Science of the Total Environment 434 (2012) 51–61

Contents lists available at SciVerse ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Nitrogen and phosphorus use efficiencies and losses in the food chain in China at regional scales in 1980 and 2005

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ARTICLE INFO

Article history:
Received 5 June 2011
Received in revised form 12 December 2011
Accepted 8 March 2012
Available online 28 April 2012

Keywords:
Integrated assessment
Nutrient cycling
Food consumption
Nutrient use efficiency
Crop production
Animal production

ABSTRACT

Crop and animal production in China has increased significantly during the last decades, but at the cost of large increases in nitrogen (N) and phosphorus (P) losses, which contribute to ecosystem degradation and human health effects. This information is largely based on scattered field experiments, surveys and national statistics. As a consequence, there is as yet no comprehensive understanding of the changes in N and P cycling and losses at regional and national scales.

Here, we present the results of an integrated assessment of the N and P use efficiencies (NUE and PUE) and N and P losses in the chain of crop and animal production, food processing and retail, and food consumption at regional scale in 1980 and 2005, using a uniform approach and databases. Our results show that the N and P costs of food production–consumption almost doubled between 1980 and 2005, but with large regional variation. The NUE and PUE of crop production decreased dramatically, while NUE and PUE in animal production increased. Interestingly, NUE and PUE of the food processing sector decreased from about 75% to 50%. Intake of N and P per capita increased, but again with large regional variation. Losses of N and P from agriculture to atmosphere and water bodies increased in most regions, especially in the east and south of the country. Highest losses were estimated for the Beijing and Tianjin metropolitan regions (North China), Pearl River Delta (South China) and Yangzi River Delta (East China).

In conclusion, the changes and regional variations in NUE and PUE in the food chain of China are large and complex. Changes occurred in the whole crop and animal production, food processing and consumption chain, and were largest in the most populous areas between 1980 and 2005.

1. Introduction

Nitrogen (N) and phosphorus (P) are key elements for the growth and functioning of plants, animals and humans. Sub-optimal supply leads to poor growth and/or malfunctioning, while over-optimal supply may also lead to malfunctioning and, worse to increased N losses to air and waters and P losses to waters (e.g. Marschner, 1995; Suttle, 2010). Hence, there has been a constant search for finding the optimum N and P application levels, basically from the foundation of the mineral theory of plant nutrition in the 1840s. However, the increased availability of cheap fossil energy, needed for N and P fertilizer production, and the rapidly increasing demand for crop and especially animal-derived food by the increasing human population have led to over-use of N and P in crop and animal production in various parts of the world from the second half of the 20th century. It has also led to the neglect of N and P in animal manures, crop residues and human wastes, and to low use efficiencies of N and P. As a result, N and P losses to air and waters have increased dramatically and have led to a series of environmental, ecological and human health effects, which are of concern especially in areas with large populations and intensive agriculture (Conley et al., 2009; Townsend et al., 2003; Galloway et al., 2008; Smil, 2000; Tilman, 1999; Bouwman et al., 2009; Cordell et al., 2009; Villalba et al., 2008).

In China, crop production has greatly increased from the 1980s, mainly due to the use of improved crop varieties and the use of more fertilizers, pesticides and irrigation water. For example, the average N application for the winter wheat–summer maize double cropping system in the North China Plain increased nearly 5 times in the past 30 years (Zhen et al., 2006; Cui et al., 2008a, 2008b). Also, animal production has greatly increased, largely on the basis of increased imports of animal feed. The increased amounts of N and P in animal manures and crop residues have been largely neglected as a nutrient source in China, while fertilizer use has increased much more than N and P withdrawal with harvested crop (Gao et al., 2006). Further, there are

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doi:10.1016/j.scitotenv.2012.03.028

inefficiencies in food processing, retail and households. In 2005, a total 11 kg of N was needed to provide 1 kg of protein N on the plate of the Chinese consumers, while 10 kg of N was wasted in the crop and animal production–food processing–food consumption chain (Ma et al., 2010). As a consequence, N and P losses to air and waters are large and have contributed to severe environmental degradation (Liu and Diamond, 2005, 2008; Ma et al., 2008).

Though the general picture is rather clear, there are large regional differences, which are less quantified and understood. For example, in western China, fertilizer use is much lower than in the eastern half. In some areas, crop residues are used for animal feed or fuel, while animal manure is also used as fuel, and these areas may witness soil nutrient depletion (Gao et al., 2006). Further, animal production has moved in part from the rural areas to urban areas, close to the food processing industry and main food consumption centers (Xie, 2005). Various reports indicate that mean total annual N losses may range from 5 kg N ha^{-1} in the province Qinghai to 243 kg N ha^{-1} in the province Sichuan (Wang et al., 2010). However, these estimates have been derived in various ways from only a part of the food chain and no estimate exists for many other provinces. Hence, estimates of N and P use efficiencies and N and P losses in the food production–consumption chains at regional scales are either partial, uncertain or lacking.

The aim of the research presented in this paper was to assess the N and P use efficiencies (NUE and PUE) in the food production–consumption chains, and the N and P losses from crop and animal production at regional level in 1980 and 2005. Provinces were chosen as the basis for regions, because of data availability. The year 1980 was chosen as it is generally seen as the start of rapid economic growth and increased fertilizer use. The year 2005 was the most recent year for which we had access to data at the start of this research. The findings of this study are based on the integrated assessment modeling tool NUFER (Nutrient flows in Food chains, Environment and Resources use) (Ma et al., 2010), statistical databases and farm surveys.

2. Materials and methods

2.1. Brief description of agriculture in the 31 provinces

Fig. 1 depicts the sizes of the human and animal populations and the areas of cultivated land in the 31 provinces of China. Slightly more than 10% of the total land area is used for intensive crop production, most in the east. The other 90% is largely desert, mountainous and/or forest, used in part for (very) extensive production, and urban and infrastructural areas. The highest human population density is found in the Beijing and Tianjin metropolitan regions, Pearl River Delta and Yangzi River Delta. Animal density is presented in terms of biomass per hectare cultivated land. We made a distinction between traditional smallholder systems, pastoral (grazing systems) and landless industrial systems. A very high animal density is found around big cities (i.e., Beijing, Shanghai and Guangzhou), but rural areas in the East and Southeast with traditional smallholder systems have also high animal density. Low-density grazing systems are found in the 5 main pastoral districts: Inner Mongolia, Gansu, Qinghai, Tibet, and Xing Jiang. We considered these grasslands as natural ecosystem and not as agricultural land, which obviously leads to an over-estimation of animal density in these areas.

2.2. General description of NUFER model

Balances and use efficiencies of N and P in the food production–consumption chain, and N and P losses via NH_3 and N_2O emissions, denitrification and N and P leaching, runoff and erosion were calculated by NUFER (Ma et al., 2010). NUFER is a deterministic and static model that calculates N and P inputs and outputs in crop and animal production and food processing, retail and consumption at the regional scale on an annual basis (Ma et al., 2010). The food chain in each region (province) and for the whole of China was perceived as a 'pyramid' with four main compartments, namely (i) crop production (including the rootable soil layer, i.e., the upper 1 m of soil), (ii) animal production (including managed aquaculture), (iii) food processing and retail, and (iv) households (Fig. 2). New N and P enter the pyramid via fertilizers, biological N_2 fixation and via imported products (from other regions or countries). Nitrogen and P leave the pyramid via exported products and via losses to air and waters. There are exchanges of N and P within the pyramid between the compartments via crop and animal products, and also between the food pyramids of different regions. Natural grasslands, rough grazings, forests, lakes and seas are perceived as natural ecosystems, and the products harvested from these systems are considered as inputs to the pyramid. Grasslands and lakes were considered part of the food pyramid when the harvested yields of these systems were increased through management interactions (i.e., managed grasslands, fish ponds). Further, a distinction was made between 'new' N (imported from outside the pyramid, through bio-fixation, fertilizers, and products from natural grass and fish from natural waters), and 'recycled' N (from recycled material within the pyramid, such as manure, crop residues, wastes, etc.).

NUFER was used to analyze the N and P use efficiencies and losses in each compartment of the food chain at regional level in 1980 and 2005, using the equations listed below (see also Ma et al., 2010).

2.3. Calculations of N and P use efficiencies, surpluses and losses

Nitrogen use efficiency in crop production (NUEc) and animal production (NUEa) were defined by the ratio of N output in (main) products and the total N input into crop and animal production (Ma et al., 2010):

$$\mathrm{NUEc} = \left(\mathrm{Oc}_{\mathrm{main\ product}}/\mathrm{Ic}_{\mathrm{Total}}\right) \times 100\% \quad (1)$$

$$\mathrm{NUEa} = \left[\left(\mathrm{Oa}_{\mathrm{Meat}} + \mathrm{Oa}_{\mathrm{Egg}} + \mathrm{Oa}_{\mathrm{Milk}}\right)/\mathrm{Ia}_{\mathrm{Total}}\right] \times 100\% \quad (2)$$

where

Oc output from crop production,
Ic input to crop production,
Oa output from animal production,
Ia input to animal production,
$\mathrm{Ic}_{\mathrm{Total}}$ $\mathrm{Ic}_{\mathrm{fertilizer}} + \mathrm{Ic}_{\mathrm{Irrigation}} + \mathrm{Ic}_{\mathrm{Deposition}} + \mathrm{Ic}_{\mathrm{BNF}} + \mathrm{Ic}_{\mathrm{Seed}} + \mathrm{Ic}_{\mathrm{manure}} + \mathrm{Ic}_{\mathrm{wastes}} + \mathrm{Ic}_{\mathrm{By\text{-}products}}$
$\mathrm{Ia}_{\mathrm{Total}}$ $\mathrm{Ia}_{\mathrm{Main\ crop\ products}} + \mathrm{Ia}_{\mathrm{By\text{-}products}} + \mathrm{Ia}_{\mathrm{Crop\ residues}} + \mathrm{Ia}_{\mathrm{Grass}} + \mathrm{Ia}_{\mathrm{Animal\ by\text{-}product}} + \mathrm{Ia}_{\mathrm{Kitchen\ residue}} + \mathrm{Ia}_{\mathrm{Residue\ feed}}$
$\mathrm{Ic}_{\mathrm{fertilizer}}$ input via single and compound fertilizers,
$\mathrm{Ic}_{\mathrm{Irrigation}}$ input via irrigation and flooding,
$\mathrm{Ic}_{\mathrm{Deposition}}$ input via atmospheric deposition,
$\mathrm{Ic}_{\mathrm{BNF}}$ input via biological N_2 fixation,
$\mathrm{Ic}_{\mathrm{Seed}}$ input via seed,
$\mathrm{Ic}_{\mathrm{manure}}$ input via animal manure,
$\mathrm{Ic}_{\mathrm{wastes}}$ input via human wastes (excrements),
$\mathrm{Ic}_{\mathrm{By\text{-}products\ plant\ food\ processing}}$ input via residues from food processing sector (cakes and meals),
$\mathrm{Ia}_{\mathrm{Main\ crop\ products}}$ input via grain and roots,
$\mathrm{Ia}_{\mathrm{By\text{-}products\ food\ processing}}$ input via by-products of the processing of crop products,
$\mathrm{Ia}_{\mathrm{Crop\ residues}}$ input via crop residues,
$\mathrm{Ia}_{\mathrm{Grass}}$ input via grass from natural grasslands,
$\mathrm{Ia}_{\mathrm{Animal\ by\text{-}product}}$ input via animal bones and other animal by-products of food processing,
$\mathrm{Ia}_{\mathrm{Kitchen\ residue}}$ input via kitchen residue, and
$\mathrm{Ia}_{\mathrm{Residue\ feed}}$ input from rough grazings and forests.

Eqs. (1) and (2) were also used in the calculation of P use efficiency in crop production (PUEc) and animal production (PUEa).