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Influence of root zone nitrogen management and a summer catch crop on cucumber yield and soil mineral nitrogen dynamics in intensive production systems

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Abstract Nutrient and water management is crucially important in shallow-rooted vegetable production systems characterized by high input and high environmental risk. A 2-year field experiment on greenhouse cucumber double-cropping systems examined the effects of root zone nitrogen management and planting of sweet corn as a catch crop in the summer fallow period on cucumber yield and soil $N_{\min}$ dynamics compared to conventional practices. Cucumber fruit yields were not significantly affected by root zone N management and catch crop planting despite a decrease in N fertilizer application of 53% compared to

conventional N management. Soil $N_{\min}$ content to a depth of 0.9 m decreased markedly and root zone (0–0.3 m) soil $N_{\min}$ content was maintained at about 200 kg N ha⁻¹. Root zone N management efficiently and directly reduced apparent N losses by 44% and 45% in 2005 and 2006, respectively. Sweet corn, the summer catch crop, depleted $N_{\min}$ residue in the soil profile of 1.8 m at harvest of winter–spring season cucumber by 304–333 kg N ha⁻¹, which contributed 19–22% reduction in N loss. Compared to conventional N management, N loss was reduced by 56% under root zone N management and catch crop planting.

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Introduction

Recent investigations have revealed that excessive N fertilizer applications with fertilizer N recovery rates of less than 10% are commonly practiced in intensive greenhouse vegetable production systems in northern China (Chen et al. 2004; Zhang et al. 1996; Zhu et al. 2005). Consequently, very high proportions of unused nutrients accumulate in the soil, and N is released into the environment through nitrate leaching, denitrification and NH₃ volatilization (Cabrera and Chiang 1994; Fox et al. 1996; Gollany et al. 2004; He et al. 2007; Ramos et al. 2002). Double cropping systems with two vegetable crops per year are widespread in northern

China using unheated greenhouses constructed with a clay or brick wall with bamboo supports attached that are covered with polyethylene film. High soil fertility, long term continuous cropping and low soil temperatures from late autumn to early spring are important factors that may inhibit root development in greenhouse vegetables. This may lead to low nutrient use efficiency with consequent negative environmental impacts.

Due to the requirements of high yield and good quality it is necessary to maintain adequate N concentrations and water supply in the root zone in greenhouse vegetable (including cucumber) growth (Mayfield et al. 2002). However, rapid growth rates and poor root systems in greenhouse vegetables result in relatively high critical levels of water and nutrient supply. Frequent and excessive N side-dressing and irrigation are major features of conventional management systems, and are employed to maintain adequate N concentrations in the root zone. The result is poor control of root zone N supply and ready leaching of nitrate out of the root zone because of the shallow rooting systems of some vegetable species (Thorup-Kristensen 2006; Verma et al. 2007).

Achieving the optimum N addition to maximize yield while minimizing environmental impact is an important goal of best management practices. Root zone N management based on the soil $N_{\min}$ test before N side-dressing and the N uptake pattern of the plants may be the key to improving N use efficiency. This involves (1) maintaining a critical N concentration in the root zone by determining the N supply from the soil and from organic and inorganic fertilizers, (2) synchronizing nutrient supply with critical crop nutrient demand at different growth stages, and (3) spatially optimizing nutrient and water supply in the root environment. Using these strategies 73% of N fertilizer was saved in a continuous three-season greenhouse tomato cropping system (He et al. 2007). However, significant losses of nitrate-N in drainage discharge still continued to occur because of long-term surplus nutrient supply and very high soil fertility through excessive application of organic manures and nitrogen fertilizers, together with excessive irrigation (He et al. 2007; Strock et al. 2004) and heavy rainfall events in the summer season when the polyethylene covered greenhouses are opened on the North China Plain (Chen et al. 2005; He et al. 2003).

High soil N mineralization rates may contribute to the leachable N outside the crop growing period

(Addiscott et al. 1991; Powlson 1993). It is possible to recover residual soil mineral N by prolonging the vegetable growing season or planting a catch crop during the fallow period (Thorup-Kristensen et al. 2003). A number of crops with deep root systems and high N uptake have been selected as winter cover crops to scavenge residual NO_3^- during the winter in Europe and the United States (Kuo and Jellum 2002; Logsdon et al. 2002; Meisinger et al. 1991; Thomsen and Christensen 1999; Thomsen 2005; Weinert et al. 2002). It seems that non-leguminous cover crops may potentially lower NO_3^- leaching by 29–94% in comparison to legumes for which the corresponding range was 6–48% (Sainju and Singh 1997). Kuo et al. (1995) found that rye and annual ryegrass (*Lolium multiflorum* Lam.) with extensive root systems significantly lowered NO_3^- concentrations in soil leachates in comparison with fallow soil, whereas hairy vetch actually increased the leachate NO_3^- concentrations.

Cucumber, one of the most important vegetables in China, is commonly planted in open fields and greenhouses. Two-season cucumber is continuously planted from February to June in the winter–spring season (WS season) and from September to the following January in the autumn–winter season (AW season) in greenhouses in northern China. Features of cucumber root systems include widely spreading surface laterals and a vertically penetrating taproot. The horizontally spreading roots in the surface soil were found to make substantial growth in transplanted cucumber (Weaver and Bruner 1927). Because of the very rapid and extensive growth of the roots (largely in the surface layers of the soil) the top 0.3 m of the soil profile is regarded as the root-zone layer. Furthermore, shallow and poor root development due to continuous cropping contributes to an increasing risk of nitrate leaching.

It would be preferable to select a plant species with rapid biomass accumulation and high N uptake capacity (especially C_4 plant species) as summer catch crops in order to deplete residual N in the soil profile (Snapp et al. 2005; Wang et al. 2005). In the present study sweet corn was selected as a possible catch crop in the cucumber double cropping system and our objectives were (1) to investigate the combined cucumber yield responses to reduced N inputs and inclusion of the catch crop in the rotation and (2) to monitor the effects of root zone N management and catch crop planting on soil $N_{\min}$ dynamics during the year-round cropping system.

Materials and methods

Experimental site

A typical 5-year-old commercial greenhouse was randomly selected for the field experiment in Changping county, Beijing suburbs from 2005 to 2007. The greenhouse was covered with polyethylene film (ground area 6×72 m) without supplementary lighting or heating. Field experiments were conducted on a silty loam soil. The surface soil in the greenhouse (0–0.3 m layer) had a pH (in water) of 6.1, an electrical conductivity (EC) value with the extracting ratio of 1:5 (soil/water) of $214 \mu\text{S cm}^{-1}$, an initial soil $N_{\min}$ of 255 kg N ha^{-1} and an organic matter content of 24.0 g kg^{-1} prior to the experiments. Total N, Olsen-P and $\text{NH}_4\text{OAc-K}$ were 1.78 g kg^{-1} , 305 mg kg^{-1} and 470 mg kg^{-1} , respectively. Soil texture and soil bulk density in the top 1.8 m of the soil profile are shown in Table 1. Groundwater with a nitrate concentration of 0.44 mg L^{-1} was used for irrigation.

Daily soil temperature, air temperature and precipitation were recorded during the summer seasons of 2005 and 2006 (Fig. 1). Total amounts of precipitation were 299 and 491 mm in 2005 and 2006, respectively (Fig. 1). From 21 July to the harvest of sweet corn in both years, the precipitation rates were 270 and 244 mm in 2005 and 2006, respectively, and the greenhouse was uncovered during this period. Precipitation data were collected from a nearby weather station. Air temperatures were recorded daily at 10:00 during the experiment (Fig. 1).

Crop establishment and management

Cucumber seedlings (*Cucumis sativus* L. cv. Jinglu no. 3 in 2005 and cv. Zhongte no. 25 in 2006) with two leaves were transplanted by hand, with double rows of

0.9-m row spacing and 0.3-m seedling spacing on the seedbed (Fig. 2) on 11 March 2005 and 15 February 2006 (WS season), and 8 September 2005 and 10 September 2006 (AW season). Fruit harvesting started on 21 April and 18 October in 2005 and 9 April and 9 October in 2006 (Fig. 3). Once the final harvest was completed, cucumber vines were immediately removed from the greenhouse to minimize infection with root fungal diseases. Sweet corn seedlings with three leaves were transplanted with 0.6-m row spacing and 0.3-m plant spacing in the treatments with summer catch crop planting at the end of June and the sweet corn was harvested in September.

Experimental treatments

The treatments were designed as follows:

- (1) N00: Neither organic manure nor chemical fertilizer N was applied.
- (2) Nm0: Only organic manure was broadcast as a basal fertilizer and no chemical N fertilizer was applied. 75, 22.5, 11 and 18 t ha^{-1} of chicken manure (with total N inputs of 671, 200, 146 and 205 kg N ha^{-1}) were broadcast before transplanting in the four growing seasons. Organic matter, total P and total K contents of the organic manures used in 2006 were 30.9%, 12.6 g kg^{-1} (P_2O_5) and 2.45 g kg^{-1} (K_2O).
- (3) Nmt: With the same application of chicken manure as the Nm0 treatment, N fertilizer was side-dressed in the cucumber growing period based on conventional practice in the region. The total N rates applied by topdressing were 710, 675, 666, and 590 kg N ha^{-1} in the WS and AW seasons of 2005 and WS and AW seasons of 2006, respectively.
- (4) Nmr: with the same application rate of chicken manure as Nm0 treatment, N side-dressing was

Table 1 Soil texture and bulk density at different soil depths in the experimental field at Changping

Soil depth (m)	Soil bulk density (kg m^{-3})	Soil particle distribution at different depths (μm)		
		20–2,000	2–20	≤ 2
0–0.3	1,420	38.6	60.6	0.9
0.3–0.6	1,620	39.0	59.4	1.7
0.6–0.9	1,510	27.8	69.1	3.1
0.9–1.2	1,510	12.1	84.8	3.2
1.2–1.5	1,550	9.1	86.6	4.3
1.5–1.8	n.d. ^a	21.1	76.0	3.0

^a n.d. Not detected

Fig. 1 Daily precipitation and air temperature during the growing seasons in greenhouse cucumber cropping systems in the Beijing suburbs

based on the N target value (including soil $N_{\min}$ buffer and crop uptake) and soil $N_{\min}$ in the root zone. The equation was as follows:

$$\begin{aligned} \text{Recommended fertilizer N} &= [\text{Output (crop N uptake + soil } N_{\min} \text{ buffer)}] \\ &\quad - [\text{Input (soil } N_{\min} \text{ in the root zone before side} \\ &\quad \text{— dressing)}] \end{aligned} \quad (1)$$

Here, soil $N_{\min}$ buffer refers to the critical soil residual $N_{\min}$ in the root zone required to maintain crop growth, which was modified to 200 kg N ha^{-1} , referenced from substrate cucumber experiments (Kotsiras et al. 2002). Seasonal N uptake by cucumber shoots was calculated based on the following formula describing cucumber yield formation in the same county (Pei 2002).

Fig. 2 Field layout of cucumber (A) and sweet corn (B) planting and the locations of soil and root sampling of cucumber and sweet corn

Fig. 3 Planting periods of different seasonal greenhouse cucumber and the summer catch crop (sweet corn) during the period 2005–2006. WS Winter–spring season, AS autumn–winter season

WS season:

$$\text{Nuptake} = -0.0337 \text{ DAT}^2 + 8.2533 \text{ DAT} \\ - 216.04$$

AW season:

$$\text{Nuptake} = -0.0174 \text{ DAT}^2 + 4.1953 \text{ DAT} \\ - 79.94$$

where DAT denotes days after transplanting.

The total side-dressing N rates in Nmr were 152, 405, 319 and 310 kg N ha⁻¹ in the WS and AW seasons of 2005 and the WS and AW seasons of 2006, respectively.

- (5) Nmr+C: On the basis of the Nmr treatment, sweet corn was planted as a catch crop during the summer fallow period and no straw of sweet corn was incorporated into the soil after harvest.
- (6) Nmr+CS: On the basis of the Nmr+C treatment, the straw of sweet corn was incorporated into the soil after harvest.

The experiment was a completely randomized block design with three replicates and the size of each replicate plot was 4.8×5.5 m. Furrow irrigation systems were adopted in the greenhouse based on the conventional schedule. Urea was dissolved and flushed into the soil with furrow irrigating water for N side-dressing. The total irrigation rates were 367, 330, 266 and 198 mm in the WS and AW seasons of 2005 and the WS and AW seasons of 2006, respectively (Fig. 4). No irrigation or fertilizer was applied during the sweet corn planting season except for 35 mm of irrigation at transplanting.

Field management followed conventional practices. Weeds were removed by hand. Fungicide sprays were used to control powdery mildew and downy mildew which frequently occur during cucumber growth.

Nitrogen balance calculation

N balance was calculated following Eq. 2 as described by Patil et al. (2001).

$$\text{N}_{\text{balance}} = \text{N}_{\text{min initial}} + \text{N}_{\text{manure}} + \text{N}_{\text{fer}} - \text{N}_{\text{crop}} \\ - \text{N}_{\text{min harvest}} \quad (2)$$

Where:

$\text{N}_{\text{balance}}$	N balance
$\text{N}_{\text{min initial}}$	soil N_{min} to 0.3 m depth before transplanting
N_{manure}	N from chicken manure
N_{fer}	N from applied chemical fertilizer
N_{crop}	total N uptake in cucumber aboveground parts
$\text{N}_{\text{min harvest}}$	soil N_{min} to 0.3 m depth at harvest

Sampling and analysis

Soil samples were taken from the top 0.9 m in each plot at 0.3 m intervals two or three days before N side-dressing during the cucumber growing season. In the sweet corn growing and fallow periods soil sampling was conducted from the 0–0.3, 0.3–0.6 and 0.6–0.9 m soil layers every 2–3 weeks. Before planting and after harvesting of cucumber and sweet corn, soil samples were taken to 1.8 m depth at 0.3-m intervals. Six soil cores were mixed thoroughly and passed through a 4-mm sieve. Sub-samples of 12 g soil were extracted at a ratio of 1:10 (dry soil weight/extractant volume) with 0.01 mol/L CaCl₂, shaken for 1 h and filtered. The filtrates were analyzed for mineral N with a TRAACS Model 2000 continuous flow autoanalyzer (Houba et al. 1986). Water contents in the soil samples were determined gravimetrically to calculate soil N_{min} on a dry soil basis.

Cucumber samples were taken at intervals of 2–3 weeks to measure dry matter weight and N content.

Fig. 4 N side-dressing/irrigation rates and soil N_{min} contents in the soil profile to a depth of 0.9 m under different treatments from 2005 to 2006. WS Winter–spring season, AS autumn–winter season, SF summer fallow season. N00, Nm0, Nmt, Nmr, Nmr+C and Nmr+CS denote control, N from organic manure,

conventional N management and root zone N management, root zone N management with sweet corn as catch crop and root zone N management with sweet corn as catch crop and with residue incorporation after the sweet corn harvest. Bars represent SD of means with three replicates per treatment

Commercial fruits (2.5–3.0 cm in diameter and 25–30 cm long) were picked following conventional harvest practice and weighed from 24 plants in each plot. Sweet corn was sampled when soil sampling was conducted. Fresh shoot samples were collected and dried at 70°C to constant weight. The dried shoots were ground before determination of total N content. A modified Kjeldahl method with addition of salicylic acid was used to analyze total N in the plant samples.

Cucumber and sweet corn roots were sampled at harvest. Root samples were taken with an Eijelkamp root auger (length 0.15 m, diameter 0.08 m) to a depth of

0.6 m in the case of cucumber and 1.05 m for sweet corn in 0.15-m increments (Fig. 2). Soil cores with root samples were stored for a maximum of 6 days in polyethylene bags under refrigeration (4°C) before washing. Roots were collected after the soil was passed through a 0.5-mm sieve with flowing tap water. Debris, weeds, and dead roots were sorted by hand from the fresh roots during washing, based on visual observation of fresh roots appearing light in color. Samples were frozen prior to length determination. Root length was estimated using a line intersect method (Tennant 1975) with 1.0×1.0 cm square grids.

Data analysis

The data were subjected to analysis of variance and pairs of mean values were compared by least significant difference (LSD) at the 5% level using version 6.12 of the SAS software package (SAS Institute Inc., Cary, NC, USA).

Results

Cucumber yields and sweet corn biomass

Figure 5 summarized the variation in marketable yield of cucumber with different N fertilizer and catch crop treatments. The fruit yield of cucumber in the AW season was significantly lower than that in the WS season due to low temperatures during the fruiting stage in the AW season. No significant difference was found in cucumber yield between Nmr and Nmt treatments in the four growing seasons despite the 53% reduction in fertilizer N application in the Nmr treatment. Root zone N management, sweet corn cropping and straw incorporation played no significant part in fruit yield loss in the first and second succeeding cucumber growing seasons or with the sum of the four cucumber seasons, indicating that sweet corn may be intro-

duced as a summer catch crop in greenhouse cucumber cropping systems.

Adequate rainfall in the summer season created optimum growth conditions for sweet corn. At harvest the dry biomass reached 9,876 and 8,786 kg ha⁻¹ in 2005 and 2006, respectively. Fresh yields of sweet corn averaged 7,671 and 7,115 kg ha⁻¹ in 2005 and 2006.

Root distribution of cucumber and sweet corn

Seasonal differences in root growth were found in the later growth stages of cucumber between the WS and AW seasons (Table 2). Lower temperatures could be an important explanation for the lower root length densities in the later growth stages of cucumber in the AW season compared with the WS season. Nearly 90% of cucumber root length was distributed in the top 0.3 m of the soil profile in the later growth stage of cucumber in both growing seasons.

The rapid root development stage of sweet corn occurred before the polyethylene film was removed (21 July) during the summer season (Table 3). 89% of total root length measured to a soil depth of 75 cm was distributed within the top 0.3 m of the soil profile in both years. At harvest, sweet corn roots had penetrated to a depth of 1.05 m and the root length below 0.3 m depth accounted for 24–29% of total root length in the top 1.05 m of the soil profile.

Fig. 5 Fruit yield of cucumber under different N management and sweet corn treatments. WS Winter–spring season, AS autumn–winter season. N00, Nm0, Nmt, Nmr, Nmr+C and Nmr+CS denote control, N from organic manure, conventional N management and root zone N management, root zone N management with sweet corn as catch crop and root zone N

management with sweet corn as catch crop and with residue incorporation after the sweet corn harvest. Bars represent SD of means with three replicates per treatment. The same letter in the same season denotes no significant difference by LSD at the 5% level

Table 2 Mean root length density (cm cm^{-3}) of greenhouse cucumber in the Nmr treatment in the autumn–winter season of 2005 and winter–spring season of 2006

Soil depth (m)	2005 autumn–winter season			2006 winter–spring season		
	18 Oct	18 Nov	30 Dec	5 Apr	3 May	21 Jun
0–0.15	0.79	1.62	0.66	0.79	1.52	1.46
0.15–0.30	0.32	0.81	0.37	0.32	0.75	0.51
0.30–0.45	n.d.	0.34	0.12	n.d.	0.37	0.24
0.45–0.60	n.d.	0.07	n.d.	n.d.	0.09	n.d.

^a n.d. Not detected

Soil $N_{\min}$ dynamics under fertilizer N management

Soil $N_{\min}$ content at 0–0.9 m depth was greatly reduced by root zone N management during the experiment in contrast to conventional N management (Fig. 4). Furthermore, soil $N_{\min}$ content with root zone N management was maintained near to the $N_{\min}$ buffer used in the determination of N recommendations.

Residual $N_{\min}$ in the soil profile was greatly influenced by different N management practices during the experiment (Fig. 6). More N was retained in the 0.3–1.8 m soil layer by frequent N side-dressing in both 2005 and 2006 (Table 4). After the cucumber harvest in the WS season of 2005, residual soil $N_{\min}$ below the cucumber root zone increased by 176 kg N ha^{-1} in the N00 treatment, 354 kg N ha^{-1} in Nm0, 818 kg N ha^{-1} in Nmt and 418 kg N ha^{-1} in Nmr contrast to that before transplanting (10 March 2005). During the subsequent fallow period there was an evident increase in $N_{\min}$ content in the 0.3–1.8 cm zone of the soil profile of 193 (N00), 293 (Nm0), 538

(Nmr) and 768 kg N ha^{-1} (Nmt) compared to the cucumber harvest in WS season in 2005.

However, by the harvest of the 2006 WS season soil $N_{\min}$ content in the 0.3–1.8 m soil layer was significantly lowered by 895 (N00), 1,068 (Nm0), 1,536 (Nmt) and 1,217 kg N ha^{-1} (Nmr) compared to the end of the fallow period in 2005. A rapid decrease in soil $N_{\min}$ content in the 0.3–1.8 m soil layer was found from the end of the fallow period in 2005 (26 Aug 2005) to the end of the cucumber harvest in the WS season of 2006 (21 Jun 2006). During the 2006 fallow period, there was a smaller increase in soil $N_{\min}$ with Nm0, Nmt and Nmr treatments in comparison with the 2005 fallow period. At the cucumber harvest in the 2006 AW season the soil $N_{\min}$ content in the 0.3–1.8 m soil layer decreased by 65 (N00), 180 (Nm0), 162 (Nmt) and 115 (Nmr) kg N ha^{-1} in contrast to the end of the 2006 fallow period, indicating that the amount of organic manure applied was important for soil N accumulation below the root zone. In 2005, 671 kg N ha^{-1} in organic manure was applied as a basal fertilizer,

Table 3 Mean root length density and percentage of total root length at different soil depth categories in sweet corn under the Nmr+C treatment in 2005 and 2006

Soil depth (m)	Root length density (cm cm^{-3})				Percentage of total root length at different soil depth categories (%)			
	21 Jul		At harvest		21 Jul		At harvest	
	2005	2006	2005	2006	2005	2006	2005	2006
0–0.15	1.08	1.54	1.17	1.06	66	67	46	51
0.15–0.30	0.38	0.51	0.65	0.49	23	22	25	24
0.30–0.45	0.10	0.12	0.36	0.28	6	5	14	13
0.45–0.60	0.05	0.09	0.19	0.14	3	4	7	7
0.60–0.75	0.04	0.07	0.07	0.03	2	3	3	1
0.75–0.90	n.d. ^a	n.d.	0.07	0.04			3	2
0.90–1.05	n.d.	n.d.	0.06	0.02			2	1

^a n.d. Not detected

Fig. 6 $N_{\min}$ content in the top 1.8 m of the soil profile of at the end of harvest over four cropping seasons in the greenhouse cucumber cropping system. Bars represent SD of means with three replicates per treatment

which can be regarded as traditional practice, and an evident increase in soil $N_{\min}$ was observed from the beginning of the 2005 WS season to the end of the 2005 fallow period. Thereafter, N from organic manure was controlled at around 200 kg N ha⁻¹ for cucumber growth, and no increase in $N_{\min}$ occurred in the soil profile (except in the 2006 fallow period) under the range of N application rates examined.

N uptake, soil $N_{\min}$ and soil water dynamics under sweet corn cropping

Total N uptake by sweet corn at harvest was 187 kg N ha⁻¹ in 2005 and 154 kg N ha⁻¹ in 2006 (Fig. 7). Shoot N

uptake by sweet corn was up to 42 and 56 kg N ha⁻¹ from sweet corn transplanting to 21 July in 2005 and 2006. During the later growth stages of sweet corn (from 20 July to the end of the harvest), the amounts of N removed by the sweet corn shoots were 131 and 112 kg N ha⁻¹ in 2005 and 2006.

No rainfall reached the interior of the greenhouse before 21 July because the greenhouse was covered with polyethylene film and strong $N_{\min}$ mineralization was found in the top 0.9 m of the soil profile in 2005, but not in 2006 (Fig. 7). The initial soil N supply at the beginning of the fallow period might partly explain this result. After three continuous cucumber growing periods with root zone N management, soil

Table 4 Soil $N_{\min}$ content (kg N ha^{-1}) in the 0.3–1.8 m deep soil zone at the end of the cucumber harvest the in greenhouse cropping system during 2005–2006

Treatment	2005 WS ^b 10 Mar	2005 WS 21 Jun	2005 Fallow 26 Aug	2006 AW 4 Jan	2006 WS 21 Jun	2006 Fallow 4 Sept	2006 AW 30 Dec
N00 ^a	745	921 b ^c	1,114 d	597 b	219 c	190 d	125 d
Nm0	745	1,099 b	1,392 c	774 b	324 c	419 c	239 c
Nmt	745	1,564 a	2,332 a	1,361 a	796 a	965 a	802 a
Nmr	745	1,163 b	1,701 b	1,342 a	484 b	705 b	590 b

^a N00, Nm0, Nmt and Nmr denote control treatment, N from organic manure, conventional N management and N recommended management.

^b WS and AW denote winter–spring season and autumn–winter season.

^c The same letter in the same column denotes no significant difference by LSD ($P < 0.05$)

$N_{\min}$ was lower at the beginning of the fallow period in 2006 than in 2005. In 2005 no significant difference was found in $N_{\min}$ content between sweet corn cropping and the fallow treatment in the top 0.3 m of the soil profile. However, sweet corn cropping evidently depleted $N_{\min}$ compared to the fallow treatment in 2006. In both years soil $N_{\min}$ at 0.3–0.9 m depth was reduced by sweet corn cropping with root growth and N uptake occurring in contrast to the fallow period. At the sweet corn harvest less $N_{\min}$ was retained in the top 1.8 m of the soil profile under sweet corn cropping compared with the fallow period (Fig. 8). Soil $N_{\min}$ in the top 1.8 m of the soil profile was reduced by 333 and 304 kg N ha^{-1} with sweet corn cropping compared to the fallow treatment in 2005 and 2006 and soil water content in the 0–1.8 m soil layer increased with or without sweet corn cropping in contrast to the beginning of the fallow period. No significant difference in soil water content was found between Nmr and Nmr+C treatments after the fallow period (Fig. 8).

Soil N supply following incorporation of sweet corn straw

After the sweet corn harvest, N incorporation in sweet corn straw amounted to 91 and 68 kg N ha^{-1} in 2005 and 2006, and sweet corn straw biomass reached 5,239 and 4,183 kg ha^{-1} in 2005 and 2006. Figure 3 showed that sweet corn cropping with or without soil incorporation of the catch crop at harvest had little effect on $N_{\min}$ in the top 90 cm of the soil profile in the 2005 AW season or the 2006 WS season. However, soil $N_{\min}$ in the top 0.3 m soil layer under Nmr+C and Nmr+CS treatments appeared to be low in contrast to

the Nmr treatment in the 2006 AW cucumber season due to continuous sweet corn cropping during the fallow period, but there were no apparent differences among these treatments in $N_{\min}$ content at 0.3–0.9 m depth. Although no difference in soil $N_{\min}$ at 0–0.9 m depth was observed between Nmr+C and Nmr+CS treatments, soil $N_{\min}$ at 0–0.9 m depth under Nmr+CS tended to increase at the cucumber harvest in the 2006 AW season.

N balance

The different N fertilizer treatments had pronounced effects on N balance (Table 5). A balanced N recommendation strategy in the Nmr treatment has allowed substantial reductions in N losses of 44% and 45% compared to traditional N management (Nmt) in 2005 and 2006. Compared to the Nmr treatment, N losses were reduced by 22% and 19% with sweet corn cropping in 2005 and 2006. The incorporation of sweet corn residues at harvest may have lowered N losses by 22% in 2005 but had little effect on N losses in 2006 compared to the Nmr treatment. There was little difference in N loss between Nmr+C and Nmr+CS treatments in 2005. However, in 2006 N loss under the Nmr+CS treatment increased by 19% in contrast to the Nmr+C treatment.

Discussion

Excessive N in the soil–plant system is associated with environmental hazards (Crews and Peoples 2005; Olfs et al. 2005). Synchronizing cucumber N demand with

Fig. 7 Soil $N_{\min}$ content to a soil depth of 0.9 m with or without sweet corn as catch crop in the summer fallow period in the greenhouse cucumber cropping system in 2005 and 2006. Bars represent SD of means with three replicates per treatment

critical nutrient supply at different growth stages is the key objective to solve the conflict between high yields and environmental protection. The effects of N fertilization practice on cucumber yield have been discussed in detail by Guo et al. (2008). Compared to traditional N management, the fertilizer N input was reduced by 53% by means of root zone N management (Nmr), taking into account soil and environmental N supply and N uptake by cucumber. In our experiments, root zone N management was a very efficient and direct

method of lowering N losses by 44% and 45% in 2005 and 2006, respectively. However, at least $386\ kg\ N\ ha^{-1}$ (not including soil N mineralization) per season was lost from the plant–soil system even with lowered N inputs. The high $N_{\min}$ buffer of $200\ kg\ N\ ha^{-1}$ for cucumber production far exceeded the ecological threshold of $90\ kg\ N\ ha^{-1}$ in soil (Declercq et al. 2001), which led to unavoidable nitrate leaching risk. From the results of our 2-year experiment, $200\ kg\ N\ ha^{-1}$ of soil $N_{\min}$ buffer was appropriate for the intermediate growth

Fig. 8 Soil $N_{\min}$ content (A) and soil water content (B) throughout the top 1.80 m of the soil profile with or without sweet corn as catch crop in the summer fallow period in the greenhouse cucumber cropping system. Bars represent SD of means with three replicates per treatment

stage of cucumber, characterized by rapid N uptake and dry matter accumulation in both the WS and AW seasons (Guo et al. 2008). However, 200 kg N ha⁻¹ of soil $N_{\min}$ buffer was relatively high in the early and later growth stages, characterized by slow N uptake and dry matter accumulation (Guo et al. 2008), especially in the later growth stages during the AW season with low temperatures. The $N_{\min}$ buffer should therefore be adjusted during the different cucumber growth stages according to N uptake and dry matter accumulation.

N leaching outside the growing season may appear to be completely outside the control of the grower because of high residual $N_{\min}$ and high precipitation typical of

the summer fallow season on the North China Plain. To prevent leaching of nitrogen after harvest and potential contamination of groundwater, the nitrogen used for the $N_{\min}$ buffer can be removed from the soil by growing a cover crop of another species (Strock et al. 2004; Weinert et al. 2002).

Ju et al. (2007) demonstrated the high risk of nitrate leaching in the summer season and suggested that deep-rooted species such as corn can be used as a catch crop to intercept soil nitrate deep in the soil profile to control nitrate leaching. Integrated N management with catch crops could maintain low residual $N_{\min}$ at transplanting of succeeding vegetable crops to protect

Table 5 N balance in the top 0.3 m of the soil profile under different N treatments in greenhouse cucumber experiments in Changping, Beijing suburbs from 2005 to 2006 (kg N ha⁻¹)

Component		2005						2006					
		N00 ^a	Nm0	Nmt	Nmr	Nmr+C	Nmr+CS	N00	Nm0	Nmt	Nmr	Nmr+C	Nmr+CS
N inputs	Total	254	1,125	2,510	1,682	1,682	1,682	100	524	1,886	1,263	1,265	1,376
	N _{min} before transplanting	254	254	254	254	254	254	100	173	279	283	285	396
	Manure N	0	871	871	871	871	871	0	351	351	351	351	351
	Chemical N	0	0	1,385	557	557	557	0	0	1,256	629	629	629
N outputs	Total	422	548	831	743	946	953	364	416	814	676	792	790
	N uptake	362	455	437	476	659	645	339	386	505	503	622	649
	N _{min} after harvest	60	93	394	267	287	308	25	30	309	173	170	141
N balance		-168	577	1,679	939	736	729	-264	108	1,072	587	473	586

^a N00, Nm0, Nmt, Nmr, CNmr and CNmr+C denote control, N from organic manure, conventional N management and root zone N management, reduced-N management with sweet corn as catch crop and root zone N management with sweet corn as catch crop and with residue incorporation after the sweet corn harvest.

the environment from pollution in intensive greenhouse cropping systems. Furthermore, deep-rooted cover crops may help alleviate the effects of soil compaction and succeeding crops may benefit from root channels left by the decomposing roots of cover crops as demonstrated in soybean cropping systems following cover crops (Williams and Weil 2004). A number of experiments were conducted to compare the suitability of different crop species as catch crops under greenhouse conditions. The crops studied were sweet corn, hairy vetch and Chinese onion. The results indicate that sweet corn was the most suitable catch crop, not only for depleting soil nitrogen, but also because of farmer preference and economic performance (data not shown). In our experiment apparent N losses were further reduced by 19–22% by using sweet corn as a summer catch crop based on reduced N inputs with no significant reduction in the yield of succeeding cucumber. Depletion of N_{min} in the top 0.9 m of the soil profile was found to be associated with the root growth of sweet corn. Kristensen and Thorup-Kristensen (2004a) reported that soil N depletion by catch crop species was highly correlated with their rooting depth but there was little correlation with root density. According to Wiesler and Horst (1994), sweet corn roots may penetrate the soil to a depth of 1.5 m. However, Kristensen and Thorup-Kristensen (2004b) observed shallow rooting (0.3 m) by sweet corn in minirhizotrons and they attributed the differences in their results to relatively low temperatures in spring and summer. In our experiment

sweet corn rooting depth approached 1.1 m, which was in accordance with the results of Ren (2003) at Dongbeiwang in the Beijing suburbs. This was likely adequate to deplete soil N_{min} below 0.3 m in the soil profile. Kristensen and Thorup-Kristensen (2004b) found N utilization efficiencies of sweet corn at 0.2, 0.4, 0.6 and 0.8 m depths of up to 23%, 6%, 3% and 0.8% in a 6-day study using NO₃-¹⁵N isotope techniques. However, we observed differences between 2005 and 2006 in the pattern of scavenging by sweet corn in the top 0.3 m of the soil profile. Low N availability to sweet corn may explain the evident exhaustion of N in the root zone in 2006. Although Thorup-Kristensen et al. (2003) included adequate N supply to increase the growth and N uptake by the cover crop over a short time period, in our experiment strong N mineralization due to high N inputs in 2005 may have masked the effects of N uptake by sweet corn on soil N_{min} depletion in the top 0.3 m of the soil profile.

Cover crops reduce the potential for NO₃ leaching by (1) taking up and storing soil active N in plant tissues during the leaching-prone fallow period with heavy precipitation during soil water recharge and (2) absorbing and transpiring water and lessening water percolation (Weinert et al. 2002; Thorup-Kristensen et al. 2003). In the present study no significant difference in water content was found between the Nmr and Nmr+C treatments after sweet corn cropping. Changing soil water flux is a complex process and we did not measure drainage under the different treatments in our experi-

ment. It is therefore difficult to explain N movement on the basis of soil water flux. The amount of N taken up by sweet corn reached to 154–187 kg ha⁻¹. However, compared to the fallow treatment a reduction of 303–333 kg N ha⁻¹ in the 0–1.8 m deep soil zone was achieved by sweet corn cropping. This raises the question of whether sweet corn retains more N in organic form in the soil by root activity compared to fallow conditions. Parkin et al. (2006) speculated that using living rye plants as a winter cover crop may have increased immobilization of N in the organic N pools. However, the amounts by which N loss calculated by the difference between N inputs and N outputs under the Nmr+C treatment were reduced were 203 and 114 kg ha⁻¹, respectively. Soil organic N mineralization, which was not considered as an N input factor, may partly account for the differences that occur using the different methods of calculation. Substantial soil organic N mineralization may occur during the fallow period because of high summer temperatures. Over-fertilization can lead to greater release of N from unavailable forms (Stevens et al. 2005) and this may be responsible for a large proportion of the increase in N_{min} in the top 1.8 m of the soil profile in the Nmt treatment.

Cover crops are used to reduce N leaching losses from the soil and also to improve the N nutrition of subsequent crops. Some risk of inadequate nitrogen supply to succeeding crops might occur if soil N_{min} in the root zone were depleted and nitrogen fertilizer recommendations would increase due to low N_{min} in the root zone, an unexpected effect in cover cropping systems. One effect of cover crops on the nitrogen nutrition of the succeeding crop is mineralization or immobilization caused by the decomposition of the plant residues in the soil (Thorup-Kristensen 1993). Immobilization of nitrogen by the catch crop residues is usually regarded as a disadvantage of the system because it makes soil N unavailable to the succeeding crop (Jensen 1991). However, in greenhouse cucumber cropping systems soil N was vulnerable to leaching about 40 days after transplanting because of the chicken manure application, high residual N_{min}, poor root growth and frequent irrigation. N immobilization by sweet corn straw during this period was expected to reduce the risk of nitrogen leaching. However, in our experiment no evident effect of sweet corn residues on soil N_{min} content was observed because the same N topdressing was applied as in the Nmr treatment. In future studies, therefore, the recommended N applica-

tion rate should be calculated by taking account of mineralization by sweet corn residues which may replace part of the urea fertilizer nitrogen. In addition, cucumber residues, the N removal of which accounted for almost half of total N uptake, were removed from the greenhouse to protect subsequent cucumber crops from disease. If the residues are co-composted with manure and then applied as basal fertilizer with catch crop residues this may provide a more effective means of contributing to the N nutrition of subsequent vegetable crops.

Conclusions

Reduced N input was an efficient tool to reduce the risk of N losses in an intensive greenhouse cropping system. Based on recommended N fertilizer management, N losses were further reduced by growing sweet corn as a summer catch crop with no significant decrease in yield of cucumber fruits. Sweet corn can therefore be introduced as a supplementary biological N management tool to minimize N leaching losses in greenhouse cucumber cropping systems. Incorporation of sweet corn residues had little effect on lowering N loss compared to the treatment without residue incorporation. The change in soil N_{min} resulting from residue incorporation was due to a masking effect of N topdressing that can occur in field experiments. Appropriate adjustment of the recommended N application rate would therefore be advisable.

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