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Tracking nitrogen losses in a greenhouse crop rotation experiment in North China using the EU-Rotate_N simulation model

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Abstract:
Vegetable production in China is associated with high inputs of nitrogen, posing a risk of losses to the environment. Organic matter mineralisation is a considerable source of nitrogen (N) which is hard to quantify. In a two-year greenhouse cucumber experiment with different N treatments in North China, non-observed pathways of the N cycle were estimated using the EU-Rotate_N simulation model. EU-Rotate_N was calibrated against crop dry matter and soil moisture data to predict crop N uptake, soil mineral N contents, N mineralisation and N loss. Crop N uptake (Modelling Efficiencies (ME) between 0.80 and 0.92) and soil mineral N contents in different soil layers (ME between 0.24 and 0.74) were satisfactorily simulated by the model for all N treatments except for the traditional N management. The model predicted high N mineralisation rates and N leaching losses, suggesting that previously published estimates of N leaching for these production systems strongly underestimated the mineralisation of N from organic matter.

Keywords: EU-Rotate_N model; greenhouse; cucumber; fertiliser recommendations; nitrogen loss

Capsule

The EU-Rotate_N model can satisfactorily simulate crop N uptake and N_{min} dynamics in a *typical greenhouse cucumber production system of North China*

1. Introduction

Over the past two decades the area of greenhouse vegetables has greatly increased from 20,000 ha to 600,000 ha in China (Li, 2005). Efficient nutrient and water management is crucially important in sustainable vegetable production. Shallow-rooted vegetable production in greenhouses is associated with high inputs of water and nutrients posing a high risk of N losses to the environment in North China. Recent investigations have revealed that excessive N fertiliser applications with less than 10% of fertiliser N being recovered are commonly found in the intensive greenhouse vegetable planting systems in northern China (Chen et al., 2004; Zhu et al., 2005). Consequently, high proportions of unused nitrogen are lost to the environment by nitrate leaching, denitrification and NH_3 volatilisation (Cabrera and Chiang, 1994; Fox et al., 1996; Gollany et al., 2004, He et al., 2007; Ramos et al., 2002). The intensification of greenhouse vegetable production has been accompanied by an increase of nitrate concentrations in groundwater. For example, nitrate-N concentrations in shallow wells (<15 m) around greenhouses in Huimin, Shandong Province, ranged from 9 to 274 mg N L^{-1}, with 99% of surveyed wells exceeding 10 mg N L^{-1}, more than half of the samples (53%) exceeding 50 mg N L^{-1}, and 26% exceeding 100 mg N L^{-1} (Ju et al., 2006).

Double-cropping is typical for greenhouse planting systems without supplementary heating or illumination on the North China Plain. The first cucumber crop is grown in the winter-spring (WS) season from February to June and the second in the autumn-winter (AW) season from September until the following January. In the summer season, no crop is grown in the greenhouse due to hot weather conditions. Fertiliser applications are not based on official recommendation systems as none are available. However, different methods are at hand to optimise the N fertiliser input for maximum yield with minimum environmental impact.

Root zone N management based on the measurement of soil mineral N (N_{min}) before N side-dressing (N_{min} method) and on the N uptake pattern of the plants is considered to be a key method to improve N use efficiency. Using this strategy N fertiliser application could be reduced by 73% in a continuous three-season greenhouse tomato cropping system (He et al., 2007) in Shouguang and by 50% in a continuous four-season greenhouse cucumber

cropping system (Guo et al., 2008a) in Beijing suburb without yield reduction. The N balance between N input (fertiliser N + initial N_{min} + N in irrigation water) and N output (crop N uptake + residual N_{min} at harvest) confirmed that N loss was greatly reduced by root zone N management. A catch crop planted during the summer fallow period further reduced apparent N loss in a greenhouse cropping system (Guo et al, 2008b). N leaching was considered the most important pathway of N loss (Zhu et al. 2005), although it was never measured. For this reason, a reliable process based model for N cycling under vegetable production was utilised to facilitate better estimation of N leaching from the greenhouse system. The EU-Rotate_N model (Rahn et al. 2010) was developed with the help of European Commission funding to simulate N utilisation and cycling in rotations of field vegetable crops. Losses of N by leaching together with crop growth and root development, the release of N from soil organic matter and crop residues and their subsequent fate are simulated. Nendel (2009) demonstrated that the model is a useful tool to improve N management in rotations of field grown vegetables with minimal effect on yield whilst greatly reducing nitrogen losses. The objective of this study was (i) to test the model performance in greenhouse vegetable cropping systems in North China Plain by comparing model predictions of crop N uptake and soil mineral N with experimental data testing different strategies of N management in a continuous four-season greenhouse cucumber cropping system, and (ii) to estimate N mineralisation and N losses of the production systems to help developing Best Management Practices (BMP) for N fertilisation to protect groundwater resources.

2. Materials and methods

2.1. The EU-Rotate_N simulation model

EU-Rotate_N was developed as a tool to optimise nitrogen use in rotations of field crops across Europe. The dynamic and process-based simulation model was extensively revised from the N_ABLE model (Greenwood et al., 1996) upon which it is based. The model has been described in detail by Rahn et al. (2010). The EU-Rotate_N simulation model has been tested against a number of organic and conventional vegetable crop rotation experiments across Europe and demonstrated fitness for purpose. In the present investigation the model is tested against data from a greenhouse cropping system for the first time. The version number of the model used in this study is 1.6, which was released in 2007.

2.2. Model input variables

The model requires a set of input variables for weather, soil characteristics, fertilisation and irrigation (Table 1). Mean air temperature and mean relative humidity were measured on-site on a daily basis. Precipitation data was obtained from a local weather station. Maximum and minimum temperature and daily sum of global radiation was estimated from data outside the greenhouse using transfer functions.

Soil organic matter content and particle size distribution was measured from soil samples taken prior to the experiment. The soil water content at field capacity, permanent wilting point and saturation for the 0 – 0.3, 0.3 – 0.6 and 0.6 – 0.9 m soil layers were derived from soil texture classes (AG Bodenkunde 1994). Water infiltration into the soil largely depends on the position within the furrow system and its distance to the water inlet. Measured soil water contents were used to calibrate the model in order to inversely estimate

the water flux at the simulated position in the greenhouse. The parameter describing the wetted surface area of the furrow system (Guo et al. 2008a) was used as adjustable parameter in this procedure.

((Table 1))

2.3. Model output

Water and N dynamics were simulated for 0.3 m soil layers down to 0.9 m depth. Cumulative daily crop N uptake from the soil was simulated using target cucumber and sweet corn yields. Cumulative N mineralisation was simulated from soil and added organic matter pools for manure and sweet corn residues respectively. Cumulative N leaching was predicted for the profile boundaries below 0.3 cm and 0.9 cm soil depth. Simulated gaseous N losses are presented both on daily basis and as a cumulative total figure.

2.4. Experimental site

A typical five-year-old commercial greenhouse was selected for the field experiment in the Changping County, in the suburbs of Beijing from 2005 to 2006. The greenhouse is of typical design with loam back and side walls and a quadrant metal frame supporting a removable polyethylene cover facing south. Crops are grown in soil and the cover is removed completely during the summer period. The maximum height is 4 m and the ground area is 6 m × 72 m. No supplementary lighting or heating is provided. Before the beginning of the experiment, the greenhouse soil, a silty loam, had a five-year history of traditional N fertilisation characterised by high inputs (1200 – 1500 kg ha^{-1} N per year) of

manure and fertiliser N. The surface soil in the greenhouse (0 – 0.3 m layer) had a pH (in water) of 6.1, an electrical conductivity (EC) value of 214 s cm^{-1} (1:5 ratio soil/water), a density of 1370 kg m^{-3}, an initial 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 NH_4OAc-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 soil profile to 1.8 m are shown in Table 2.

((Table 2))

Total precipitation of 299 mm and 491 mm were recorded at a local weather station in 2005 and 2006, respectively. Effective precipitation (during the period in which the greenhouse was uncovered between 21 July and the harvest of sweet corn) amounted 270 mm and 244 mm in 2005 and 2006, respectively.

2.5. Crop establishment and management

Cucumber seedlings (*Cucumis sativus* L. cv. Jinglu No. 3 in 2005 and cv. Zhongte No.

25 in 2006) were transplanted by hand at the two-leaf stage, into double rows of 0.9 m row spacing and 0.3 m seedling spacing on 11 March 2005 and 15 February 2006 (WS season), and 8 September 2005 and 10 September 2006 (AW season), respectively. Fruit harvesting started on 21 April and 18 October in 2005 and 9 April and 9 October in 2006. Once the final harvest was completed, cucumber vines were quickly removed from the greenhouse in order to reduce the risk of root fungal diseases in future crops. Sweet corn seedlings at the three-leaf stage were transplanted on 28 June 2005 and 30 June 2006, respectively, with 0.6

m row spacing and 0.3 m plant spacing in the treatments with summer catch crop. Sweet corn harvest was conducted on 28 August 2005 and 2 September 2006, respectively.

2.6. Experimental treatments

The treatments were designed as follows:

(1) **N00:** The control treatment where neither manure nor fertiliser N was applied.

(2) **Nm0:** Chicken manure was broadcast at rates of 75, 22.5, 11 and 18 t ha^{-1} (with total N inputs of 671, 200, 146 and 205 kg N ha^{-1},) before transplanting in the four growing seasons, respectively. Organic matter, total P and total K contents of the organic manure used in 2006 were 30.9%, 12.6 g kg^{-1} (P_2O_5) and 2.45 g kg^{-1} (K_2O), respectively. No additional N fertiliser was used.

(3) **Nmt:** Chicken manure was applied before transplanting as in the *Nm0* treatment. In addition, N fertiliser was side-dressed in the cucumber growing period following conventional practice in the region. The total N rates applied by side-dressing 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**: Chicken manure was applied before transplanting as in the *Nm0* treatment. In addition, mineral N side-dressing was applied, based on the following approach:

N_{rec} N_{uptake} N_{buffer} $N_{initial}$ min Eq. 1

where N_{rec} is the recommended N fertiliser dosage, N_{uptake} is the expected amount of N taken up by the crop until harvest, N_{buffer} is the minimum soil mineral N content in the rooting zone to maintain optimum crop growth and $N_{min\ initial}$ denotes the soil mineral N content in the rooting zone at planting. N_{buffer} was set to 200 kg N ha^{-1}, according to

substrate cucumber experiments carried out by Kotsiras (2002). N uptake in cucumber shoot was based on the following function describing the relationship between growth and uptake (Pei, 2002).

WS season:

$N_{uptake} = -0.0337 \cdot DAT^2 + 8.2533 \cdot DAT - 216.04$ Eq. 2

AW season:

$N_{uptake} = -0.0174 \cdot DAT^2 + 4.1953 \cdot DAT - 79.94$ Eq. 3

where DAT denotes days after transplanting.

In 2005 the total side-dressing N rates in Nmr were 152 kg N ha^{-1} in the WS season and 405 kg N ha^{-1} in the AW season. In 2006, the total side-dressing N rates in Nmr were 319 kg N ha^{-1} in the WS season and 310 kg N ha^{-1} in the AW season.

(5) **Nmr+C**: Based the Nmr treatment, but with a sweet corn catch crop planted during the summer fallow period. The residue of sweet corn shoots were removed from soil after harvest.

(6) **Nmr+CS**: based on the Nmr+C treatment, but with the sweet corn shoot residue incorporated into the soil after harvest.

The experiment had a completely randomised block design with three replicates and the size of each replicate plot was 4.8 m x 5.5 m. The furrow irrigation system and the irrigation schedule were carried out according to normal commercial practice. The side dressings of nitrogen were made by dissolving Urea in water which was distributed to the plots in the irrigation water. The water input which included irrigation during covered and precipitation during uncovered periods is shown in Fig 1. No irrigation or fertiliser was applied during the summer period except for 35 mm at the transplanting of sweet corn.

((Fig. 1))

2.7. Sampling and analysis

Soil samples were taken from the top 0.9 m in each plot in 0.3 m layers two or three days before N side-dressing during the cucumber growing season. In the sweet corn growing and fallow periods soil samples were collected from the 0 – 0.3, 0.3 – 0.6 and

0.6 – 0.9 m soil layers every 2 – 3 weeks. Six soil cores were taken from each plot, which were thoroughly mixed before being 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^{-1} $CaCl_2$, shaken for 1 h and filtered. The filtrates were analysed for mineral N with a TRAACS 2000 continuous-flow auto-analyser (Houba et al. 1986). Water contents in the soil samples were determined gravimetrically by drying the soil at 105°C and determining the water loss by weighing. NH_4^+ concentration always corresponded to values below 17.6 kg N ha^{-1}, indicating that NH_4^+ fixation would not significantly affect N dynamics. A 2 mol L^{-1} KCl extraction was carried out additionally for some samples. However, this extraction method yielded comparable results (maximum 11.4 kg N ha^{-1}).

Samples of whole crop were taken at intervals of 2 – 3 weeks to assess dry matter yield and N content of cucumber crop. Commercial fruits (2.5 – 3.0 cm in diameter and 25 – 30 cm long) were picked and weighed from 24 plants in each plot every one to three days following commercial harvest practice. Sweet corn was sampled when soil sampling was conducted. Fresh shoot samples were collected and dried at 70ºC 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 analyse total N including NO_3-N in the plant samples.

2.7. Model evaluation

The following four statistical indices were chosen to evaluate the model performance: The mean bias error (*MBE*, Addiscott and Whitmore, 1987), the root mean square error (*RMSE*, Fox 1981), Modelling Efficiency (*ME*, Nash and Sutcliffe, 1970) and Willmott's Index of Agreement (*d*; Willmot, 1982). *MBE* provides information on any systemic over- or underprediction of the model (Eq. 4). *RSME* describes the average absolute deviation between observed and predicted values (Eq. 5). *ME* compares the difference between predicted and observed values against the variance of the observed values during the period under investigation (Eq. 6). It ranges between –1.0 (no correlation) and 1.0 (perfect fit). An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model. d represents the ratio of the mean square error and the potential error (Eq. 7). It ranges between 0 (no correlation) and 1 (perfect fit).

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \quad \text{(Eq. 4)}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad \text{(Eq. 5)}$$

$$ME = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad \text{(Eq. 6)}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(\left|P_i - \bar{O}\right| + \left|O_i - \bar{O}\right|\right)^2} \quad \text{(Eq. 7)}$$

where n is the number of samples, P_i and O_i are the predicted and observed values, and $\bar{O}$ is the mean of the observed data.

3. Results

3.1. Nitrogen uptake and soil mineral nitrogen content simulations

The seasonal differences in N uptake of cucumber in this experiment have been reported in Guo et al. (2008a). The N uptake of cucumber at harvest averaged 207 (N00), 257 (Nm0), 294 (Nmt), 304 (Nmr), 304 kg (Nmr+C), and 304 kg N ha^{-1} (Nmr+CS), respectively, in WS season while the N uptake was on the average of 125 (N00), 157 (Nm0), 184 (Nmt), 190 (Nmr), 176 (Nmr+C) and 187 kg N ha^{-1} (Nmr+CS), respectively in winter-autumn season. Model simulations of the N uptake of cucumber and sweet corn were compared with observed values for a range of treatments (Fig 1 – 6). In general, the model produces the observed value well, showing d between 0.94 and 0.98, and ME of between 0.80 and 0.92 (Table 3).

For N_{min} content in the 0 – 0.3, 0.3 – 0.6 and 0.6 – 0.9 m soil layers the model performed with d ranging between 0.58 and 0.92 and ME between –0.35 and 0.74. The model overestimated N_{min} with Nmt treatment in the 0 – 0.3 m soil layer. In general, both observed and simulated N_{min} in the 0 – 0.9 m soil profile was lower in the Nmr managed treatments as compared to Nmt.

((Fig 1 – 6))

((Table 3))

3.2. Simulation of nitrogen mineralisation

The model simulated that 339 kg N ha^{-1} N would be mineralised from soil organic matter per year over two continuous experimental years, where no fertiliser or manures had been applied. It predicted an additional 105 kg N ha^{-1} being released from decomposing roots of the cucumber plants (Fig 7). The total being close to the total N uptake of cucumber shoot during the four seasons. Simulations of total N mineralisation were dramatically increased by 41% and 92% with the application of chicken manure, respectively, reaching 748 kg ha^{-1} per year. The application of N fertiliser had little effect on the simulated amount of soil N mineralisation. Sweet corn cropping reduced total N mineralisation by 140 kg N ha^{-1} over two years (Fig 8), with lasting impact on the subsequent AW season. The incorporation of sweet corn residues had marginally smaller effect on soil N mineralisation compared with Nmr+C treatment.

((Fig 7))

((Fig 8))

3.3. Simulation of gaseous nitrogen losses

Annual gaseous N loss simulated by the model for the different treatments were 0.41 (N00), 1.78 (Nm0), 21.7 (Nmt), 9.9 (Nmr), 9.9 (Nmr+C) and 10.0 (Nmr+CS) kg N ha^{-1} (Table 4). Gaseous N losses were simulated to be larger for the WS season than for the AW season. Fertiliser and manual N inputs greatly increased simulations of N gaseous losses.

Comparing Nmt and Nmr treatments gaseous losses could be reduced by 54% where lower amounts of fertiliser were applied. Sweet corn cropping and incorporation of sweet corn straw had little effect on gaseous N losses. Fertiliser greatly increased the percentage of gaseous N losses in WS season. Gaseous N losses predicted with conventional and recommended N management in WS season account for 72% – 83% of total gaseous N loss per year while gaseous N losses in AW season accounted for 14% – 24%.

((Table 4))

3.4. Simulations of nitrate leaching.

The simulations of N leaching below 0.3 m and 0.9 m (Table 5) were greatly increased by N inputs. Compared with Nmt treatment, N leaching loss was reduced by 34% (below 0.3 m) and 37% (below 0.9 m) with Nmr treatment and 49% (below 0.3 m) and by 44% (below 0.9 m) with the treatment of Nmt+C. The reduced losses of N below 0.3 m indicated the benefits of sweet corn in reducing N leaching in both the summer fallow period and in the subsequent AW season. However, nitrate leaching simulated by model below 0.9 m was reduced by sweet corn cropping only in AW season but not in summer fallow period. Incorporation of sweet corn residues had little effect on N leaching losses.

((Table 5))

4. Discussion

4.1. Simulated nitrogen mineralisation

Model-predicted N release from soil organic matter in the manure treatments (Nm0)

was always higher than the predicted release from soil organic matter in the unfertilised treatment (N00). This is due to the fact that the model assumes a fraction of added organic manure to be transformed into soil organic matter, which in turn mineralises and releases N. Model-predicted cumulative N mineralisation from soil organic matter and added organic manure was high with an average of 15.5 kg N ha^{-1} $week^{-1}$. For those treatments with manure, N mineralisation only from soil organic matter averaged 9.9 kg N ha^{-1} $week^{-1}$ in the experimental period (2005 – 2006). These high N mineralisation rates are explained by the long-term history of high N inputs into intensive vegetable production systems. He et al. (2005) reported N mineralisation rates from a 28-day lab incubation experiment with soils used for vegetable production being in the range of 9.9 to 14.1 mg kg^{-1} per week, which is 1.5-1.7 times than that found in soils with a grain crops history. In 2007, an in-situ experiment was conducted by Wang et al. (2008) at the same experimental site in Beijing to measure soil N mineralisation of soils with different histories of N management using micro-lysimeters (Nendel et al. 2005). No fertiliser was applied to the soils in the micro-lysimeters. From this experiment, weekly soil N mineralisation was measured as 3.4, 4.7, 6.9 and 5.7 kg N ha^{-1} with N00, Nm0, Nmt and Nmr treatment, respectively (Wang, 2008). The observed N mineralisation rate with the N00 treatment in 2007 was low compared with the rate predicted by model in 2005 and 2006 but no manure or fertiliser had been applied since 2005 exhausting of the soil organic matter pool. The observed N mineralisation rate was high in the Nmt treatment reflecting the history of high fertiliser and manure applications (Wang, 2008), indicating that high N mineralisation rates predicted by the model from 2005 to 2006 were in the range of measured values in a greenhouse cropping system.

4.2. Simulation of nitrogen losses

The results of the simulations showed that gaseous N loss was only a small fraction of the total N losses in the greenhouse cropping system, similar to the results reported by Zhu et al. (2005) and He et al. (2009). The EU-Rotate_N model does not distinguish between

NH_3 or N_2O forms of gaseous N emissions which limits the evaluation of the simulation results. Zhu et al. (2005) reported that seasonal ammonia volatilisation in a greenhouse experiment with organic manure input of 178 kg N ha^{-1} and urea input of 600 kg N ha^{-1} was just 9 kg N ha^{-1}. Low pH and high soil moisture contents were assumed to be the explanation for low ammonia volatilisation (Zhu et al. 2005). He et al. (2009) reported an annual N_2O emission rate of 8.8 kg N ha^{-1} with traditional N treatment, applying N fertiliser rates similar to our experiment. According to Zhu et al. (2005) and He et al. (2009), the sum of N_2O losses and NH_3 volatilisation was 29 kg N ha^{-1} per year in Shouguang, Shandong Province, which was only marginally higher than the gaseous loss predicted by the model (22 kg N ha^{-1}) for the Beijing region. Furthermore, the model was able to predict seasonal variations in gaseous N losses. Higher gaseous N losses were simulated in the WS season compared to the AW season, similar to the findings of He et al. (2009).

N leaching was predicted to be the main source of N losses in our experiment according to the result of the simulations. N leaching predicted for the Nmt treatment added up to 590 kg N ha^{-1} per season below 0.3 m and 684 kg N ha^{-1} per season below 0.9 m in average of four growing seasons, with an average N application rate of 305 kg N ha^{-1} as chicken manure and 660 kg N as urea. A lysimeter experiment conducted in Shouguang measured 231 kg N ha^{-1} leaching below 0.9 m during WS season with 178 kg N ha^{-1} from chicken

manure and 600 kg N ha^{-1} from urea in a greenhouse hot pepper cropping system (Zhu et al, 2005). This suggests that N leaching predicted by model in our simulations may be overestimated. However, there was still 392 kg N ha^{-1} unaccountable in the hot pepper cropping system according to the calculation of N balance. Dissolved organic N, which was neither considered in the experiment nor in the simulation model, may help explaining part of this gap.

In this experiment and that reported by Zhu et al. (2005), a furrow irrigation system with double-row cropping was used, so water and nitrogen input into the soil was not distributed evenly in the greenhouse area. The model simulations apply to a single point in the furrow, where water infiltration and N input is much higher than in other zones of the greenhouse. A set of simulations will be needed to represent the whole greenhouse including spatial information on water infiltration and N distribution. However, beneath the furrow, high N leaching losses are still expected.

N management based on the approach given in Eq. (4) reduced fertiliser N input by 53% for the experiment. Consequently, the simulated leaching of N in this treatment was reduced by 37%. However, nitrogen leaching under the Nmr treatment still accounted for 81% of total fertiliser and manure N input, which was similar to the traditional N treatments.

Sweet corn could further reduce N leaching loss by prolonging the period of crop N uptake. Total N mineralisation was reduced by sweet corn cropping as summer catch crop, presumably by lowering the soil water content due to transpiration and thus impairing the conditions for soil organic matter mineralisation. The main effect of sweet corn was to intercept rainfall and thus reduce infiltration and the downward movement of nitrate in the soil. This was observed in a labelled ^{15}N experiment conducted in 2006, where more ^{15}N was kept in the 0-0.3 m soil layer as organic nitrogen under sweet corn cropping as compared with a fallow treatment (Data unpublished).

Although the simulation study indicates that the amount of N released from organic matter in the soil is high and greatly contributes to N leaching losses, an experimental verification of this hypothesis would be desirable to quantify the fluxes in the system with more accuracy and validate the predictions of the EU-Rotate_N model.

4.3. Deriving nitrogen fertiliser recommendations

In the past fifteen years, several research groups have reported on the effects of conventional N input on soil mineral N accumulation, groundwater condition and greenhouse gas emission in the intensive greenhouse vegetable cropping areas of the North China Plain (Chen et al., 2004; He et al., 2009; Ju et al., 2006, 2007; Shen et al., 2009; Zhang et al., 1996). It has been commonly recognized that uncontrolled N losses to groundwater and atmosphere are a serious problem and closely related to high N input from either fertiliser or manure. Improved N management is urgently required for environmentally sound and sustainable vegetable production. Among the possible approaches to improve N management, both crop rotation planning (Zhou et al., 2008) and root zone N management have become increasingly popular. Modified root-zone N management based on N_{min} method proved to reduce N fertilizer input and N loss efficiently (Guo et al., 2008a; He et al., 2007, 2009). However, in their experiments the impact of mineralisable N from soil organic matter and manure is ignored in deciding upon fertiliser recommendations. The results of the EU-Rotate_N model suggest a significant N input from soil organic matter and manure over the growing season not

previously accounted for. Consequently, the recommended N rate for our experiment could be further reduced.

5. Conclusion

It can be concluded that EU-Rotate_N, which was initially designed for the use in European outdoor field conditions, can be applied in typical greenhouses in China without major modifications. The model-predicted leaching of N supports the hypothesis that N losses of vegetable production systems can be large and cannot easily be estimated from observed N_{min} data alone. It also suggested that the mineralisation of N from soil organic matter as well as N release from organic amendments need to be considered to improve fertiliser recommendations. Furthermore, the EU-Rotate_N model could be considered as a tool for deriving N fertiliser recommendations, since it works without the requirement for frequent soil sampling and analysis, and thus is less expensive and laborious for agricultural advisors and policy-makers in contrast to the system of recommended N management that we used for this experiment. Future codes of BMP for greenhouse vegetable production in China could be developed with the help of EU-Rotate_N.

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Table 1: Model input variables

Variable	Unit	Data source
Daily weather parameter		
Mean air temperature	°C	Measured on site
Maximum air temperature	°C	Estimated from daily air temperature

		outside the greenhouse
Minimum air temperature	°C	Estimated from daily air temperature outside the greenhouse
Precipitation	mm	Obtained from local weather station
Mean relative humidity	%	Daily measured on site
Global radiation	MJ m^{-2} day^{-1}	Estimated from data outside the greenhouse and data inside the greenhouse in 2007
Soil		
Texture	kg kg^{-1}	Measured
Total organic carbon	kg kg^{-1}	Measured
Bulk density	g cm^{-3}	Measured
Field capacity	m^3 m^{-3}	Estimated from soil texture
Permanent wilting point	m^3 m^{-3}	Estimated from soil texture
Saturation	m^3 m^{-3}	Estimated from soil texture
pH		Measured
Soil C/N		Measured
Initial N_{min} content	kg N ha^{-1}	Measured
Initial soil water content	m^3 m^{-3}	Measured
Fertilization		
Fertilization rate (manure and chemical fertilizer)	kg N ha^{-1}	Measured
Characteristics of fertilizer		Defined in model
Irrigation		
Irrigation amount	mm	Assessment from measurement and soil moisture content predicted by model
N concentration in irrigation water	mg l^{-1}	Measured
Crop		
Crop dry matter at planting	kg ha^{-1}	Measured
Fruit dry matter at harvest	t ha^{-1}	Measured
N concentration in transplant	%	Measured

Table 2: Soil texture and soil bulk density at different soil depths in Changping experimental field

Soil depth (m)	Soil bulk density kg m^{-3}	Soil texture classes (%)		
		20-2000 μm	2-20 μm	$<$2 μm
0 – 0.3	1420	38.57	60.55	0.87
0.3 – 0.6	1620	38.95	59.38	1.68

0.6 – 0.9	1510	27.80	69.06	3.14
0.9 – 1.2	1510	12.09	84.76	3.15
1.2 – 1.5	1550	9.07	86.63	4.30
1.5 – 1.8	n.d.[a]	21.09	75.95	2.97

[a] n.d., not done

Table 3: Model performance indices (*MBE* = Mean Bias Error, *RMSE* = Root Mean Squared Error, *d* = Index of Agreement and *ME* = Modelling Efficiency) for soil mineral N in different layers and crop N uptake for different N treatments in a greenhouse cucumber-sweet corn rotation system

Treatment	Parameter	MBE	RMSE	d	ME
N00	Soil N_{min} 0 – 0.3 m	–33.65	57.69	0.79	0.40
	Soil N_{min} 0.3 – 0.6 m	–33.92	54.09	0.89	0.64
	Soil N_{min} 0.6 – 0.9 m	–24.19	43.48	0.92	0.72
	Crop N uptake	–8.57	19.50	0.98	0.92
Nm0	Soil N_{min} 0 – 0.3 m	5.02	45.58	0.91	0.74
	Soil N_{min} 0.3 – 0.6 m	–1.24	54.67	0.90	0.49
	Soil N_{min} 0.6 – 0.9 m	11.92	55.81	0.89	0.64
	Crop N uptake	–10.30	25.30	0.98	0.92
Nmt	Soil N_{min} 0 – 0.3 m	130.02	209.12	0.69	–0.35
	Soil N_{min} 0.3 – 0.6 m	25.37	117.61	0.61	–0.01
	Soil N_{min} 0.6 – 0.9 m	35.13	110.68	0.58	–0.49
	Crop N uptake	–16.77	28.88	0.97	0.91
Nmr	Soil N_{min} 0 – 0.3 m	40.78	102.64	0.68	0.24
	Soil N_{min} 0.3 – 0.6 m	10.47	65.29	0.82	0.52
	Soil N_{min} 0.6 – 0.9 m	20.69	66.75	0.76	0.34
	Crop N uptake	–19.15	29.65	0.97	0.91
Nmr+C	Soil N_{min} 0 – 0.3 m	10.00	71.29	0.86	0.62
	Soil N_{min} 0.3 – 0.6 m	–0.08	65.82	0.84	0.55
	Soil N_{min} 0.6 – 0.9 m	15.16	53.90	0.83	0.54
	Crop N uptake	–8.46	28.71	0.97	0.90
Nmr+CS	Soil N_{min} 0 – 0.3 m	17.61	74.48	0.83	0.55
	Soil N_{min} 0.3 – 0.6 m	3.51	53.04	0.88	0.64
	Soil N_{min} 0.6 – 0.9 m	18.65	59.02	0.80	0.46
	Crop N uptake	–13.94	40.54	0.94	0.80

Table 4: Model simulations of gaseous N loss in different treatments (Unit: kg N ha^{-1})

Treatment	2005 WS[a]	2005 SF

			2005 AW	2005 WF	2006 WS	2006 SF	2006 AW	Total
N00[b]	0.16	0.14	0.11	0.01	0.17	0.14	0.10	0.82
Nm0	1.77	0.71	0.30	0.24	0.21	0.35	0.14	3.55
Nmt	21.20	0.70	3.50	0.20	14.00	0.40	3.30	43.30
Nmr	7.54	0.70	1.86	0.30	6.60	0.50	2.30	19.80
Nmr+C	7.54	0.14	1.86	0.22	7.24	0.50	2.30	19.80
Nmr+CS	7.54	0.14	1.92	0.23	7.27	0.50	2.30	19.90

[a]WS, SF, AW and WF denoted winter-spring season, summer fallow period, autumn-winter season and winter fallow season.

[b]N00, Nm0, Nmt, Nmr, Nmr+C and Nmr+CS denote control treatment, N from organic manure treatment, conventional N management, reduced-N management, reduced-N management with sweet corn as catch crop and reduced-N management with sweet corn as catch crop with residue incorporation after sweet corn harvest.

Table 5: Model simulations of N loss through leaching with different treatments below 0.3 m and 0.9 m (Unit: kg N ha^{-1})

Treatment	2005 WS[a]	2005 SF	2005 AW	2006 WS	2006 SF	2006 AW	Total
Below 0.3 m							
N00[b]	170	96	90	52	14	101	522

Nm0	339	175	197	177	5	236	1129
Nmt	408	688	467	683	19	800	3065
Nmr	342	288	330	452	65	470	1947
Nmr+C	342	196	229	411	51	322	1552
Nmr+CS	342	196	232	408	50	321	1549
Below 0.9 m							
N00	177	175	208	67	0	99	728
Nm0	181	256	402	209	-1	216	1263
Nmt	208	372	858	796	4	872	3110
Nmr	208	308	533	503	15	547	2114
C+Nmr	208	329	378	429	23	375	1741
C+CNmr	208	329	380	426	23	375	1740

[a]WS, SF, AW and WF denoted winter-spring season, summer fallow period, autumn-winter season and winter fallow season.

[b]N00, Nm0, Nmt, Nmr, Nmr+C and Nmr+CS denote control treatment, N from organic manure treatment, conventional N management, reduced-N management, reduced-N management with sweet corn as catch crop and reduced-N management with sweet corn as catch crop with residue incorporation after sweet corn harvest.

Figure captions

Figure 1: Simulated (lines) and observed (dots) dynamics of crop nitrogen uptake (A) and soil mineral nitrogen contents in the 0 – 0.3 m (B), 0.3 – 0.6 m (C) and 0.6 – 0.9 m (D) soil layer of the N00 treatment. Error bars indicate the standard deviation of the observations; WS, SF, AW and WF denote the winter-spring season, summer fallow period, autumn-winter season and winter fallow period.

Figure 2: Simulated (lines) and observed (dots) dynamics of crop nitrogen uptake (A) and soil mineral nitrogen contents in the 0 – 0.3 m (B), 0.3 – 0.6 m (C) and 0.6 – 0.9 m (D) soil layer of the Nm0 treatment. Error bars indicate the standard deviation of the observations; WS, SF, AW and WF denote the winter-spring season, summer fallow period, autumn-winter season and winter fallow period.

Figure 3: Simulated (lines) and observed (dots) dynamics of crop nitrogen uptake (A) and soil mineral nitrogen contents in the 0 – 0.3 m (B), 0.3 – 0.6 m (C) and 0.6 – 0.9 m (D) soil

layer of the Nmt treatment. Error bars indicate the standard deviation of the observations; WS, SF, AW and WF denote the winter-spring season, summer fallow period, autumn-winter season and winter fallow period.

Figure 4: Simulated (lines) and observed (dots) dynamics of crop nitrogen uptake (A) and soil mineral nitrogen contents in the 0 – 0.3 m (B), 0.3 – 0.6 m (C) and 0.6 – 0.9 m (D) soil layer of the Nmr treatment. Error bars indicate the standard deviation of the observations;

WS, SF, AW and WF denote the winter-spring season, summer fallow period, autumn-winter season and winter fallow period.

Figure 5: Simulated (lines) and observed (dots) dynamics of crop nitrogen uptake (A) and soil mineral nitrogen contents in the 0 – 0.3 m (B), 0.3 – 0.6 m (C) and 0.6 – 0.9 m (D) soil layer of the Nmr + C treatment. Error bars indicate the standard deviation of the observations; WS, SF, AW and WF denote the winter-spring season, summer fallow period, autumn-winter season and winter fallow period.

Figure 6: Simulated (lines) and observed (dots) dynamics of crop nitrogen uptake (A) and soil mineral nitrogen contents in the 0 – 0.3 m (B), 0.3 – 0.6 m (C) and 0.6 – 0.9 m (D) soil layer of the Nmr + CS treatment. Error bars indicate the standard deviation of the observations; WS, SF, AW and WF denote the winter-spring season, summer fallow period, autumn-winter season and winter fallow period.

Figure 7: Model predictions for nitrogen mineralised from soil organic matter and from all organic sources for different nitrogen treatments in the period from 2005 to 2006. The treatments were: no fertiliser (N00), organic manure application (Nm0), conventional N management (Nmt), reduced N management (Nmr), reduced N management with sweet corn as catch crop (Nmr + C) and reduced N management with sweet corn as catch crop with residue incorporation after harvest (Nmr + CS)

Figure 8: Model predictions for total mineralised nitrogen for different nitrogen treatments

in the winter-spring season (WS), the summer fallow period (SF), the autumn-winter season (AW) and the winter fallow period (WF). The treatments were: no fertiliser (N00), organic manure application (Nm0), conventional N management (Nmt), reduced N management (Nmr), reduced N management with sweet corn as catch crop (Nmr + C) and reduced N management with sweet corn as catch crop with residue incorporation after harvest (Nmr+CS)