K, indicating the important role of nutrient supply from the subsoil. However, our current knowledge on subsoil nutrition remains vague (Kautz et al., 2013). This research showed that with the length of greenhouse cultivation, the mineralized N in the 20- to 40-cm soil layer was significantly increased. This could be explained by the repeated and large additions of organic manures and fertilizer and the downward movement of soluble organic matter in the solar greenhouse (Murphy et al., 2000). Enrichment of N in the subsoil improves N supply ability in the newly built greenhouse soils. In contrast, it

Fig. 2 The relationships between potentially mineralizable N (N_0) and organic matter, total N in 0- to 20-cm and 20- to 40-cm layers of the different soils of the solar greenhouses. (A) Soil N_0 vs. OM in 0- to 20-cm; (B) soil N_0 vs. OM in 20 to 40 cm; (C) soil N_0 vs. total N in 0 to 20 cm; (D) soil N_0 vs. total N in 20 to 40 cm. OM = organic matter.

could increase the risk of N losses by denitrification and leaching in solar greenhouses.

Our study found that with increasing time since the greenhouses were constructed that not only total N content but also the ratio of the potentially mineralizable N (N_0) to soil total N was increased. He et al. (2005) also reported that the mineralized N and its ratio to soil total N in vegetable fields were significantly greater than the soils under arable crops. It indicates that with time, the N pool size and its activity soil of greenhouse were both increased. This further confirms that the application of manure in solar greenhouse improves the soil N supply capacity.

Implications for N management in the solar greenhouse. Chinese farmers have the tradition of adding different manures to their greenhouses. They believe that manure is beneficial for soil fertility (Yang, 2006). That's the reason why farmers usually apply high rates of different manures in the newly built greenhouses in study region (Gao et al., 2012). However, they usually ignore available N input from the manures. In our study, the N input from manures was as high as

inorganic N fertilizer in the greenhouses (Table 2). Although the bulk of N in manures is in organic form, and is not readily available to crop, it could be released by microbial mineralization after application. If one-third of total organic N in manure is mineralized during the first growth season (Agehara and Warncke, 2005; Brady and Well, 1996; DEFRA, 2010), the available N from manure in the greenhouse could meet the crop need. Therefore, ignoring total N input from manures is one main reason that explains the overapplication and accumulation of N in the most greenhouses in China.

N uptake during crop growth includes mineral N that existed in soil before planting and N mineralized from organic matter during the crop growth season (Li, 2008). The mineral N that had accumulated in greenhouse soils was very high and was mainly in nitrate form, which is an available N pool, and also easily lost by leaching due to high rate of irrigation in greenhouse (Yan et al., 2012). Our results show that the potentially mineralizable N (N_0) in the topsoil was significantly greater than the mineral N before planting (Table 3). In addition, the

potentially mineralizable N (N_0) in both 0- to 20-cm and 20- to 40-cm soil layers was increased significantly with time since the greenhouse was built. The optimum water and temperature conditions in solar greenhouses favor soil organic N mineralization. Thus, the mineralizable N from SOM under the greenhouse cultivation can substantially contribute to the available N for vegetable crops. As a result, to avoid overaddition of nitrogen, we recommend reducing the application rate of manures and synthetic N fertilizer in the older greenhouses. Field experiments are needed to determine the optimum N application rates from manure and synthetic N fertilizers.

Conclusions

Our study found that the potentially mineralizable N_0 in both the 0- to 20- and 20- to 40-cm soil layers increased significantly with time since a solar greenhouse was built. This is related to the rapid increasing SOM and total N over time due to high application of manures and fertilizers in solar greenhouses. The rapid increasing mineralizable N under

the greenhouse soil can substantially contribute to the available N for vegetable crops. Therefore, it is needed to take into account this N pool when calculating N fertilizer requirements. For the established solar greenhouse, N input both in manure and N fertilizer should be decreased.

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