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Spatial characteristics of nitrogen flows in the crop and livestock production system of Shanxi Province, China

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ABSTRACT

Nitrogen (N) use and flows in agriculture are largely related to the spatial distributions of crop and animal production systems. However, only limited quantitative information on the spatial variation is available related to nutrient flows, losses, and use efficiencies for crop–animal production systems. In this study, we comprehensively and quantitatively analyzed the N flows, losses, and use efficiencies (NUE) in the crop and animal production systems of Shanxi Province by using the simulation model — Nutrient flows in Food chains, Environment and Resources use (NUFER). Data were coupled with a geographical information system and a large, detailed statistical database collected from 11 municipalities of Shanxi Province in 2012. The results were classified into three production system levels, i.e., crop, animal, and crop–animal production systems.

First, crop production systems of Shanxi created a total N input of 953 Gg (equivalent to 240 kg/ha) in 2012, with fertilizer as the largest input source, accounting for 59.2% of the total N input. Overall, southern regions of Shanxi experienced significantly higher N input than northern Shanxi. For example, the crop production N input of Yuncheng and Linfen municipalities was 178 and 143 Gg (equivalent to 320 kg/ha and 289 kg/ha), respectively; however, the N input of Taiyuan and Yangquan municipalities was 27 and 13 Gg, respectively. The harvested N from crop production was 110 Gg in Yuncheng and only 7 Gg in Yangquan. The large and varied N surpluses from the crop production systems across municipalities ranged from 74 to 150 kg/ha, potentially creating the risk of environmental pollution and highlighting an urgent need to improve N management in the crop production system. Second, the total N input in the animal production systems also varied widely across the municipalities, ranging from 65 kg/ha in Xinzhou to 187 kg/ha in Jincheng municipality. The harvested N from animal production was the highest (16 Gg) in Shuozhou and lowest in Yangquan (1 Gg), among all the municipalities. Third, the N input to the crop–animal production system of Shanxi was 1000 Gg in 2012 and among all the municipalities, was highest in Yuncheng (167 Gg), and lowest in Yangquan (12 Gg). Large amounts of N (425 Gg) were released from crop residues and animal excreta, but only 47% of this (200 Gg) was recycled to the cropland. Overall, the NUE of crop production (NUEc), animal production (NUEa), and coupled crop–animal production (NUEc + a) was 36%, 20%, and 15%, respectively. These low NUEs were mainly caused by the excessive N input during crop production and the low recycling rate of N from crop residues and animal excreta. The total N losses from crop–animal production were 610 Gg, accounting for 61% of total N input. Of the total N losses, 41.4%, 30.6%, 26.8%, and 1.2% were lost via NH_3 volatilization from cropland and animal manure, the combined effects of runoff, erosion, and leaching from cropland and manure, de-nitrification from cropland, and N_2O emissions from cropland, respectively. In addition, N flows varied widely at the regional scale, e.g., N input and loss were significantly higher in the southeast than in the northwest. Large amount of straw residues and animal manure in Jincheng was used as nutrient input to the croplands in Yuncheng and Linfen, which are the two major agricultural regions. In conclusion, a quantitative understanding of the spatial distribution of nutrient flows, losses, and use efficiencies in the crop–animal system is necessary for improving the productivity and sustainability of agriculture while minimizing environmental impacts. N management should be optimized in both crop–animal production systems and at regional levels to significantly improve the NUE of Shanxi Province; this will reduce the risk of environmental pollution and ensure the sustainable development of agriculture.

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1. Introduction

Nitrogen (N) lies at the core of integrated nutrient resource management [1]. The application of N fertilizer allows the world to be capable of feeding 48% more of the population [2], and China is able to solve the problem of feeding 1.37 billion people [3]. Meanwhile, the continuous increase in N input to farmland ecological systems has caused a series of problems, including wasted resources, environmental degradation and negative effects on human health. For example, volatilization of ammonia releases N_2O into the atmosphere, causing air pollution [4]. Through runoff, erosion and leaching, N enters into surface water, causing water pollution [5]. Surplus N frequently enters into the ecosystem, further endangering human health [6]. China has the world's largest livestock population that produces large amounts of manure annually [7]. However, livestock excreta that are mainly produced in intensive animal farming facilities cannot be returned to farmland as organic fertilizers; this causes not only a huge amount of nutrient loss, but also poses a serious threat to the environment [8]. Therefore, the State Council of the People's Republic of China has initially issued *Regulations on the prevention and treatment of pollution from large-scale livestock farming* (State Council Decree No. 643), to provide standards and to constrain nutrient loss and environmental emissions caused by livestock manure from large-scaled animal farming. Accordingly, characterizing N flows in regional scale crop and livestock farming systems, along with analyzing existing problems and proposing appropriate mitigation and countermeasures will provide practical and significant guidelines for achieving regional integrated nutrient resource management, improving N use efficiency (NUE), and protecting the environment.

In recent years, a large number of studies related to N flows in regional scale farming systems have been conducted both in China and abroad. In Germany, Isermann [9] initially considered the entire system of crop production and food consumption an established N cycling and N mass model for German farms, including aspects of animal husbandry, production processing, farm family activities, waste treatment, and environment systems; these findings were used to examine N flows and emissions in the German food production and consumption system from 1958 to 1998, and to estimate biomass productivity and NUE. Bouwman [10] investigated N flows in the farmland/livestock system from 1900 to 2050 on a global scale, and showed that most surplus N in the system had negative environmental impacts. In China, Chen et al. [11] applied fully integrated N balance and N flow models for the farming–feeding system in China (NFM-FFS) to examine and study N flows and related environmental effects in China's farming–breeding system in 2003; they reported that human activity was the most important factor affecting ecosystem balance, whereas nitrification–denitrification was the most important aspect of the N loss pathway. Hou et al. [12] applied nutrient flow analysis and modeling to characterize N flows in the farmland–livestock production system in the suburbs of Beijing; they showed that currently NUE in the farmland–livestock production system was relatively low, and nutrient recycling from waste was an effective means of reducing the loss of environmental nutrients from the system. Zhang et al. [13] studied the features of N and phosphorus flows in crop and livestock production of Hebei Province and their regulatory pathways; they pointed out a series of current issues related to N management, including excessive exogenous N input, low N use efficiency, poor nutrient cycling, high environmental emissions, and loose integration between crop and livestock production, and made various recommendations based on scenario analysis. Ma et al. [14] applied modeling and material flow analysis to systematically examine regional N flows in the food production and consumption system of the Huang-Huai-Hai area, and showed that with the rapid development of animal husbandry this area, the long-term regional accumulation of animal waste derived from N in animal feed would cause serious environmental problems in the near future.

These above studies have quantitatively characterized N flows in the crop–livestock system on different scales. However, studies on the spatial change in regional N input–output budgets on a provincial scale have been scarce. In particular, no relevant study on any province has addressed situations where resource-based industry serves as the leading industry of an area (e.g., Shanxi). Shanxi has a complex topography with very variable climates both with changes in elevation and between northern and southern parts of the province. The province features diverse planting and land use patterns as well as soil types. Crop and livestock production are relatively tightly coupled. In addition, the social economy in Shanxi has reached a critical stage of development, transformation, and integration. Therefore, in the present study, using the Nutrient flows in Food chains, Environment and Resources use (NUFER) model, combined with statistical yearbook data and existing research results, we systematically characterized the spatial variance in N flows in the crop–livestock production system of Shanxi Province under a variety of complex natural and social conditions. In addition, we explored the relevant factors influencing N flows to provide a basis for the development of government regulations related to nutrient resource management, and to provide technical support for future regional nutrient management.

2. Materials and methods

2.1. Study area

Shanxi Province, an inland province, encompasses much of the Loess Plateau on the east bank of the middle reaches of the Yellow River, west to the North China Plain, 34°34′–40°244′N, 110° 14′–114°33′E, with a land area of 156,000 km^2 (Fig. 1). Shanxi Province includes 11 municipalities and 119 county-level administrative regions, with a total population of 36,108,000 (2012). Mountains and rivers surround the periphery of Shanxi Province, creating clear natural landmarks as borders with the neighboring provinces (regions). In the north, neighboring Hebei Province is delineated by the Taihang Mountains. To the west and south, Shaanxi and Henan provinces lie across the Yellow River. In the north and northwest, it borders the Inner Mongolian connection with the Outer Great Wall.

Shanxi is a typical mountain plateau widely covered by loess. Elevations vary from high in the northeast to low in the southwest. Most regions of the province stand at elevations over 1500 m a.s.l., with a range from 180 m to 3061.1 m. Inside this plateau rivers and valleys cross the undulating terrain creating complex and diverse landforms. Mountains and hills cover 80.1% of the province, while plains and valleys account for the remaining 19.9%. Two primary river systems, the Yellow and Haihe rivers, are fed by more than 100 rivers of Shanxi Province, with six river basins: the Datong, Xinding, Taiyuan, Luan, Linfen and Yuncheng basins.

The temperate continental monsoon climate of Shanxi shows substantial elevational and south–north differences. Generally, the climate features long, cold and dry winters with rainfall concentrated in the long or short summers in the south and north, respectively. Obviously, climatic conditions vary across the province. Rather frequent sandstorms occur in spring; the short autumn season typically brings mild weather. The province experiences plenty of sunshine and has abundant heat resources. Severe weather events occur frequently, and local people say “nine years with drought in ten.” Temperatures fluctuate dramatically between day and night. Cinnamon soil dominate and account for 49.8% of the province's total area [15], while other soil types include chestnut, skeletal, loessial and fluvo-aquic soils.

The Datong, Xinding, Taiyuan, Linfen and Yuncheng basins are major agricultural areas in Shanxi. Main crops include maize, wheat, sorghum, millet, beans and tubers while cash crops include cotton, tobacco, sugar beets and flax. In recent years, the Shanxi provincial government has attached great importance to the development of animal husbandry, an industry that has shifted from the “backyard mode” featuring “every household engaging in sideline production by having two sheep and one pig” in the past to large-scale intensive farming. From the starting