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Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain

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Intensive greenhouse vegetable production systems may pose a greater nitrogen pollution threat than apple orchards or cereal rotations to soil and water quality in north China.

Abstract

The annual nitrogen (N) budget and groundwater nitrate-N concentrations were studied in the field in three major intensive cropping systems in Shandong province, north China. In the greenhouse vegetable systems the annual N inputs from fertilizers, manures and irrigation water were 1358, 1881 and 402 kg N ha^{-1} on average, representing 2.5, 37.5 and 83.8 times the corresponding values in wheat (*Triticum aestivum* L.)–maize (*Zea mays* L.) rotations and 2.1, 10.4 and 68.2 times the values in apple (*Malus pumila* Mill.) orchards. The N surplus values were 349, 3327 and 746 kg N ha^{-1}, with residual soil nitrate-N after harvest amounting to 221–275, 1173 and 613 kg N ha^{-1} in the top 90 cm of the soil profile and 213–242, 1032 and 976 kg N ha^{-1} at 90–180 cm depth in wheat–maize, greenhouse vegetable and orchard systems, respectively. Nitrate leaching was evident in all three cropping systems and the groundwater in shallow wells (<15 m depth) was heavily contaminated in the greenhouse vegetable production area, where total N inputs were much higher than crop requirements and the excessive fertilizer N inputs were only about 40% of total N inputs.

Keywords: Nitrogen balance; Wheat–maize rotations; Greenhouse vegetables; Apple orchards; Groundwater nitrate contamination; North China Plain

1. Introduction

There has been a strongly increasing trend towards the growth of crops of high economic value (including vegetables and fruit trees) in China over the last 20 years. From 1980 to 2002 the area under cereal crops stabilized at about 110 M ha but the area under vegetables increased from 3.16 to 17.35 M ha and under fruit trees from 1.78 to 9.10 M ha (China Agricultural Yearbook, 1981–2003). However, there has been poor development of rational fertilizer recommendations in the areas with rapidly expanding production systems, with the result that farmers usually apply large amounts of N fertilizers and organic manures in order to ensure high yields. A systematic investigation conducted in Shandong province in 1997/1998 found that the average N fertilizer rate was 280 kg N ha^{-1} in 957 winter wheat fields, 208 kg N ha^{-1} in 896 summer maize fields, 1700 kg N ha^{-1} per crop in 147 protected vegetable fields (plastic film greenhouses), and 848 kg N ha^{-1} in 217 apple orchards (Ma, 1999). Excessive N fertilizer application is therefore very common, especially in intensive vegetable and fruit producing areas, and might be expected to lead to nitrate pollution of groundwater.

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In a European study, the nitrate concentration in groundwater samples from 22% of the agricultural area exceeded the threshold recommended by the World Health Organization (50 mg NO_3 L^{-1}) for drinking water (Laegreid et al., 1999). Legislation has been introduced to enforce the control of N balance on a farm scale in some European countries to control nitrate pollution of groundwater (Eichler and Schulz, 1998). In a US study conducted in Wisconsin, NO_3^--N concentrations exceeding 10 mg N L^{-1} (the threshold for drinking water set by the US Environmental Protection Agency) were found in 10% of 800,000 wells, and 17–26% of wells in the agricultural production areas exceeded the limit (Postle, 1999). Nitrate contamination in groundwater is closely related to the corresponding agricultural management practices (Keeney and Follett, 1991; Rass et al., 1999). Using ^{15}N tracer techniques, Townsend et al. (1996) found that high nitrate-N concentrations (12–60 mg N L^{-1}) in groundwater in the southwest of Kansas resulted from high application rates of N fertilizer to sugar beet fields. Thorburn et al. (2003) investigated groundwater nitrate-N concentrations in intensive agriculture areas of northeast Australia using ^{15}N techniques and found that 14–21% of the wells were contaminated by nitrate, and in about half of these the nitrate was derived from N fertilizer application. A survey of groundwater nitrate-N concentrations conducted by staff of the Chinese Academy of Agricultural Science in the provinces of Beijing, Tianjin, Hebei, Shandong and Shanxi showed that about 45% of 600 groundwater samples exceeded the WHO and European limit for nitrate in drinking water of 11.3 mg NO_3^--N L^{-1} (50 mg NO_3^- L^{-1}), with the highest nitrate-N concentration reaching 113 mg L^{-1} (Zhang et al., 2004). The proportion of samples above the limit was much higher in intensive vegetable farming regions than in other cropping areas. However, there have been few systematic studies comparing the impacts of different cropping systems on soil nitrate accumulation and groundwater contamination in China, and there is an urgent need for reliable information on N losses to the environment in different intensive cropping systems.

High nitrate accumulation and the free flow of water in the soil profile are pre-conditions for nitrate leaching into the subsoil or groundwater. Residual nitrate can move continuously downwards and be lost even if it is not leached during the season of application. Davies and Sylvester-Bradley (1995) found that the annual amount of NO_3^--N leached in agricultural land in Britain increased by 36 kg N ha^{-1} over a 50-year period and one-third was derived from residual nitrate. Another study showed that 68% of NO_3^--N accumulation occurred outside the rooting zone and 20% of NO_3^--N accumulation in the root zone in the soil profile moved into groundwater annually (Yadav, 1997). In addition to environmental factors such as climate and soil properties, nitrate leaching is also strongly affected by management practices such as fertilizer application, irrigation and planting patterns. Differences in the N uptake capacity of crops, fertilizer management, and irrigation in different cropping systems may lead to different patterns of nitrate accumulation in the soil profile. In particular, when the N application rate exceeds crop demand, considerable nitrate accumulation occurs in the soil profile (Granstedt, 2000; Ju et al., 2004). Accumulated nitrate is prone to leaching into the subsoil after high irrigation rates or heavy rainfall (Ju et al., 2003), and thus irrigation agriculture poses a high risk of groundwater nitrate contamination when combined with high fertilizer and water inputs (Diez et al., 2000; Stites and Kraft, 2000). The relationships between soil nitrate accumulation and groundwater nitrate concentrations in different cropping systems are still not fully understood.

Calculation of N balance is one potentially useful method for predicting the risk of nitrate leaching into groundwater (Barry et al., 1993; Puckett et al., 1999). Many factors influence the degree to which different inputs and outputs can maintain soil fertility while minimizing environmental pollution (Schroder et al., 1996; Parris, 1998). A study by Schleef and Kleihanss (1994) indicated that 100 kg ha^{-1} of annual N surplus could be regarded as a baseline for nitrate leaching into ground- or surface-water on a regional scale. The climate on the North China Plain is warm-temperate subhumid continental monsoon, with cold winters and hot summers. The annual cumulative mean temperature for days with mean temperatures over 10 °C is 4000–5000 °C and the annual frost-free period is 175–220 days (Sun et al., 1994). Taking into account the abundance of solar radiation and the high temperatures, shortages of water and nutrients are the main limiting factors for adequate crop yields (Zhu et al., 1994; Sun et al., 1994). The annual precipitation is 500–700 mm, with 60–70% of the rainfall occurring during summer (June–August). The amount and distribution pattern of rainfall vary widely among years as affected by the continental monsoon climate. Farmers in this region usually irrigate with large amounts of water and apply large amounts of N fertilizer to obtain high yields (Chen, 2003). These practices lead to a large accumulation of nitrate in the soil profile. The accumulated residual nitrate is readily leached down to deeper soil layers during the summer maize growing season due to heavy rainfall, resulting in the pollution of shallow surface water bodies (Zhang et al., 1996; Liu et al., 2003). The objectives of the present study were therefore to compare the N balance, soil nitrate accumulation and groundwater nitrate contamination in three typical intensive cropping systems in order to understand the impacts of changes in crop N management practices on the environment.

2. Materials and methods

2.1. Site description

Huimin County, Shandong province was selected as the study site because it was considered to be representative of the intensive agricultural areas on the North China Plain. The site is located on the north shore of the lower reaches of the Yellow River in the northeast of Shandong province on the alluvial plain at 37°6′–37°36′ N, 117°16′–117°49′ E. There is an area of flat agricultural land of 73,480 ha with a mean altitude of 12.8 m and a gradient of 1:6000 at ground surface. The average temperature is 12.3 °C with 182 frost-free days each year. Annual average precipitation is 578 mm (over a recent 30-year period), of which 61–84% occurs between June and August. The annual