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Managing irrigation and fertilization for the sustainable cultivation of greenhouse vegetables

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ABSTRACT

Nitrogen (N) leaching is an important factor that threatens groundwater safety in intensive greenhouse vegetable production regions. However, managing irrigation and fertilization to reduce nitrate leaching has rarely been carried out in long-term experiments. In this study, N leaching in two typical greenhouse vegetable systems (a cucumber-cucumber system in Shandong and a cucumber-tomato system in Ningxia) from 2008 to 2013 investigated should be studied using a lysimeter monitoring method. The total N fertilization rate was 0 to 2508 kg N ha^{-1} which included three treatments: no fertilizer (CK: 0 kg N ha^{-1}), conventional treatment (CON: Shandong 2508 kg N ha^{-1} and Ningxia 2239 kg N ha^{-1}) and reduced fertilizer application (RF: Shandong 2164 kg N ha^{-1} and Ningxia 1716 kg N ha^{-1}). The irrigation amount was 590–2919 mm year^{-1} according to vegetable water demand. The results indicated that the annual total N leaching were 344.8 kg ha^{-1} (192.3–508.3 kg ha^{-1}) in Shandong and 170.7 kg ha^{-1} (134.9–203.7 kg ha^{-1}) in Ningxia for the CON treatments. Compared with CON treatment, RF significantly decreased ANLL, while simultaneously maintaining the yield and increasing the downward trend of the annual TN leaching factor (ANLF) year by year. Meanwhile, a concomitant annual cost reductions associated with the RF treatment estimated at $187 million USD for Shandong and $20 million USD for Ningxia. ANLL increased linearly with the N input ($p < 0.05$). More than half of ANLL came from fertilizer N (including chemical and manure fertilizer) under CON treatments, while more than half of ANLL came from soil and water N under RF treatments. The results indicated that mitigation measures for N leaching pollution from greenhouse vegetable fields should consider regulations on irrigation and fertilization.

1. Introduction

Many regions all over the world are entirely dependent on groundwater resources for various uses (Siyal et al., 2012; Advіento-Borbe et al., 2018). Nitrate contamination of this groundwater, largely caused by agricultural nitrate leaching, is a growing problem, globally, due to population growth and increased food demand (Zhang et al., 2017) and can threaten the health of local populations (Gu et al., 2013; Huang et al., 2017). Severe nitrate contamination of groundwater is mainly associated with greenhouse vegetable cultivation, due to high rates of fertilization and irrigation (Shi et al., 2009; Zhao et al., 2010).

Vegetable production in relatively simple plastic greenhouses is an essential and rapidly growing industry in different parts of the world (Chang et al., 2011). China, in particular, has rapidly increased greenhouse vegetable cultivation over the last three decades as it is highly profitable (Yu et al., 2010). By 2010, greenhouses covered approximately 4.67 million hectares in China, accounting for 65% of the total economic value of vegetable production and comprising > 90% of the greenhouse fields in the world (Chang et al., 2013). To achieve a high level of production, the annual average N inputs from chemical fertilizers and manures were 1358 and 1881 kg N ha^{-1} respectively, and even beyond 3000 kg N ha^{-1} in North China (Ju et al., 2009; Yu et al., 2010), while the average irrigation rate was 1600–2400 mm per annum for the greenhouse vegetable systems (Sun et al., 2012).

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Table 1

Baseline soil physical and chemical properties at the start of experiment.

Sites	System	Items	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm
Shandong	Double Cucumber	NO- 3-N (mg kg^{-1})	159.7	97.8	62.9	10.4	19.3
		NH+ 4-N (mg kg^{-1})	13.9	9.7	6.8	1.3	3.2
		BD (g cm^{-3})	1.12	1.24	1.52	1.60	1.65
		SOC (g kg^{-1})	18.8	–	–	–	–
		TN (g kg^{-1})	1.3	–	–	–	–
		pH	8.3	–	–	–	–
		Clay (%)	30	29	29	28	28
		Silt (%)	51	52	53	49	50
		Sand (%)	19	19	18	23	22
Ningxia	Tomato-Cucumber	NO- 3-N (mg kg^{-1})	27.1	9.7	10.7	6.2	8.2
		NH+ 4-N (mg kg^{-1})	4.4	5.8	6.6	4.3	7.0
		BD (g cm^{-3})	1.37	1.37	1.55	1.63	1.45
		SOC (g kg^{-1})	20.7	–	–	–	–
		TN (g kg^{-1})	2.1	–	–	–	–
		pH	8.0	8.4	8.8	8.7	8.6
		Clay (%)	14	17	13	12	15
		Silt (%)	30	26	28	27	30
		Sand (%)	56	57	59	61	55

NO- 3-N: nitrate nitrogen; NH+ 4-N: ammonium nitrogen; BD: bulk density; SOC: soil organic carbon; TN: total nitrogen.

Generally, the total N uptake by vegetables is less than 400 kg N ha^{-1}, thus, fertilizer N use efficiency calculated using the subtraction method in those vegetable systems could be less than 10% with conventional management practices (Zhu et al., 2005). Excess N fertilizer applied with furrow irrigation to greenhouse vegetable fields results in nutrient accumulation in soils and substantial nitrate leaching (Thompson et al., 2007; Wang et al., 2016).

Nitrogen leaching losses from intensive vegetable systems have been identified as a major source of non-point source pollution (Shrestha et al., 2010; Min and Shi, 2018). Mounting public concern about the negative effects of excessive N fertilization and irrigation, and increasing risk of groundwater pollution, has now made it imperative to accurately quantify N leaching from agriculture (Xu et al., 2013; Delin and Stenberg, 2014) and to develop practical N-management strategies to reduce N leaching without reducing yield (Min et al., 2012; Barzegari et al., 2017).

A number of studies have been conducted to investigate N leaching from croplands (Song et al., 2009; Yang et al., 2017), but most of them focused on cereal crops. Observations regarding greenhouse vegetable systems are lacking or are based on short-term studies (Min et al., 2012). Moreover, attention was focused on the concentrations of nitrate and the amount of N leaching losses in the leachate from different fertilizer applications and irrigation (Sharmasarkar et al., 2001; Chen et al., 2014). There was no systematic analysis to build up the relationships between N leaching losses, N fertilizer rate and water input in a long-term experiment. Owing to the synthesized influences of vegetable growing conditions, soil properties, irrigation and N application, a considerable variation of annual N leaching losses exists, making it hard to characterize N leaching in cultivated lands merely on the basis of short-term experiments (Min et al., 2011a). The same conclusion was also drawn by (Li et al., 2007), believing that results obtained from short-term experiments were insufficient to explain the variations of nitrogen leaching losses from croplands in an arid or semi-arid district. There is an urgent need to investigate N leaching trends with different N application and irrigation rates in greenhouse vegetable systems and to provide practical measures to reduce N leaching, while maintaining yield in those systems.

Here, it was hypothesized that N application rate and water input have a stable relationship with N leaching, and that optimised N and water application rates could lead to less N leaching and consistent yields. In this study, we chose two typical greenhouse vegetable planting areas that are experiencing rapid growth and development: one located in Shandong Province, in which greenhouse vegetables are maintained with higher N fertilizer application (2508 kg N ha^{-1}) and irrigation rates (ranging from 1426 to 2919 mm); while the second is located in the Ningxia Hui Autonomous Region, in which N fertilizer application (2239 kg N ha^{-1}) and irrigation rates (ranging from 590 to 846 mm) are lower.

Six-year (2008–2013) field experiments were conducted under different irrigation and fertilizer regimens to determine N leaching losses using PVC lysimeters. The specific objectives of this study were: (1) to investigate the leached water and the amount of total N (TN), nitrate N (NO- 3-N), ammonium N (NH+ 4-N) and soil organic nitrogen (SON) in the leachate; (2) to define the relationships between irrigation (I) and leachate (L), and between total N application rate and N leaching losses; and (3) to decrease N leaching losses by adjusting the traditional N rates to an optimum level without yield losses.

2. Materials and methods

2.1. Study area

The field experiment was conducted in two greenhouse vegetable production areas located in Northern China: the Daotian Town, Shouguang City, Shandong Province (36.8 °N, 118.9 °E) with a system of cucumber-cucumber; and the Xingqing District, Yinchuan City, Ningxia Province (38.4 °N, 106.4 °E) with a system of tomato-cucumber.

Shandong has an average altitude of 23 m and a typical warm temperate monsoon climate with an average annual rainfall of 593.8 mm and annual temperature of 12.7℃. The experimental soil was classified as cinnamon soils with sandy loam texture. The first quarter of the cucumber growing season was from late-January to mid-July, with variety Century Star 08; the second quarter of the cucumber growing period was from early-August to late-December, with variety 787. The planting density of cucumber was 48,000 plants per hectare.

Ningxia has an average altitude of 1100 m and a typical continental monsoon climate with an average annual rainfall of 233.0 mm and annual temperature of 9℃. The experimental soil was classified as irrigation silting soils with sandy soil. The tomato growing season was from early-January to mid-June, with variety Maria; while the cucumber growing period was from early-August to late-December, with variety Del 99. The planting density of tomato and cucumber was 45,000 and 48,000 plants per hectare, respectively.

The experiments were established in 2008, with the baseline soil physical and chemical properties at the start of the experiment listed in Table 1.