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Exploring optimal catch crops for reducing nitrate leaching in vegetable greenhouse in North China

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ABSTRACT

Chinese intensive greenhouse vegetable systems are characterized by high input of water and nutrients, which are not sustainable. There is an urgent need to explore smart and practical strategies to convert the "high input-low output" systems to "optimal input-output" ones. This study aimed to evaluate the effects of different catch crops on reducing nitrate leaching in the vegetable greenhouse during the summer fallow season. A two-year field experiment with three catch crops, i.e., sweet corn (SC), amaranth (A) and sweet sorghum (SG), and no catch crop (CK) were conducted in vegetable greenhouse in Dingzhou city, Hebei province, China. The measured soil water content and inorganic nitrogen (N) content in soil profile, biomass and crop N uptake were used to validate the WHCNS (Soil Water Heat Carbon Nitrogen Simulator) model, soil water movement and nitrate leaching were simulated. The results showed that the catch crops decreased the water drainage by 18.2–29.0% and nitrate leaching by 23.3–42.3% respectively, compared with CK. The water drainage reduction ranked as SC > SG > A, while the nitrate leaching reduction was A > SC > SG. The biomass was SC > SG > A, while the crop N uptake was SC > A > SG. Sweet corn could absorb the residual nitrate in the deep soil layers due to the long root system, while amaranth could absorb most residual nitrate in the surface soil. Amaranth showed greater N-uptake capacity than sweet corn, and the nitrate was mainly accumulated in the surface soil. Planting amaranth as summer catch crop reduced nitrate leaching in the vegetable greenhouses. Our study provides a guideline for selecting effective catch crops in intensive vegetable greenhouses in North China.

1. Introduction

The greenhouse vegetable cultivation has developed rapidly in China because of its whole year production and high income. In the past 30 years, the vegetable acreage of China has increased from 3.3 million ha in 1978 to 22 million ha in 2015 (National Bureau of Statistics of China, 2016). However, these "high input-low output" systems were not sustainable due to large nutrient loss, especially nitrogen (N) loss and contamination of groundwater. Li et al. (2013a) investigated 13 intensive agricultural areas in the peri-urban areas of Beijing and found that groundwater was contaminated by nitrate, i.e., about 26% of study areas exceeded the standard for drinking water quality (nitrate content > 10 mg N L^{-1}). Zhang et al. (2010) investigated intensive agricultural areas in Shandong province, North China and reported that the nitrate content of shallow groundwater under the vegetable greenhouses reached to 25.3–279.6 mg L^{-1}, the average content is 121.6 mg L^{-1}, and 87% of the samples exceeded the standards for drinking water quality. Pang et al. (2013) found that the groundwater pollution under the vegetable fields was more severe than the cropland in the North China Plain (NCP). The average of nitrate content is 86.8 mg L^{-1} and even reached up to 258.0 mg L^{-1} in some areas, which seriously threats to the human health.

Overuse of the fertilizer, especially the N fertilizers were mainly reported in intensive production systems. Fertilizer N input in vegetable field is about seven times more than that in cropland (Ju et al., 2007), fertilizer N inputs in some greenhouses even reached 1000 kg N ha^{-1} (Song et al., 2009; Min et al., 2011b; Sun et al., 2012, 2013). Due to shallow root of vegetables, the excessive fertilizer N inputs had led to the low N use efficiency and large N accumulation in soil or loss to the environment. Zhou et al. (2016) reported that the amounts of residual N in greenhouse reached 1269 ± 114 kg N ha^{-1}. Hence, there is a greater potential risk of N leaching from a greenhouse system than that

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of cropland in China, and an urgent need to explore strategies to convert such “high input-low output” systems to “optimal input-output” ones.

In NCP, the summer season is from June to September, characterized with high temperature and large amounts of precipitation, 70% of annual precipitation occurs in the summer. The temperature may reach 50 °C in the greenhouse, which is not optimal for vegetable growth. In such cases, farmers often open the roof and spare the land as fallow in the summer. Given large amounts of residual nitrate in the soil profile after harvest, high temperature also enhances the mineralization of organic N in the soil, accelerating the accumulation of the inorganic N in the soil profile (Trindade et al., 2001). When heavy rainfall occurs, the nitrate was prone to leaching out of soil profile and caused the groundwater nitrate contamination (Li et al., 2007). So the summer season is the main period for nitrate leaching in NCP. It is necessary to explore effective measures to reduce soil nitrate leaching in the greenhouse during the summer fallow season.

Many studies reported that the catch crops could effectively reduce the water drainage and nitrate leaching. For example, Plaza-Bonilla et al. (2015) evaluated the effects of different leguminous catch crops on water drainage through a three-year crop rotation experiments in France. It found that leguminous catch crops could reduce the water drainage from an annual average of 737 mm to 544 mm. Sapkota et al. (2012) reported that fodder radish decreased N leaching by 79% compared with the fallow treatment. Constantin et al. (2012) assessed the long-term effects of catch crops (mustard and ryegrass) on N dynamics in arable farming and found that catch crops reduced N leaching by 33–55%. Hansen et al. (2015) pointed out the fodder radish as the catch crop could effectively reduce the nitrate leaching from 44 kg N ha^{-1} in the fallow treatment to 5 kg N ha^{-1} in Denmark. Guo et al. (2018) found sweet corn as summer catch crop significantly reduces N leaching by 12.6% compared to the fallow treatment in protected vegetable production systems in North China. Some studies also found sweet corn could decrease the nitrate leaching by about 30.4% compared with the fallow treatment in the Tai Lake region (Min et al., 2011a; Lu et al., 2013). Wortman (2016) reported that cover crops reduced potential N loss by 26% compared to weedy fallow. Carey et al (2017) found the oats as catch crop could decrease the N leaching by 25% compared with the ryegrass using a lysimeter method in New Zealand. Wang et al. (2011) compared the effects of four kinds of catch crops on reducing N leaching based on pot experiment in Lanzhou City, and found that the waxy corn, pea, amaranth and oat could reduce N leaching rate by 100%, 96%, 82% and 58%, respectively compared with the CK treatment.

The processes of soil N transformation are very complicated. Weather and soil properties can affect the crop uptake of water and N. The traditional field experimental method did not consider the effects of various uncertain environmental variables on crop growth and nitrate leaching. The simulation model provides a quantitative tool to evaluate the effects of catch crops on the processes of soil water movement and N transport. In the last decades, many process-based models had been used to simulate water consumption, N fates, and crop growth in agricultural systems (Jones et al., 2003; Keating et al., 2003; Kersebaum et al., 2007). However, the performance of these models in the Chinese context was not satisfactory due to various field management practices in the highly intensive agricultural production systems in North China, such as conservation tillage, double cropping system, high planting density, film mulching, and intensive water and fertilizer inputs. Recently, Liang et al. (2016a) developed the Soil Water Heat Carbon Nitrogen Simulator (WHCNS) model and the model had been successfully applied to analyze and evaluate the effects of various field management practices on soil water dynamic, fates of N, and crop growth in North China (Li et al., 2015a; Liang et al., 2016a, 2016b).

According to the survey (Ye et al., 2010), the average cumulative N amount of 0–100 cm-soil profile in greenhouse vegetable field in Dingzhou, Hebei province, reached to 815.0 kg N ha^{-1}, which is 12.3 times of the cropland, which exists a great potential risk of groundwater pollution by nitrate leaching. Currently, most studies on nitrate leaching were conducted via field experiments, few studies combined modeling approach to evaluate the effects of catch crops on nitrate leaching under high soil residual nitrate conditions.

Therefore, the objectives of this study were i) to calibrate and validate the WHCNS model using the data of two-year experiment with three catch crops in typical vegetable greenhouse in North China, ii) to evaluate the effects of these catch crops on reducing N leaching and water drainage during the summer fallow season.

2. Materials and methods

2.1. Study area

The study was conducted in south district of Dingzhou City, Hebei Province, China (38°8′ N, 115°4′ E). The soil texture is sandy loam. The average altitude is 43.6 m, and average annual sunshine time is 2427.4 h. It is a typical warm temperate and semi humid continental monsoon climate. The annual mean temperature is 13.0 °C, with average annual precipitation and evaporation 523 mm and 1910 mm, respectively. The frost free period is 190 day. The groundwater depth is about 15 m.

The greenhouse of this experiment was built in 2001, which consisted of a common wall structure, with a length of 41.3 m and a width of 6.2 m, total area of 256 m^2. The surface soil (0–20 cm) properties were: pH (1:2.5, soil/water) 7.5, organic matter 10.7 g kg^{-1}, total N 1.07 g kg^{-1}, Olsen P 275.79 mg kg^{-1} and exchangeable K 222.36 mg kg^{-1}. The physical and hydraulic properties of the soil profile in the greenhouse were shown in Table 1.

2.2. Experiment design and measurements

The greenhouse was used to plant cucumbers from January to June every year. After the harvest of cucumbers, the cover of the greenhouse was removed as common practices. The experiment consisted of four treatments: no catch crop planted during the fallow season (CK) and three catch crops treatments, i.e., sweet corn (*Zeamays L.*, SC), amaranth (*Amaranthus spp.*, A) and sweet sorghum (*Sorghum Linn.*, SG). The catch crops were planted from June 21 to September 28 in 2008 and from June 28 to October 10 in 2009, respectively. The plant densities were 6.7 plants/m^2 for SC, 10 plants/m^2 for A and SG. Because of the

Table 1
Soil physical and hydraulic properties for soil profile.

Soil layer	BD	Particle fraction (%)			θr	θs	*FC*	*WP*	*Ks*
(cm)	(g cm^{-3})	Sand	Silt	Clay	(cm^3 cm^{-3})	(cm^3 cm^{-3})	(cm^3 cm^{-3})	(cm^3 cm^{-3})	(cm d^{-1})
0-20	1.37	54	34	12	0.05	0.40	0.28	0.12	39.1
20-80	1.50	49	39	12	0.04	0.36	0.27	0.14	21.2
80-100	1.34	48	38	13	0.05	0.37	0.28	0.10	31.1

Note: BD is bulk density; θr is the residual soil water content; θs is the saturated soil water content; *FC* is the field capacity; *WP* is the wilting point; *Ks* is the saturated hydraulic conductivity.