Nutrient use efficiency in the food chain of China

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Thesis committee

Promotor
Prof. Dr O. Oenema
Professor of Nutrient Management and Soil Fertility
Wageningen University

Co-promotors
Dr G.L. Velthof
Senior scientist, Alterra
Wageningen University and Research Centre

Prof. Dr F. Zhang
Professor of Plant Nutrition
China Agricultural University, Beijing, China

Other members
Prof. Dr C. Kroeze, Wageningen University
Prof. Dr I.J.M. de Boer, Wageningen University
Prof. Dr A.F. Bouwman, Utrecht University
Dr M. Roelcke, Braunschweig University of Technology, Germany

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Abstract

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Nitrogen (N) and phosphorus (P) fertilizer applications have greatly contributed to the increased global food production during the last decades, but have also contributed to decreasing N and P use efficiencies (NUE and PUE) in the food production - consumption chain, and to increased N and P losses to air and water, with major ecological implications.

The aim of this thesis is to increase the quantitative understanding of N and P flows and losses in the food production - consumption chain in China at regional level in the past 30 years and to develop strategies to increase NUE and PUE in the food chain. A novel 'food chain' approach and the NUFER model were developed to analyse N and P flows in crop production, animal production, food processing and retail, and households. Data were derived from statistical sources, literature and field surveys.

Between 1980 and 2005, NUE and PUE decreased in crop production, increased in the animal production and decreased in the whole food chain. Total N losses to water and atmosphere almost tripled between 1980 (14.3 Tg) and 2005 (42.8 Tg), and P losses to water systems increased from 0.5 to 3.0 Tg. There were significant regional differences in NUE, PUE, and N and P losses; regions with high N and P losses were in Beijing and Tianjin metropolitans, Pearl River Delta, and Yangzi River Delta. Urban expansion is a major driving force for change; total N losses increased 2.9 folds, and P losses increased even 37 folds during the development of Beijing metropolitan, between 1978 and 2008. Scenario analyses indicated that implementation of a package of integrated nutrient management measures, combined with diet changes and increased imports of animal food and feed, are the most effective management options for increasing NUE and PUE, and for decreasing N and P losses.

Application of the food chain approach and the NUFER model can help policy makers in China to plan food production - consumption chains, and thereby manage N and P flows in this chain at regional level.

Key words: Nitrogen, phosphorus, food chain, food pyramid, food system, food security, food cost, environmental impacts, nutrient cycling, nutrient management

Contents

Parts of this thesis have been published as peer-reviewed scientific articles. For this thesis, the text of the published articles or the submitted manuscript has been integrally adopted. Editorial changes were made for reasons of uniformity of presentation in this thesis. Reference should be made to the original article(s).

CHAPTER 1

General introduction

1.1 Background

Nitrogen (N) and phosphorus (P) are essential nutrients for the growth and development of plants and animals, and are hence critical for the production of sufficient nutritional food for the increasing world population (Smil, 2000a). However, the increased use of N and P for food production, especially during the last decades has also resulted in increased losses of N and P to atmosphere and water systems with severe environmental impacts regionally (Conley et al., 2009; Galloway et al., 2008). The changes of N and P uses and their environmental impacts follow from changes in human population and their diets, urbanization, agricultural practices and waste recycling (Bouwman et al., 2011).

In the past century, the scientific and societal debates about 'resource use' have focused on water, land and fossil energy in relation to sustainable food and energy consumption, and the debate about 'environment' has centered on CO_2 emissions in relation to climate change (Tilman et al., 2011; Tilman et al., 2002). However, it becomes increasingly clear that alteration of the world's N and P cycles represents a major emerging challenge for the twenty-first century. The pollution via excess reactive N poses an equivalent important challenge as the carbon-CO_2 challenge, since N has many complex effects as it cascades through many chemical forms (Sutton et al., 2011). In addition, modern food production is dependent on P derived from phosphate rock, and phosphate rock is a non-renewable resource, which may be depleted in 100 to 300 years (Cordell et al., 2009; Gilbert, 2009; IFDC, 2010).

The recent report "Our Nutrient World" summarized the global challenges related to nutrient management (Sutton et al., 2013), as follows:

- There is an urgent need to develop joined-up approaches to optimize the planet's nutrient cycles for delivery of our food and energy needs, while reducing threats to climate, ecosystem services and human health;
- Such joint-up approaches must take account of local and regional conditions and focus on a shared aim to improve nutrient use efficiency;
- Efforts should be made to quantify 'Full-chain nutrient use efficiency', together with the component terms, to incorporate all influences and opportunities for improvement; and
- The intergovernmental institutional options to improve management of regional and global nutrient cycles need to be further explored.

Before the Green Revolution, our society managed to produce food for about one-third to one-half of the current population using traditional farming practices. Emphasis was put on efficient utilization of all possible resources of organic manures aiming at the recycling of nutrients from animal manures, human excreta, crop residues, cooking ash, and compost in ‘crop-animal’ mixed farming systems. Currently, the global society is in a rapid transition from a society relying on nutrient recycling to a society relying on external nutrient inputs, which provide high crop yields but also high nutrient losses (Tilman et al., 2001). It has been postulated that current societies can learn from the past; nutrient use efficiencies can be increased through improved recycling of N and P from animal manures, human excreta, crop residues, cooking ash, and compost. The potential impact of such transition is as yet unclear, because of the lack of insight in the potentials for recycling and its impacts on N and P use efficiencies in the food production-consumption chain.

China is strongly facing the aforementioned challenges related to nutrient use. It is the most populous country in the world and in a rapid economic, social and cultural transition. Its agriculture, and in particular its crop production and animal production sectors, have transformed from traditional, but environmental sound systems, to high-input and high-output systems, with high nutrient losses. The N and P use efficiencies have decreased and environmental problems related to N and P losses have increased greatly (Liu et al., 2013; Qu and Kroeze, 2010; Vitousek et al., 2009). Forecasts indicate that the Chinese population will increase further from 1.3 billion in 2005 to about 1.5 billion in 2030 (United Nations, 2010). In the same period, the ratio of the urban to rural populations will be reversed from 1:2 to 2:1, and the proportion of animal-derived protein in human diets will increase further (United Nations, 2010). However, there are large differences between regions.

The N and P use efficiency of the food production - consumption chain in China at national and regional level is not well-quantified, and the factors that affect the N and P use efficiency are not well-understood. There is a need to increase the understanding of how human’s activities affect nutrient flows in food the production and consumption chain. There is also a need for improved management strategies to increase nutrient use efficiency and decrease nutrient losses from the food chain (Zhang et al., 2005).

1.2 Nutrient management at regional and national levels

Nutrient management at farm and field levels has been defined as achieving agronomic and environmental objectives through an iterative series of six consecutive steps: analysis, decision making, planning, execution, monitoring and evaluation. It requires proper systematic analysis of nutrient budgets, nutrient cycling and losses. Based on the analyses, the best options need to be selected, planned and implemented by farmers. Then, the yield and nutrient losses need to be monitored and evaluated (Oenema and Pietrzak, 2002). Such a concept has not been defined and described at regional levels yet. Nutrient management at regional level is important and necessary, because without coherent and sound nutrient management strategies at regional and national levels, the objectives of nutrient management in the food chain cannot be achieved, and thereby the objectives at farm level.

At the regional level, there are multiple actors, including farmers, industries, retailers, households, and policy makers, all with different goals. Managing the flows of nutrients in crop and animal products between farmers and consumers and vice versa, within or among regions, requires that these flows are quantified and understood. The exchange of nutrients in crop and animal by-products and wastes (e.g. animal manure and crop residues etc.) among farms also requires monitoring and assessment at regional level. Markets and governmental policies will fail to improve nutrient management at regional level, if there is lack of adequate information, tools and incentives. Therefore, nutrient management at regional level should start with analysing nutrient flows and budgets in the food production and consumption chain, for achieving the objectives of providing sufficient food, and minimizing nutrient losses at regional level simultaneously.

1.3 Analyses of nutrient flows in the food chain at regional and national levels

Material flow analysis has been used to analyse resource use at a wide range of geographical scales, to aid environmental management in the field of (industrial) ecology (Ayres and Ayres, 2002; Brunner and Rechberger, 2004). Nutrients, in particular N and P, have been the subject of many material flow analysis studies by agronomists, environmentalists and ecologists, with different objectives and also perspectives.

Agronomists focus especially on the effectiveness and efficiency of fertilizer and manure use, using nutrient balances at different spatial and temporal scales (e.g., Bouwman et al., 2009; Liu et al., 2010; MacDonald et al., 2011; Potter et al., 2010), also for identifying nutrient limited crop production and yield gaps (Foley et al., 2011; Vitousek et al., 2009).

Environmentalists focus on N and P losses and their environmental impacts (Galloway et al., 2003; Galloway et al., 2008; Smil, 2000b; Smil, 2002). Also, they assess the N cost and P cost of food production (Galloway et al., 2002; Liu et al., 2008; Villalba et al., 2008). Increasingly, they focus on N and P losses from intensive livestock productions and their environmental impact (Bouwman et al., 2011; Pelletier and Tyedmers, 2010).

Ecologists tend to focus on resource use, depletion and scarcity (Van Vuuren et al., 2010). Opportunities for improving the use efficiencies of N and P were addressed via improved recovering and reusing of wastes in the food production and consumption chain, while minimizing the negative impacts (Cordell et al., 2011; Erisman et al., 2013; Fowler et al., 2013; Galloway et al., 2013).

Researchers also extended material flow analysis to the food chain. Analyses of N flows in the food chain have been made for several countries, e.g. Norway (Bleken and Bakken, 1997), Germany (Isermann and Isermann, 1998), United States (Howarth et al., 2002) and countries in East Asia (Shindo et al., 2003; Shindo et al., 2006). Studies on P flows in the food chain have been carried out for example for United States (Suh and Yee, 2011), Australia (Cordell et al., 2013), Japan (Matsubae-Yokoyama et al., 2009; Matsubae et al., 2011), and the Netherlands (Smit et al., 2010).

However, these food chain studies used a ‘black-box’ approach, without detailed analyses of N and P use efficiencies, recycling and losses in the different compartments and the whole of the food production - consumption chain. For example, these studies did not distinguish (1) different emission factors among categories of crops and animals, (2) ‘new’ and ‘recycled’ N and P in the food chain, and (3) N and P use efficiencies in different compartments and the whole food chain. Therefore, we do not know (1) the main contributors of N and P losses in the food chain, (2) the best options for improving N and P use efficiency in the food chain, and (3) the possible interactions between N and P in the food production and consumption.

1.4 Research questions and hypotheses of my thesis

The main research questions of my thesis are “How to analyse nutrient use efficiency and how to manage nutrient flows in the food production - consumption chain at regional and national scales?” Plants need 14 nutrient elements in specific quantities for their growth and development (e.g., Marschner, 2012), and animals require even 22 nutrient elements for growth and development (e.g., Suttle, 2010). However, I focused on nitrogen (N) and phosphorus (P), because these elements are needed in relatively large quantities by plants and animals, the response of crops to the application of N and P is relatively large globally, and losses of N and P to atmosphere and water systems have sincere ecological and human health impacts (Sutton et al., 2013).

To answer the main research questions, I formulated the following specific research questions:

- What is the current organizational structure of nutrient management and what are the main nutrient management challenges in China?
- What are the N and P use efficiencies, and losses in crop and animal production, food processing, households, and in the whole food chain of China at regional and national scales?
- What are the effects of population growth and changes in human diets and technology development on N and P use efficiencies in the food chain?
- How did urban expansion affect N and P use efficiencies and losses in the food chain in Beijing during the past three decades?

Which options are effective and efficient for increasing nutrient use efficiency and decreasing nutrient losses in the food chain of China at regional and national scales?
The general hypotheses of my thesis are:

- H1: Lowering the net N and P costs of food requires a food chain approach;
- H2: Changes in N and P use efficiencies of the food production – consumption chain are large and regionally diverse in China during the last three to four decades, due to changes in human diets and management practices.

1.5 Objectives of this thesis

The general objective of my study is to increase the quantitative insight in the changes and controlling factors of the N and P use efficiencies and losses in the food production – consumption chain in China at national and regional levels during the past 30 to 40 years and during the next 20 years. The specific objectives are:

1. To develop a conceptual framework, an analytical model and a database for analysing N and P use efficiencies in the whole food production –consumption chain.
2. To identify and test indicators for the assessment of the N and P use in the food chain at regional and national levels.
3. To quantify changes of N and P use efficiencies, nutrient losses and greenhouse gas emissions in the food chain over time.
4. To analyse how urban expansion affects N and P use efficiency and N and P losses in the food production – consumption chain at regional level.
5. To explore options for improving N and P use efficiencies, and decreasing N and P losses and greenhouse gas emissions at regional and national levels, through scenario analyses.

1.6 Outline of this thesis

This thesis contains a general introduction, five research chapters and a general discussion.

Chapter 2 reviews the major development in nutrient management in China during the last 30 years and the major challenges for the next decades.

Chapter 3 describes the NUFER model (Nutrient flows in Food chains, Environment and Resource use), which has been developed and used in the subsequent chapters. It also presents the first comprehensive concept of the food pyramid for unravelling N and P flows, balances, losses, and use efficiencies in different compartments (crop production, animal production, food processing and households) and the food chain in China at national level in 2005.

Chapter 4 reports on the changes of N and P use efficiencies and losses in the food chain in China at regional level in 1980 and 2005.

Chapter 5 presents a case study on changes of N and P flows in the food chain of Beijing between 1978 and 2008, i.e., during a period of rapid urban expansion.

Chapter 6 provides the results of scenarios analysis with the NUFER model in which the effects of possible management options on N and P use efficiencies, and on N and P losses in the food production-consumption chain in China were explored for the year 2030.

Finally, chapter 7 discusses and integrates the results of the previous chapters. Options to increase nutrient use efficiency in the food chain of China are proposed.

Chapters 2, 3, 4, and 6 have been published in peer reviewed journals. Chapter 5 has been submitted. All key methods, data and results are presented in the Chapters, but background data and results are not included. Instead links to journal websites are provided where this supplementary information can be downloaded.

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CHAPTER 2

An analysis of developments and challenges in nutrient management in China

This chapter was published in Journal of Environmental Quality, 2013, 42 (4): 951-961. This review paper was published after chapters 3, 4 and 6 were published, and therefore benefitted from the ideas developed in chapters 3, 4 and 6. Chapter 2 also includes summary information from chapters 3, 4 and 6. Supplementary information and tables S1, S2 and S3 can be found in the link https://www.agronomy.org/publications/jeq/supplements/42/951-supplement.pdf).

Abstract
During the past 50 years, China has successfully realized food self-sufficiency for its rapidly growing population. Currently, it feeds 22% of the global population with 9% of the global area of arable land. However, these achievements were made at high external resource use and environmental costs. The challenge facing China today is to further increase food production and at the same time to drastically decrease the environmental costs of food production.

Here we review the major development in nutrient management in China during the last 50 years. We briefly analyze (1) the current organizational structure of the 'advisory system' in agriculture, (2) the developments in nutrient management for crop production, and (3) the developments in nutrient management in animal production. We then discuss the nutrient management challenges for the next decades, considering nutrient management in the whole chain of 'crop production - animal production - food processing - food consumption by households'. We argue that more coherent national policies and institutional structures are required for research - extension - education to be able to address the immense challenges ahead. Key actions include (1) nutrient management in the whole food chain, concomitant with a shift in objectives from food security only to both food security, resource use efficiency and environmental sustainability, (2) improved animal waste management, based on coupled animal production and crop production systems, and (3) much greater emphasis on technology transfer from science to practice, through education, training, demonstration and extension services.

2.1 Introduction

Food security in China is a national as well as a global concern (Brown, 1995). Fortunately, remarkable progress has been made in producing sufficient food for the rapidly increasing human population during the past five decades (Figure 2-1). China is now feeding about 22% of the global population with 9% of the global area of arable land. However, the increased crop and especially animal production has been achieved at a high cost in terms of both consumption of natural resources and degradation of the environment (Ju et al., 2009; Liu and Diamond, 2005). Forecasts suggest that food supply, and especially the supply of animal-derived food, will have to increase by another 50 to 70% by 2050, to be able to meet the demands of China's growing and increasingly prosperous population (UN, 2008).

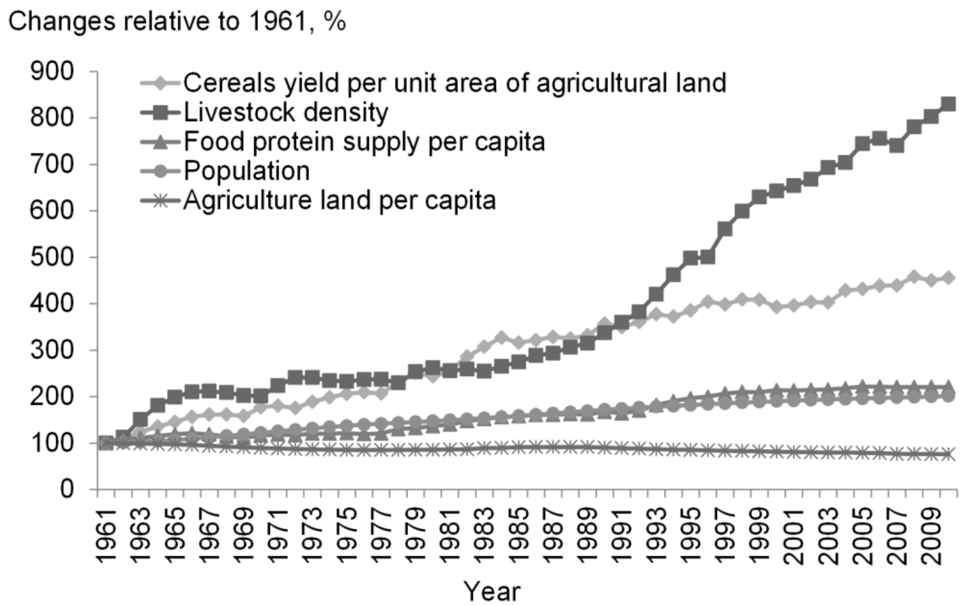

Figure 2-1 Relative changes in cereal yield, livestock density, protein supply, population and agriculture land per capita in China from 1961 to 2010. Data for 1961 were set at 100%. (Source: FAO, 2010).

For millennia, Chinese farmers practiced low - input farming based on nutrient recycling to maintain soil fertility (King, 1911). Crop yields were mainly constrained by the genetic potential of crop varieties, pests and the availability of water and nutrients. These constraints were relieved some 60 years ago, with the introduction of high-yielding crop varieties, fertilizers, pesticides, and mechanized irrigation practices, stimulated by widespread governmental support (subsidies). Unfortunately, the government policies that contributed to increased food production, also led to increased environmental damage, particularly in terms of nutrient losses to air and water (Fu, 2008; Guo et al., 2010; Ju et al., 2009).

Urbanization and the increased prosperity of at least part of the population have also contributed to a changing human diet in China, one that contains more animal protein (e.g., FAO, 2010). As a consequence, animal production has grown exponentially during the last few decades (Figure 2-1). The increase in animal production has come mainly from collective (cooperative) farms and from specialized, landless industrial farms, and much less from smallholder farms. However, the rapid increases in animal numbers, the changing nature of the production system and the lack of appropriate manure management facilities have created more environmental risk. Huge amounts of nutrients generated at animal production facilities are dumped in landfills or directly discharged into surface waters as wastes instead of being used as beneficial resources for crop production (Miao et al., 2011; Wang et al., 2010).
The recent improvements in agricultural systems and practices were made possible in part through major governmental investments in research. Hundreds of experiments have been performed and many new technologies have been developed and tested to help farmers increase crop and animal production (Chen et al., 2011). Some of these technologies have the potential to significantly increase both crop yields and nutrient use efficiency simultaneously, and thereby reduce environmental impacts. However, to date, most of these technologies, programs and recommendations have not been adopted in practice. There are more than 200 million farmers in China, and there is a huge diversity in farming systems. Apart from the numerous farmers, there are also many other people who influence the food production system, including suppliers, food processing industries, retailers, extension services, regional governors, etc., all with their own objectives, which can make practical implementation of sound nutrient management strategies a challenge.

Here, we review and analyze developments in nutrient management in China during the last five decades, and the impacts that these developments have had on food production and nutrient use. We begin our review with a brief analysis of the organizational structure of the ‘agricultural advisory system’, which has the prime task to transfer and implement new developments from research, industry and government into practice. We then summarize the structure of the crop production sector and analyze the developments in nutrient management for crop production. After this, we briefly consider the structure of the animal production sector and analyze the developments in nutrient management in animal production. We close by arguing that nutrient management for China in the 21st century has to be considered from a whole food chain perspective, i.e., the chain of ‘crop production - animal production - food processing - food consumption by household’. Our main conclusion is that nutrient management research and extension can better serve practitioners and policy-makers by developing more integrative views and concepts at farm and regional scales.

2.2 Agricultural advisory system

The ‘agricultural advisory system’ has been defined as the ‘whole of advice, guidelines, training, education, tools and incentives provided to farmers by various stakeholder people to improve the performance of agriculture’ (e.g., Anderson, 2007). The agricultural advisory system in China is highly fragmented and is still in a developmental phase (Gao and Li, 2006). There are many different stakeholders, with different objectives and (policies) instruments. Governmental organizations continue to exert a dominant influence, but following China’s policy reforms towards more market-driven production in the 1980s, industries and small businesses, and also universities and research institutes have become more important. There are many complex barriers for effective knowledge and technology transfer to the receiver side; most of the more than 200 million farmers are poorly educated, of relatively old age, with very small holdings (on average 0.1 - 0.5 ha agricultural land per farm). Well-educated young people increasingly leave rural areas for jobs in cities. Hence, it will be no surprise that 80 to 90% of household income is derived from income sources other than the farm itself, such as young family members working in cities (Wang et al., 2011). Moreover, there is a great diversity in farming systems and a wide range in agri-environmental conditions (soils, climate, topography, and cropping systems), which would necessitate farm-specific programs and guidelines for nutrient management. Also, advisors from governmental agencies and private industries have a relatively low education level and consequently limited training in modern communication skills important to advisory agencies.

The organizational structure of China’s agricultural advisory system is fragmented and includes a variety of stakeholders, with differing objectives, and varying roles in knowledge and technology transfer important to nutrient management (Figure 2-2). Increasing agricultural production and food security have been the primary objectives of the Central Government, and are undertaken by the Ministry of Agriculture (MOA). These central objectives have been translated into targets and production incentives (subsidies), to be administered by regional Bureaus of Agriculture. Regional governors, however strongly focus on industrial development and employment, because the resulting economic growth is very helpful for their own promotion to higher positions. As a result, regional governments often pay little attention to food security and environmental protection. The MOA and regional Bureaus have a strong influence on farmer’s activities, through providing direct advice and subsidies to

farmers and indirectly through subsidies on fertilizers, irrigation water, and pesticides. They are not responsible, however, for environment protection and have not supported the development and implementation of targets, thresholds and/or guidelines related to improving nutrient management and/or minimizing nutrient losses at farm level, apart from promoting soil testing and fertilizer recommendations (see below).
Environmental protection is the primary objective of the Ministry of Environmental Protection (MEP) and the associated (regional) Bureaus of Environment Protection. For example, pollutant discharge standards and technical standards for preventing pollution for livestock and poultry farms were issued by MEP in 2001. However, their influence in changing farmers' activities is limited, because they have no regulatory and monitoring authority, also because of limited funds.

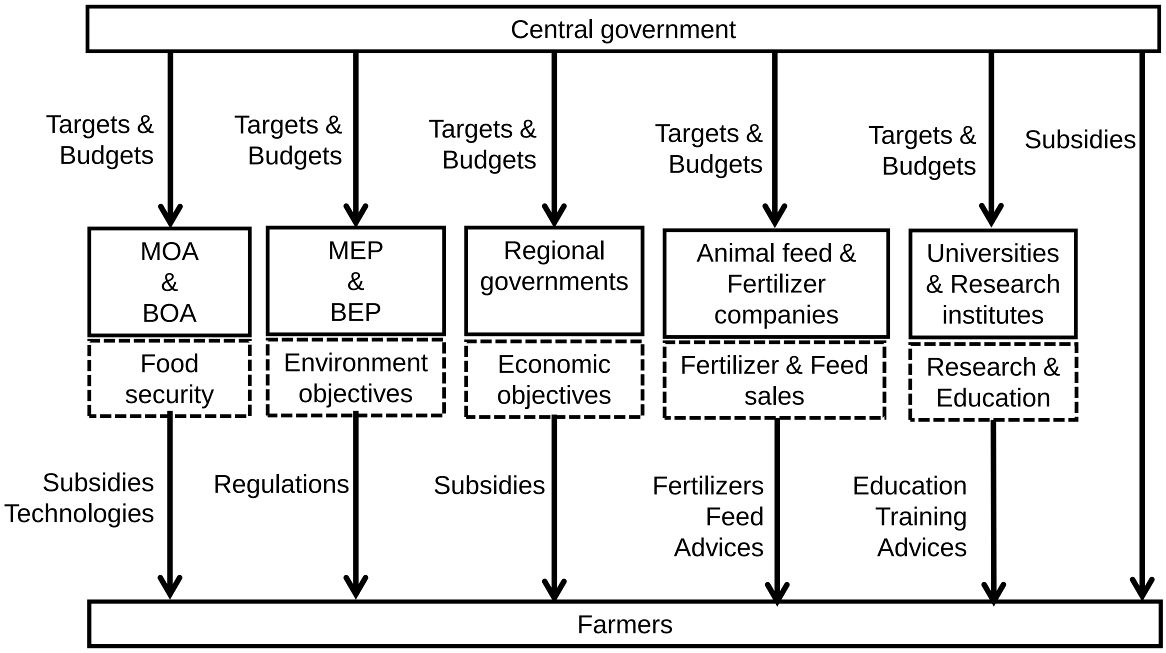

Figure 2-2. Fragmented organizational structure of current agricultural advisory system related to nutrient management in China. Boxes with solid lines represent stakeholders; boxes with broken lines are primary objectives of the stakeholder groups. Arrows indicate instruments, to achieve objectives. Note: MOA = Ministry of Agriculture-, BOA = Bureau of Agriculture, MEP = Ministry of Environmental Protection, BEP = Bureau of Environment Protection. MOA is organized into a number of BOA's, and MEP is organized into a number of BEP's.

Rural Supply and Marketing Cooperatives, which have served as an important platform for the distribution of agricultural products in rural areas, played a key role in selling and distributing fertilizers, pesticides and tools to farmers and in purchasing and collecting agricultural products until the 1980s (Wan et al., 1988). Following economic reforms in the 1980s, private industries and businesses became more important, and governmental objectives became more diverse, sometimes also contradictory, especially related to nutrient management. Following the shift from a central-planning economy to a market-driven economy from the 1980s onwards, and the concomitant privatization of the fertilizer and feed industry, fertilizer and feed manufacturers and retailers have become more important. Currently, there are some 100,000 private fertilizer and feed retailers which sell fertilizers and feeds at low and remarkably stable prices to farmers; for example, from the 1970s, farmers in China have paid 50 - 75% less for urea fertilizer than the world market price (Li et al., 2013). Agricultural universities and research institutes have also become more important in technology development and transfer following the economic reforms. Some have become actively involved in developing and testing practical tools, technologies and nutrient management strategies for farmers, and in practical demonstrations of various farming systems. In doing so, they can convey their own messages and ideas to farmers, often without much coordination and scientific consensus between the various universities and institutes.

Summarizing, China’s agricultural advisory system is fragmented and evolving, in a positive manner. There are many stakeholders and barriers, and as yet no coherent nutrient management strategy and policy. The Ministry of Agriculture and the associated Bureau of Agriculture are still the most influential to farmers through direct and indirect financial support. Fertilizer and feed industries and universities and research institutes have become more influential following reforms of the economy in the 1980s. However, resource use efficiency and environmental protection are still low on the political agenda in rural areas, which complicates any coordinated efforts to improve nutrient use efficiency by farmers.

2.3 Crop production

2.3.1 Changes in crop yields and nutrient use

Currently about 75% of China's cultivated area is used for growing cereals, i.e., rice, wheat, corn, millet and other cereal grains. During the period 1961 to 2009, national grain yields increased more than fourfold, from 110 to 483 Tg or from a mean of 1.3 to 5.4 Mg ha^{-1} (FAO, 2010). The area used for vegetables and fruit production increased during the same period from 4 to 19% of the total crop area (FAO, 2010), at the expense of the three main cereal crops (wheat, maize and rice) (See Table S1, supplementary information).

Fertilizer nitrogen (N) became increasingly available and affordable to farmers from the 1950s, thereby replacing, at least in part, millennia-old practices of recycling nutrients from crop residues and human and animal wastes in crop production (Ju et al., 2005; Miao et al., 2011). The early N fertilizer was mostly in the form of ammonium bicarbonate (NH_4HCO_3), which has a low effectiveness because of large ammonia volatilization losses, and therefore has been replaced largely by urea from the 1980s onwards. From the 1970s, crops became increasingly responsive to phosphorus (P) fertilizer application (Shen, 1998), and the use of P fertilizer increased from 0.9 Tg in 1970 to 12.8 Tg in 2009 (FAO, 2010). Similarly, little potassium (K) fertilizer was used until the 1980s, due to the initial lack of crop responses to K fertilizer application (Gao et al., 2006; Xie, 1998). However, the increased withdrawal of K with harvested crops, as yields increased, increased the area of K-responsive soils in the past two decades, and K fertilizer consumption increased almost linearly from 0.4 Tg in 1980 to 7.5 Tg in 2007 (Miao et al., 2011).

In the past two decades, the increase in fertilizer use has been much larger than the increase in crop yield and nutrient withdrawal by harvested crops in the main cropping systems, such as the wheat-maize rotation system in the North China Plain, and the rice-wheat system in the Taihu region (e.g. Zhen et al., 2006). As a consequence, mean N use efficiency (NUE) in crop production has decreased drastically, from 32% in 1980 to 26% in 2005 (Ma et al., 2012). Values for NUE in China are much lower than in many developed countries, where mean NUE in crop production has been estimated at 58% for Germany, 44% for the US and at 35% for Norway (Table 2-1). While these differences are in part related to intrinsic differences in cropping systems and in part also to methodological differences in the estimation of NUE, the trend is clear: NUE is low and decreasing in China. The same holds for P use efficiency in crop production (PUE) (Table 2-1; see supplementary information for details on calculations of N and P use efficiencies).

Table 2-1 Nitrogen use efficiencies (NUE) and phosphorus use efficiencies (PUE) in crop production (NUEc and PUEc), animal production (NUEa and PUEa) and in the whole food chain (NUEf and PUEf) in China in 1980 and 2005, and for comparison also in selected countries, all in percent (%).

Country	Year	NUEc	NUEa	NUEf	Year	PUEc	PUEa	PUEf
China	1980 (1)	32	8	16	1980 (1)	59	16	19
China	2005 (1)	26	16	9	2005 (1)	36	17	7
Global	1995 (2)	50*	13	15	2000 (3)	-**	-	11
US	1999 (4)	44	22	23	2007 (5)	62	36	18
Germany	1991 (6)	58	20	19	-	-	-	-
Norway	1991 (7)	35	20	16	-	-	-	-
The Netherlands	-	-	-	-	2005 (8)	61	32	18

* Main product and residue combined; ** no data.

(1) (Ma et al., 2010), (2) (Smil, 2002), (3) (Cordell et al., 2009; Smil, 2000), (4) (Howarth et al., 2002), (5) (Suh and Yee, 2011) , (6) (Isermann and Isermann, 1998) , (7) (Bleken and Bakken, 1997) , (8) (Smit et al., 2010).

2.3.2 Developments in nutrient management

Fertilizer recommendations based on soil and plant testing were introduced in China during the 1970s (Fan et al., 2007; Cui et al., 2010), recognizing that the likelihood of a response of a crop to fertilizer application depends on the nutrient supplying capacity of the soil. However, implementation and use of results from soil and plant tests in practice is still very limited. China has >200 million farms and field sizes are very small (on average <0.2 ha), which greatly hampers the implementation of soil and plant testing at the field and farm level. As a consequence, a uniform fertilizer application rate is commonly recommended based on the analyses of bulked samples from 15-20 ha large areas, regardless of between and within field variability (Zhu and Chen, 2002).

By the 1990s, split timing of fertilizer N applications, as opposed to one single preplant application, was introduced (Ma et al., 2006). Currently, most N fertilizer applications to cereals, vegetables and fruits are split in two or three portions: a basal application at or before seeding and one or two top dressings during the growing season. A great deal of research effort has been focused on how to optimize the timing of the top dressings on the basis of soil nitrate-N tests (Ma and Wu, 2008), crop nitrate tests, chlorophyll content of leaves (Huang et al., 2008), and leaf color, using various techniques (Peng et al., 1996; Jia et al., 2004a, b; Li et al., 2009). However, these technologies are still in the research phase and have not yet been implemented in practice.

The concept of 'integrated nutrient management' was developed by China Agricultural University in the early 2000s with the goal of simultaneously increasing crop yields and nutrient use efficiency. The key points of this strategy include (a) full accounting and integrated use of nutrients from fertilizers, soil, wastes (from both agriculture and industry) and environmental nutrient sources such as atmospheric deposition and irrigation water, (b) synchronization of nutrient supply to crop nutrient demand, and (c) integration of nutrient management with sound soil cultivation, use of new crop varieties, crop husbandry, and irrigation management practices (Fan et al., 2008). Integrated nutrient management was tested and compared with current farmers' practices on 4548 farms. Mean grain yield increased from 8.8 ton ha-1 when following typical farmers' practices to 10.5 ton ha^{-1} when using integrated nutrient management, mainly because of the introduction of high-yielding crop varieties. Interestingly, fertilizer N application decreased from about 250 to 200 kg ha^{-1}, and N use efficiency (partial factor productivity, PFP) increased from 35 to 42 kg kg^{-1} (Figure 2-3; Fan et al., 2008). The increase in NUE was mainly achieved through a better match of N supply to N demand by the crop during the growing season, using soil nitrate–N testing (Chen et al., 2010). On the basis of 1517 on-farm experiments, it was concluded that implementation of integrated nutrient management can, on average, reduce N fertilizer inputs by 26%, save P fertilizer inputs by 20%, raise grain yields by 8%, and reduce N losses by 47% compared to current farmers practice (Fan et al., 2008).

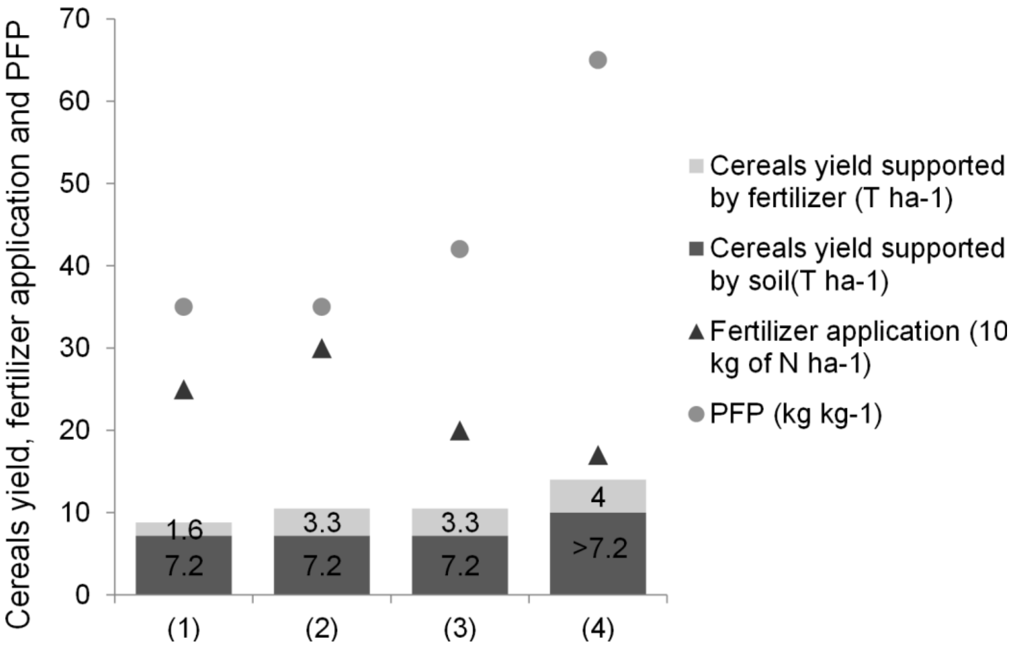

Figure 2-3. Schematic representation of changes in cereal yields; fertilizer application rate; and partial factor productivity (PFP), of a double cereal cropping system, as a function of nutrient management strategy: (1) Farmer's practice, (2) Cultivation of high-yielding crop varieties, (3) Integrated Nutrient Management (Fan et al., 2008), (4) Integrated Soil-crop System Management (ISSM) (Zhang et al., 2011).

Although the 'integrated nutrient management' concept represented a large step forward, it was found that both crop and soil management, especially the soil as nutrient resource was insufficiently accounted for in the 'integrated nutrient management' concept. This led to the development of the so-called 'integrated soil–crop system management' (ISSM) concept. The objective of ISSM is to further increase crop yield relative to 'integrated nutrient management' by making maximum use of solar radiation and favorable temperatures and by a greater synchrony over time between N demand by the crop and N supply from soil, atmosphere and applied manures and fertilizers (Chen et al., 2011). The key points of this strategy include (i) use of appropriate crop cultivars, adapted to site-specific environmental conditions, (ii) specific measures to improve soil quality, such as returning straw to the soil, (iii) integrated utilization of all available nutrient resources, and proper matching of nutrient supply to crop requirements, while accounting for the soil nutrient supply (Zhang et al., 2011). From 2006 to 2009, ISSM was tested in 43 on-farm experiments, across nine provinces. Mean maize yields were 13 t ha^{-1} and with no increase in N fertilizer use. At the same time, yield per unit fertilizer N (kg kg^{-1}) was more than twice that of farmers' practices (Chen et al., 2011). On average, the crop yields increased 30% and PFP increased by 86% compared with traditional methods used by Chinese farmers (Figure 2-3). Evidently, these technologies have the potential to significantly increase crop yields and nutrient use efficiency simultaneously, and thereby reduce the environmental impacts of N and P use (Fan et al., 2012; Zhang et al., 2009); however, to date, widespread adoption of ISSM practices has not yet to occur in China, primarily because of the lack of extension services.

2.3.3 Challenges for technology transfer in crop production systems

During the last five decades, governmental policies, together with the increased efforts by extension officers of regional Bureaus of Agriculture, have been very effective in increasing crop yields, in spite of the large number of farms and diversity of cropping systems in China. Governmental incentives were mainly based on direct and indirect financial support for wider use of high-yielding crop varieties, irrigation, fertilizers and pesticides (Li et al., 2013). Since the end of 2000s, government policies have broadened to include not only food security, but also resource use efficiency and environmental sustainability; however, the agricultural bureaus lack the knowledge, trained staff, and instruments (e.g., taxes & subsidies, regulatory authority, extension services, education & demonstration, and pollution standards) to implement a policy with three major and complex goals. There are large gaps in the knowledge level between researchers in universities and research institutes and extension officers in agricultural bureaus, fertilizer industries and local retailers. These gaps lead to ambiguous or sometimes contradictory recommendations; while universities and research institutes recommend technologies to increase crop yields and resource use efficiency simultaneously, extension officers usually only promote those intended to increase crop yields, as do most governmental incentives (Hu et al., 2009). Not surprisingly, there is a large gap between the performance of current practice and the performance demonstrated in researcher-managed, on-farm field experiments. The field tests of ‘integrated nutrient management’ and ‘ISSM’ indicate that crop yields and nutrient use efficiencies can be increased by up to 30% and 80% respectively, relative to current practice (Zhang et al., 2011). While attaining more yield with less external resources is encouraging, the much more important question is how to implement the improved management practices on hundreds of millions of Chinese farms?

Table 2-2 The percentage of farmers involved in soil testing and fertilizer recommendation programs (STFR) in 1143 farmers' survey of six main grain production provinces of China in 2009 (Wang, 2011).

Year	2005	2006	2007	2008
Farmers who know about STFR	49	86	82	93
Farmers who got the STFR card	11	52	67	79
Farmers who got training from STFR	15	32	50	53
Farmers who adopted STFR	6	37	64	63

Some progress has occurred in recent years. The Ministry of Agriculture is aware of the poor nutrient management systems in practice today throughout China and of the importance of soil testing and has therefore increased subsidies for soil and plant testing programs. For example, the National Soil Testing and Fertilizer Recommendation Program (STFR) started in 2005, and by 2009 more than 2,500 counties were involved and had received 1.5 billion Yuan (~0.2 billion US$) of financial support from the central government to establish soil testing laboratories and demonstrate the use of soil testing and fertilizer recommendations for a diverse range of cropping systems. The government's expectation is that these tests and demonstrations will increase farmers' understanding of how to simultaneously achieve high crop yields and high nutrient use efficiency. Based on a farmers' survey, Wang (2008) found that, in 2008, 93% of the farmers knew about STFR, and 79% had obtained a leaflet with recommendations of STFR, but only 53% farmers had received training about how to use STFR for their own farms (Table 2-2). The STFR program has great potential for China as results obtained from 5805 field experiments showed that grain yield, partial factor productivity (PFP) and agronomic efficiency (AE) increased on average by 8.7%, 5.3 and 27.5%, respectively, when using STFR technology compared with farmer's practice (Table 2-3) (Wang, 2011). However, whether the STFR program has changed farmers' nutrient management practices significantly still needs to be proven. One major challenge is that farmers do not gain that much economically when soil testing provides evidence for a lower fertilizer need, because fertilizers are still relatively cheap compared to the time and labor costs required to adopt the STFR technology on small farms.

Table 2-3 The comparison of fertilizer application, crop yield and nutrient use efficiency (average of maize, wheat and rice) between soil testing and fertilizer recommendation technology (STFR) and farmers' practice in 5805 experiments of 16 main grain production provinces of China from 2005 to 2009 (Wang, 2011).

	STFR	Farmers' practice
Fertilizer N (kg ha^{-1})	176	199
Fertilizer P (kg ha^{-1})	81	85
Fertilizer K (kg ha^{-1})	78	53
Yield (kg ha^{-1})	7795	7174
Agronomic efficiency (AE, kg kg^{-1})	9	7
Partial factor productivity (PFP, kg kg^{-1})	26	24

2.4 Animal production
2.4.1 Changes in animal production

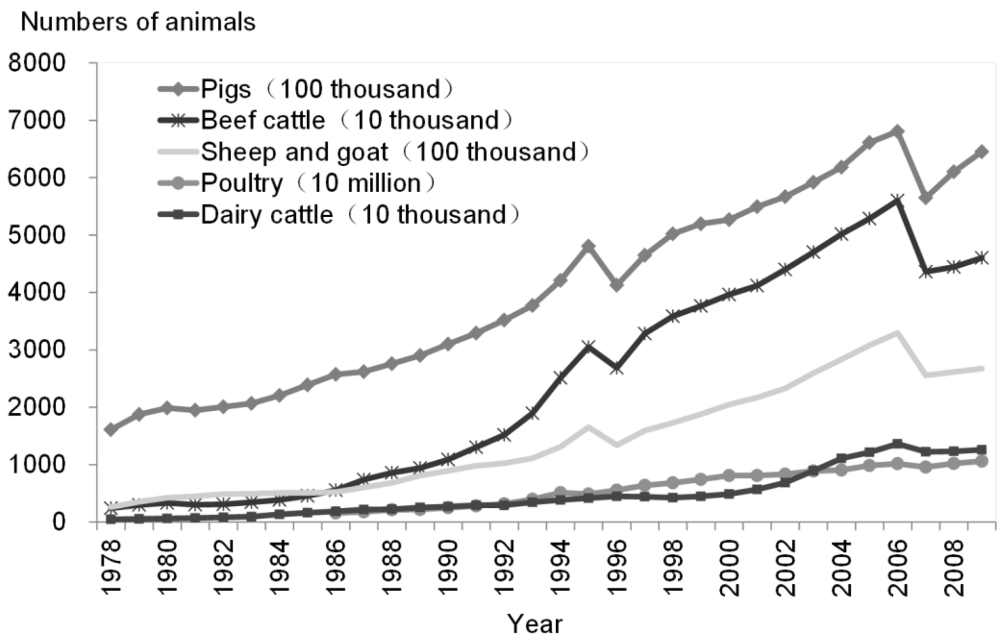

Figure 2-4 Animal numbers in China from 1978 to 2009. Note: A change occurred in the statistical counting method in 1996, while the drop in animal number in 2005-2008 was due to animal diseases e.g., porcine reproductive & respiratory syndrome (PRRS) and foot and mouth.

Animal production has increased greatly in China in recent years, especially since the initiation of economic reforms and the open-door policy in the 1980s (Figure 2-1). This 'livestock revolution' occurred basically without direct governmental support, as observed elsewhere (FAO, 2010), and happened for all main animal categories (Figure 2-4). Currently, China ranks first in global meat production. Most of the increase has almost no CAFOs, but in 2009 roughly half of the production animals in China were kept in CAFOs, although there are significant differences between animal categories (Figure 2-5). Most of the CAFOs are concentrated in the peri-urban areas of coastal provinces. The rapid increase in the number of CAFOs has been driven by the transition, especially in urban areas, towards human diets with greater amounts of animal protein and made possible by the increase in domestic cereal production and large-scale import of soybean and more recently maize. Between 1961 and 2007, the feed grain consumption increased from 18 to 120 Tg per year, and the percentage of feed grain in total grain consumption went up from 19% to 31% respectively (FAO, 2010).

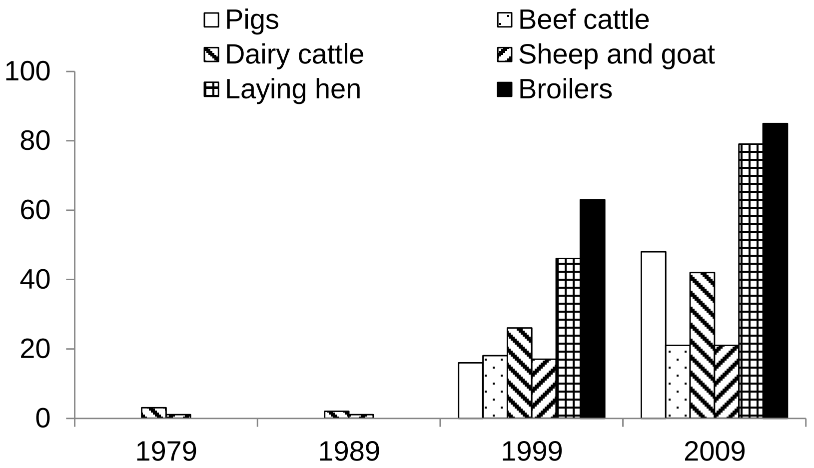

Figure 2-5 Percentage of pigs, beef cattle, dairy cattle, sheep and goat, laying hen and broilers kept in CAFOs, relative to total numbers in the period of 1979-2009 (Wang et al., 2010).

In traditional mixed, small-holder farms, there are only few animals housed in the backyard, and these are typically fed with household residues and crop residues (straw and stalks). Cattle, sheep and goat also scavenge harvested crop land, roadsides, and forests. On a dry matter basis, roughage makes the largest contribution to animal feed (35%), followed by household waste (24%), cereal grains (14%), and crop residues (13%) (Wang et al., 2010). Because of the poor quality of dietary ingredients, a relatively large proportion of the ingested feed is needed for animal maintenance and as a consequence, animal productivity in smallholder farming systems is still low (e.g., Bai et al., 2013). The establishment of CAFOs has greatly increased animal productivity and has lowered feed costs for dairy, meat and egg production. However, these CAFOs are completely disconnected spatially from crop production systems, which makes the proper reutilization of the nutrients contained in the animal manures produced in CAFOs extremely complicated (Sims et al., 2005; Wang, 2008). To date, the infrastructure and policy framework needed to recover and distribute animal waste nutrients from CAFOs to distantly located cropland in need of these nutrients has not emerged in China. This is a national strategic policy need, as the equipment, storage, transportation, and application systems required to efficiently relocate manures from CAFOs to other regions will require a major economic investment by the Chinese government and/or the CAFOs industry in combination with an appropriate monitoring system by MOE.

There is not much information about feed conversion rates and nutrient use efficiency in animal production in China. Powell et al. (2008) compared the N and P use efficiencies in dairy production in modern CAFOs with Holstein dairy cows in China with those in the US and found rather similar performances (between 22 and 30% of feed N and P was retained in milk). Also, productivity and NUE and PUE were much higher in CAFOs than in smallholder systems. Some studies have shown that mean NUE and PUE in animal production have increased in China between the 1980s and 2005, probably because of the greater percentage of animals in CAFOs (Table 2-1). The increase was less for PUE than for NUE, partly because of the relatively large supplementation of di-calcium phosphate to the feed in CAFOs (Wang et al., 2008). Notwithstanding the significant increase in animal NUE in China during the last decades, reported means for NUE and PUE are below most estimates for other countries (Table 2-1).

2.4.2 Manure management and treatment

China has a long tradition and rich experiences with the collection, storage and application of animal and human wastes for beneficial use in food production (Ju et al., 2005; King, 1911). This tradition is disappearing rapidly because of the increased availability of cheap, subsidized NPK fertilizers and the rapid establishment of landless CAFOs, without the concurrent development of a strategy that fosters application of manures to cropland. The percentage of animal manure applied to land decreased from nearly 100% in 1949 to less than 50% in 2005 (Ju et al., 2005), while the mass of manures generated, now mainly at CAFOs, has increased from 440 Tg in 1949 to 2670 Tg in 2009 (fresh weight) (Ma et al., 2013). The increasing disposal of animal manures in landfills and by direct discharge to surface waters has greatly contributed to the pollution of groundwater and surface waters (MEP et al., 2009), and is a waste of nutrient and organic matter resources that could be better used to build soil quality, reduce the use of natural resources to produce inorganic fertilizers, and generally enhance China's crop production systems.

In traditional small-holder farms, excrements of housed animals are either collected in straw and crop residues to produce ‘farmyard manure’, or urine and feces are collected and stored separately for other uses. Part of the liquids may also leak from storage confinements into the (sub) soil and surface waters. An increasing number of small-holder farms use the collected manures for biogas production via anaerobic fermentation, and then use the biogas for cooking (Tang et al., 2009). Following collection and storage, manures are manually applied to crop land in plant holes or in a furrow during or after ploughing. This practice of ‘precision’ manuring likely leads to high nutrient use efficiency relative to broadcast application on the soil surface, but there is surprisingly little quantitative information about the effectiveness of nutrients from animal manures in cropping systems in China. More researches on methods to efficiently use manures and the cost-savings associated with integrating manures into farm nutrient management plans would provide useful information for advisory agencies that seek to implement the ISSM concept on small farms.

Following the emergence of landless CAFOs, manure collection and disposal became an increasing burden to these operations and ultimately to China’s environment. Huge amounts of animal manures are directly discharged into landfills and surface waters as waste, because there is no robust regulatory system to forbid such activities. In some large-scale animal farms, animal excrements are mechanically separated in-house into a solid fraction (‘gan qing fen’) and a liquid fraction. The separation techniques were introduced in the 1990s as a solution for the lack of sufficient storage capacity for liquid manure, but also to produce a solid manure fraction (compost), which is valuable in fruit and vegetable production in the same peri-urban areas. However, the liquid fraction is discharged into surface waters without any treatment, or diluted with water and used in irrigation schemes, or discarded in large open-air lagoons located at the CAFOs where the liquids gradually evaporate or infiltrate into subsoil and shallow groundwater (Wang et al., 2010). An increasing portion of the manures produced by CAFOs is now being digested for large-scale biogas production, but most of the digested residues are not recycled into crop land, but disposed of in landfills (Tang et al., 2009; Wang, 2012).

2.4.3 Challenges of technology transfer in animal production

Though there has been a tradition of recycling manure nutrients for centuries, there is currently little scientific knowledge in Chinese research about the effectiveness of applied manure nutrients as soil amendments for crop production, unlike so in European Union and United States. Hence, there is a need for quantifying the fertilizer replacement value of different animal manures in practice and for establishing sound recommendations for their use. In addition to differences in fertilizer value between animal species, information is needed on how the agronomic value, and potential environmental impact, of ‘farm yard’ manures (small holders) may differ from manures and wastewaters produced by CAFOs.

Equally important is the implementation of incentives for recycling manure nutrients in crop production. Current subsidies on fertilizers discourage the recycling of manure nutrients. Even more important perhaps is the re-integration of animal production systems with crop production systems. Animal production in China is rapidly growing, and basically all growth is centered upon landless CAFOs, which import feed from elsewhere and have no nearby land for proper manure disposal. This is not a sustainable system (Menzi et al., 2010; Naylor et al., 2005; Sims et al., 2005). Agglomeration of animal production systems near consumers and food processors is economically attractive, but discourages recycling of manure nutrients in crop land because of the large infrastructure and transportation costs to relocate manures to farms. We believe that the central government should re-consider current national policies and re-direct development pathways for animal production that fully integrate animal manure management as a valuable resource rather than a useless waste. Opportunities for sound recycling of manure nutrients must receive high priority when designing new CAFOs and locations for animal production. Such opportunities can be obtained through spatial planning, i.e., limiting livestock density within an area, or through high-tech manure processing and subsequent transport and distribution of processed manures to crop land. When processed, manure nutrients can be less bulky and thereby cheaper to transport. However, manure processing is not without considerable economic cost (Burton et al., 2003; Schoumans et al., 2010).

Apart from the proposed interventions by the central or regional governments in the spatial planning and design of animal production system, there is need for the establishment of multidisciplinary teams of animal scientists, veterinarians, agronomists, engineers, economists and environmental scientists to develop a long-term strategy for sustainable animal production systems with sound manure management practices. Currently, these scientists often operate in isolation, and as a consequence, governments, policy makers, businesses, farmers, and the society at large receive conflicting messages. Research in animal production has mostly focused on increasing animal productivity via animal breeding and high quality feed formulations. Results of this research are adopted by CAFOs (not by the traditional small-holder mixed farming systems), but the resulting manure production is neglected. Here, multi-disciplinary research teams must develop integrated options for both improved animal production and sound manure management.

2.5 Whole food production - consumption chain

2.5.1 Changes in food consumption and nutrient use

Paralleling China's rapid economic growth during the last few decades, has been an overall improvement in human food consumption levels especially in the urban areas. Between 1961 and 2007, mean protein consumption grew from 9 to 26 kg capita^{-1} year-1, and the percentage of animal protein in diets increased from 9% to 35% (FAO, 2010). The classic Chinese diet consisting of mainly cereals (noodles, rice and coarse cereals), vegetables, and fruits with very little animal-derived products has changed to a diet much richer in poultry, eggs, pork and dairy products (Zhai et al., 2009). Moreover, there has been a shift in eating behavior from the traditional pattern of three meals per day toward a mixed pattern (meals plus snacks), and a shift from steamed and boiled food to fried food (Wang et al., 2008). As a consequence, the nutritional status of the Chinese population has changed from 'undernourished' during the 1960s to well-nourished currently and with an increasing percentage of people who are overweight or obese (Zhai et al., 2007, 2009).

Dietary changes, due to population migration from rural to urban areas, are a major driver for changes in food production systems and for nutrient inputs and use efficiency in the whole food production-consumption chain (Hou et al., 2013). Concomitant with changes in diets, there have been changes in the utilization of food residues and food wastes, which is in part related to urbanization and upscaling effects. Food residues and wastes in rural areas are fed to animals in small-holder systems and the animal manure is largely recycled to crop land. However food residues and wastes in China's urban areas are increasingly dumped in landfills or discharged in surface waters, instead of being used as feed in animal production or as composts. Hence, nutrient use efficiency in the whole food chain has declined with changes in human diets and the increasing urbanization of China's population.

The food chain can be perceived as a 'pyramid', with food production at the base and food consumption by humans at the top (Figure 2-6). Relatively large amounts of nutrients are needed to support crop production, but only a small fraction of these nutrients end up in food on the plate of consumers. Changes in nutrient use efficiency in the food production-consumption chain can be captured through analyses of nutrient inputs and outputs for each compartment of the food chain. Such nutrient budget analyses have only rarely been made, but provide useful information about nutrient use and nutrient recycling efficiencies for each part of the food chain. The first studies indicated that the base of the food pyramid has become wider during the last decades, as more ‘new’ N and ‘new’ P through fertilizer and imported animal feed and feed additives entered the food chain (Figure 2-6; Ma et al., 2010, 2012). As a consequence, the overall N and P use efficiencies in the food chain (NUEf and PUEf, defined as the ratio between N and P in food delivered to households and the total input of ‘new’ N and ‘new’ P into the food chain) decreased from 16% to 9% for N, and from 17% to 7% for P between 1980 and 2005 (Table 2-1). The main reasons for the decrease of NUEf and PUEf are: 1) reduction of NUE and PUE in crop production due mainly to fertilizer overuse; 2) the increase in the consumption of animal derived food, which has been shown to be a less efficient approach to feed national populations (Westhoek et al., 2011); and 3) the increased nutrient losses from animal production facilities, due to the decoupling of crop and animal production.

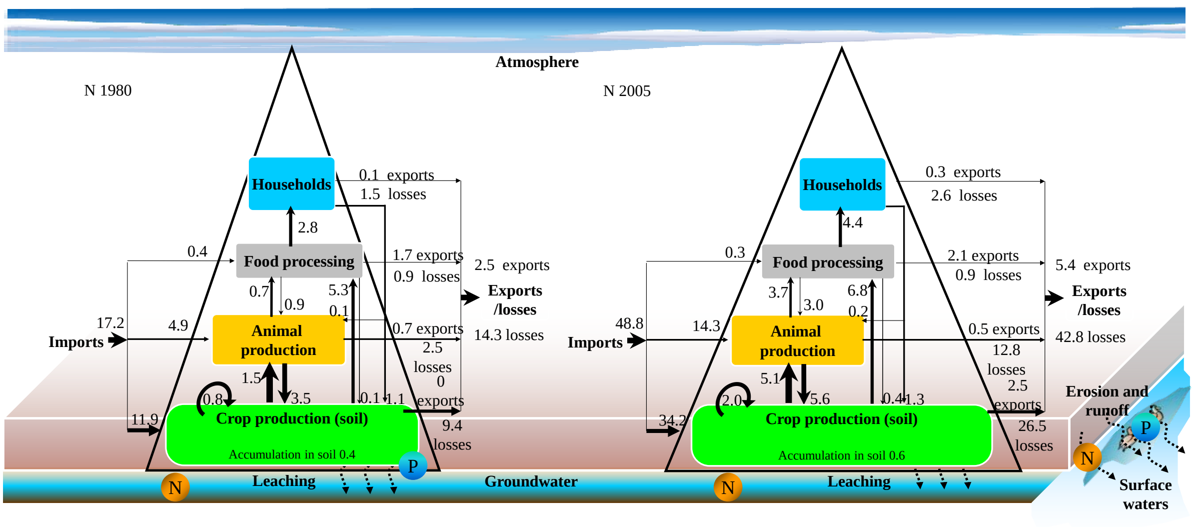

Figure 2-6 Nutrient cycling in the whole food production-consumption chain. The food chain is perceived as a ‘pyramid’ with crop production (including the rootable soil layer), animal production, food processing and households as main compartments. Nutrient inputs into the food chain are shown on the left side of ‘pyramid’, nutrient outputs (including losses to the environment) on the right side of ‘pyramid’. The left and right pyramid are the N flows in the food chain in China in 1980 and 2005 respectively (modifying according to Ma et al., 2012).

For comparison, the estimated world average NUEf is 16%, while NUEf in USA is 15%, in Germany 23% and in Norway 19%. Similarly, the world average PUEf is 11%, while PUEf is 18% for USA and the Netherlands (Table 2-1). These differences, between China and aforementioned countries, likely emanate from differences in human diets and food production systems, but also from differences in nutrient use efficiency in crop and animal production, and from differences in the recycling of nutrients in food residues and food wastes. However, today we still have little quantitative understanding of the complex details and interactions controlling nutrient use efficiency and nutrient recycling in the entire Chinese food chain. Even so, the trend is clear that although the Chinese diet is still relatively low in animal protein compared to diets in northern America and Europe, the nutrient use efficiency in the whole food chain is low in China. Forecasts indicate that the population will increase further and that the ratio of the urban to rural populations and the proportion of animal-derived protein in the human diets will increase further in China. Therefore, improvements in nutrient management must consider the whole food production – consumption chain in the coming decades.

2.5.2 Challenges of nutrient management in food chain

Nutrient budgeting and nutrient management for the food chain, including crop and animal production sectors, is a relatively new phenomenon in China, although the processes of budgeting and management do not differ fundamentally from those operating in small-holder farming systems. The food pyramid depicted in Figure 2-6 provides a holistic view of nutrient budgeting and nutrient management in the whole food production-consumption chain. Effects of changes in diets and in production systems on nutrient use efficiency can be analyzed in an integrated way and opportunities for nutrient recycling can be identified and explored. The food pyramid provides an easily understood, powerful concept and identifies the principles and tools to strive for, in order to increase food production and resource use efficiency simultaneously. A key component of the food pyramid approach is the recognition that, while operationally, nutrient management in crop and animal production systems must be addressed primarily at farm and field scales, nutrient management in the whole food chain is most meaningful at regional scales. By working at the larger, regional scale, it is possible to better combine food production sectors with the effects of food processing, retail and household waste recycling in an integrated way. This facilitates a number of new strategies, such as developing a regional scale means to improve most animal waste management systems in or near urban areas (e.g., CAFOs).

One major challenge to regional approaches such as the food pyramid is the ability to obtain accurate data needed to develop and track nutrient budgeting and nutrient management for China's large and complex food chain. This is one of the reasons why such studies are limited so far to only a few areas of the world. A second major challenge will be to analyze the effects of changes in human diets and urbanization (Hou et al., 2013), as discussed before. Finally, the effects of new technologies and techniques in crop production and animal production, single and combined/integrated, on nutrient use efficiency in the whole food chain should be analyzed, including the possible tradeoffs, also to identify the most effective (policies) options.

2.6 Concluding remarks

This review highlights the developments in nutrient management during the last decades, and the challenges faced today if China is to achieve the triple challenge of food security, resource use efficiency and environmentally sound food production and consumption. Although various promising nutrient management concepts and technologies have been developed and tested in research, especially in crop production, adoption of these concepts and technologies in practice is still negligible, because of some complex barriers and constraints. We believe that a coherent national strategy is needed to overcome most persistent limitations to widespread adoption of new approaches including:

- a greater emphasis on knowledge and technology transfer from research to practice, through education, training, demonstration and extension services
- a change in focus from merely increasing animal production to improving animal production and manure management, and linking CAFOs and crop production sectors,
- a shift in focus from nutrient management almost exclusively focused today on crop production, to nutrient management in the whole food production – consumption chain,
- concomitantly, a shift in focus in national policies from merely food security to an integrated approach, that emphasizes food security, resource use efficiency and environmentally sound production and consumption (see Figure 2-6), and
- a shift in research from largely disciplinary, separately focused studies for the crop and animal sectors to both disciplinary and multi-disciplinary studies, scenario-analyses and integrated assessments of whole food systems at different spatial levels.

In addition to the statements above, we speculate about three emerging trends on nutrient management issues in China. Firstly, China is in transition from an agrarian society to an industrial society. In the near future, it is likely that the number of small-holder farms will greatly decrease and that crop production is taken over by specialized firms (contractors). Similarly, animals will be kept more and more in collective (cooperative) farms and in industrial farms. Governmental policies are encouraging this transition by providing more job opportunities in urban areas for rural people. Therefore, a major challenge will be to train and educate the new generation of farmers, and to develop the knowledge base for sound nutrient management. Secondly, China's agriculture is in transition from government-led planning to market led planning. These changes have occurred already in fruit, vegetable and in part animal production sectors, and will continue in grain production. Likely, larger farms will be more able to develop the knowledge base and to invest in technologies for using nutrients more effectively and smartly than the current small-holder farmers. Thirdly, governmental support of agriculture should be re-directed. We recommend to abandon the (indirect) fertilizer subsidies and to increase the direct support to farmers who contribute sustainably to achieving the triple objectives of food production, resource use efficiency and environmental sustainability.

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CHAPTER 3

Modeling nutrient flows in the food chain of China

This chapter was published in Journal of Environmental Quality, 2010, 39 (4): 1279-1289. Supplementary information and tables S1, S2, S3, S4, S5 and S6 can be found in the link https://www.agronomy.org/publications/jeq/supplements/39/jeq39-4-1279.pdf.

Abstract
Increasing nitrogen (N) and phosphorus (P) fertilizer applications have greatly contributed to the increasing food production in China during the last four decades, but have also contributed to rapidly increasing N and P losses to groundwater, surface waters and air. However, the pathways and magnitude of these losses are not well known quantitatively. Here, we report on N and P use efficiencies and losses at national scale in 2005, using the model NUFER (Nutrient flows in Food chains, Environment and Resources use). NUFER was developed to analyze the N and P flows in and between crop production, animal production (including fish production), food processing, and households (food consumption). The activity data and parameters were derived from statistical offices and literature, and supplemented with data from numerous field experiments and farm and field surveys.

Total amount of 'new' N import to the food chain was 48.8 Tg in 2005. Only 4.4 Tg reached households as food. Average N use efficiencies in crop production, animal production and crop and animal production and food processing combined were 26.4, 11.1 and 8.9%, respectively. Most of the imported N was lost to the environment, i.e., 23 Tg N to atmosphere and 20 Tg to waters.

This is the first comprehensive overview of N and P balances, losses, and use efficiencies of the food chain at national in China. NUFER also allows estimating changes in N and P use efficiencies through the introduction of policy measures.

3.1 Introduction

The rapidly increasing human population in the world and the concomitant increase in prosperity in some parts of the world have greatly increased the demand for crop and animal derived food during the last few decades. Improvements in agricultural production and to a lesser extent extension of the agricultural area have allowed to rapidly increase food production and to meeting the quest for food (Bruinsma, 2002; Smil, 2000). At the same time, the quality of soil, air and water has deteriorated and the area of natural ecosystems has decreased, because of the intensification and extension of agricultural production (EMA, 2005; Galloway et al., 2008; Steinfeld et al., 2006). Evidently, there is a great need to improve resource use efficiency in agriculture and to decrease losses from agriculture to the wider environment, including nitrogen (N) and phosphorus (P), also because the quest for food will continue to rise during the next decades (e.g., Sachs, 2008; Tilman et al., 2002).

China is an interesting case here, as it is the most populous country in the world. Agricultural production is highly intensive, while N and P use efficiencies low and the environmental effects of agricultural production and N and P losses are large (Vitousek et al., 2009; Zhang et al., 2005). Forecasts indicate that the population will increase further from 1.3 billion in 2005 to about 1.5 billion in 2030 (UN, 2008). In the same period, the ratio of the urban to rural populations will be reversed from 1:2 to 2:1, and the proportion of animal-derived protein in the human diets will increase further (UN, 2008). These trends pose serious challenges to agricultural production and the management of N and P flows. Unfortunately at regional level, there is little quantitative information about N and P use efficiencies and losses to air and waters in the chain of crop production, animal production, food processing, and food consumption by households. This information would be needed to identify and assess possible options for improving agricultural production and N and P use efficiencies, and for decreasing N and P losses to air and waters. A number of studies have estimated N and P budgets for crops, farming systems and sectors (Liu, 2005; Ma et al., 2008; Wei et al., 2008), but a comprehensive overview of N and P balances, losses, and use efficiencies in the whole food production-consumption chain at national and regional scales is lacking.

Food chain analyses involve the quantification of the transfers of matter, energy and or nutrients between species or sectors within an ecosystem or a particular region. The study of Bleken and Bakken (1997) in Norway was one of the first studies in which the N cost of the food consumed by humans was assessed at national level. The N-cost, defined as the ratio between total N input and the N in foodstuff was on average 10.

This indicates that for each kg of N used in food production, only 0.1 kg ended up in food consumed while 0.9 kg was dissipated into the wider environment. Isermann and Isermann (1998) estimated the N use and losses in the food chain for Germany and arrived at similar conclusions. Howarth et al. (2002) analyzed the fate of N fertilizer in the food chain in the US for the period 1961-2000, and presented potential future trends. Shindo et al. (2003) and Shindo et al. (2006) estimated the average N use efficiency in food production and total N losses to groundwater and surface water for 13 countries in East Asia for the period 1961-2020. They showed large regional differences and changes over time in consumption patterns, N use efficiency and N losses to waters. Galloway and Cowling (2002) assessed the N-cost of food production and the N losses at global scale, while Liu et al. (2008) analyzed the P-cost of food production at global scale. All of the researches mentioned above were focus on the single nutrient and environment emission. However, a comprehensive overview of N and P balances and use efficiencies in the food production-consumption chain at national and regional scales is still lacking. There is also little quantitative insight for possible management interventions at regional and national scales.

Here, we present detailed accounts of the N and P use efficiencies and losses of N and P to air, groundwater and surface water for each step of the food chain in China at national level for the year 2005. Firstly, we describe the model NUFER (Nutrient flows in Food chains, Environment and Resources use), which was developed to analyzing N and P use efficiencies and losses in crop production, animal production, food processing and food consumption by rural and urban households at regional scale. Secondly, we discuss the N and P balances, use efficiencies and losses in the food chain for the year 2005.

3.2 Materials and Methods

3.2.1 Conceptual model of the food chain

The food chain in each region (province) and for the whole of China was perceived as a ‘pyramid’ with four main compartments, namely crop production (including the rootable soil layer), animal production (including managed aquaculture), food processing and households (Figure 3-1). Nutrient N and P enter the pyramid via fertilizers, biological N_2 fixation and via imported products (from other regions or countries). They leave the pyramid via exported products and losses to air and waters. There are internal exchanges of N and P within the pyramid between the compartments via crop and animal products. Natural grasslands, rough grazing, 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).

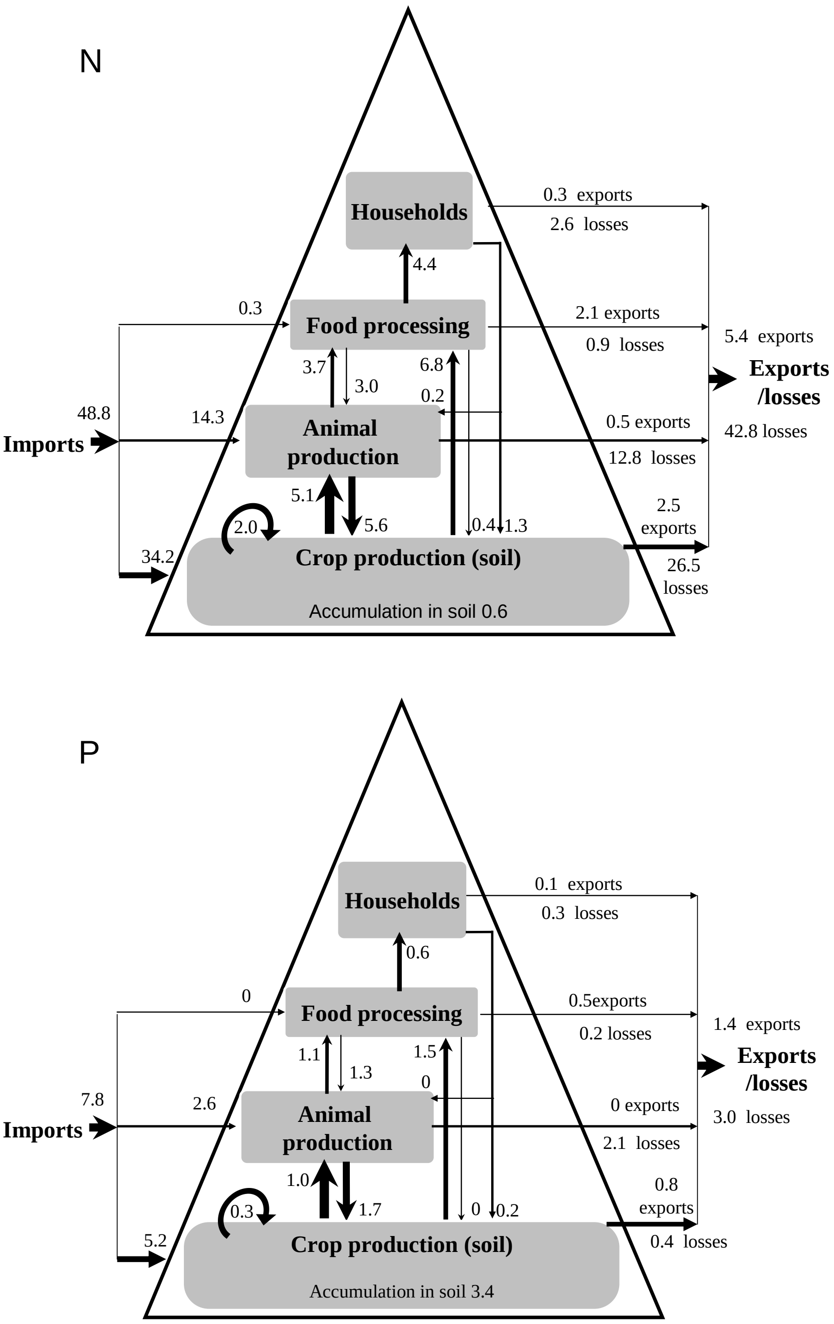

Figure 3-1 The food chain with four compartments visualized as a pyramid. The upper figure shows the N flows, the lower figure the P flows in the food chain in China at national level in 2005. Inputs into the food chain are shown on the left side, outputs (including losses to the environment) on the right side. Numbers are in million ton (Tg). Flows less than 0.1 Tg are not shown.

3.2.2 Description of the compartments

The crop production compartment included 18 crops (rice, wheat, maize, sorghum, millet, other cereal, beans, potato, peanut, rape seed, cotton, flax, sugar cane, sugar beet, tobacco, vegetable, fruit tree and managed grassland) per region, which were the main crop in China. The sown areas of 18 crops accounted for more than 95% of the total sown area.

The upper soil layer (50 cm) was considered to be part of the crop production compartment; this layer was defined by the soil volume where crops take up nutrients and water. Three textural classes (sand, loam, clay) were distinguished, on the basis of the soil map which was derived from the SOTER database (Soil Terrain Database) of World Soil Information (ISRIC, 2009).

The animal production compartment included 11 animal categories (pig, dairy cattle, dairy cattle, beef cattle, draught cattle, laying hen, broilers, sheep, horse, mule and donkey, rabbit).

The food processing compartment comprised the storage, transport, processing, packaging and retail sectors, but these sectors were lumped together as no information was available at these sector levels. Note that the transport (import and export) of processed food (and residues) between regions was considered to be part of the exchange between food processing compartments of regions, and that the transport (import and export) of unprocessed crop and animal products between regions was considered to be part of direct exchanges between the crop and animal production compartments of these regions.

The household compartment was subdivided into rural and urban households. Basically, this compartment represents the consumptions of food by humans. Including meals in restaurants. The division of rural and urban households per region was based on statistical information (ECCAP, 2006).

3.2 3 Description of NUFER

NUFER is a deterministic model with large data bases that calculates the flows, use efficiencies and emissions of N and P in the food chain of 31 regions and China on an annual basis. It uses a mass balance approach with detailed accounts of the partitioning of N and P inputs and outputs. It makes a distinction between ‘new’ N and P (from bio-fixation and imported fertilizers, natural grassland and fish), and ‘recycled’ N and P (from recycled material such as manure, crop residues, wastes, etc.).

NUFER consists of an input module with activity data and transformation and partitioning coefficients, a calculation module with equations, an optimization module and an output module. NUFER allows assessment of the N and P flows in the pyramid in two directions, viz. from the food production side and from the consumption side.

3.2.4 Input Module

Fertilizer inputs, crop yields and areas, and number of animals were based on statistical data (ECCAP, 2006; MOA, 2006). The composition of the diets of urban and rural people was based on households’ surveys in 2002 by (Zhai and Yang, 2006). Most of the other activity data were derived from unpublished reports which summarized the information collected during numerous field surveys organized by China Agricultural University and National Agriculture Technique Science Center (NATESC) from 1999 to 2008. During this period a total of 48613 farmers in 219 counties of all 31 provinces were interviewed about the farm size and structure, resources uses, farm income, and farm activities. The farmers were categorized according to farm income, farm structure and diet. The interviews addressed household composition, soil cultivation, fertilization practices, partitioning of harvested crops over main product and crop residue, animal husbandry, and manure management (NATESC, 1999a; NATESC, 1999b).

Contents of N and P in harvested crop and animal products, N and P excretion values per animal category and the partitioning of animal products in edible and other parts were derived from literature (Table 3-1). These parameters were not differentiated between regions (see Table 3-1).

Table 3-1 Summary of calculation module and references

Compartment	I /O	Item	References*
Crop production	Input	Fertilizer	20
		Animal manure	6, 12, 27, 30, 31
		Human wastes	17, 28
		Residues to field	9, 15, 20, 21, 22
		Irrigation	16, 32
		Deposition	23
		BNF	16
		Seed	5, 15, 20
		By-production of food	11, 19
	Output	Crop products, residues and grass	3, 9, 15, 20, 21, 22, 26
		NH_3 emission	12, 4
		N_2O emission	7, 38
		Denitrification, runoff, leaching, erosion and accumulation	8, 13, 14, 25, 29, 31, 33, 37
Animal production	Input	Crop products, straw and grass	3, 9, 15, 20, 21, 22, 26
		By-products of plant food processing	11, 19
		By-products of animal food processing	6, 20, 27, 30, 34, 39
		Kitchen residue	17, 28
	Output	Animal products and residues	6, 20, 27, 30, 34, 39
		Manure to natural grassland, crop land, discharge and NH_3, N_2O emission, denitrification	6, 7, 12, 27, 30, 32, 35
Food processing	Input	Crop products	9, 15, 20, 21, 22
		Animal products	6, 20, 27, 30, 34, 39
		Food import	6
	Output	Food, residues discharge, to non-food sector, to animal feed and return to field	6, 11, 19, 20, 27, 30, 34, 39
Household	Input	Plant and animal food	10, 18, 20, 24, 36
	Output	Retained in body mass, excreta applied to cropland, food residue, emission to atmosphere and discharge	17, 28

*References number: 1, Bouwman et al., 2002a; 2, Bouwman et al., 2002b; 3, CAAS, 2009; 4, Cai et al., 2002; 5, ECATEH, 1983; 6, ECCAP, 2006, 7, Eggleston et al., 2006; 8, Fu et al., 2005; 9, Gao et al., 2002; 10, Hu, 1987, 11, Li, 2007; 12, Liu, 2007; 13, Liu, 2008; 14, Lu and Higgitt, 2000; 15, Lu and Shi, 1982; 16, Lu et al., 1996; 17, Lu et al., 2008; 18, Ma, 2000; 19, Ma, 2008; 20, MOA, 2006; 21, NATESC, 1999a; 22, NATESC, 1999b; 23, Song, 2008; 24, Tao and Jin, 2003; 25, Velthof et al., 2009; 26, Wang, 1992; 27, Wang, 2008; 28, Wei et al., 2008; 29 Wischmeier, 1984; 30, Xu et al., 2005; 31, Xu et al., 2009; 32, Yang and Sun, 2008; 33, Yang et al., 2006; 34, Yang, 1991; 35, Yang, 2008; 36, Zhai and Yang, 2006; 37, Zhang et al., 2000; 38, Zhang, 2009; 39, Zhou and Chen, 1998.

3.2.5 Output Module

The output module tabulates the N and P flows, use efficiencies and emissions at compartment level at national scales. Results can be presented also in maps, showing differences between regions. In this paper, we present results for 2005, the most recent year for which all input data were available.

3.2.6 Calculation Module

Balances of N and P were calculated at compartment, regional and national levels, and in that order. For each compartment, an input-output balance was made, constraint by $I_{Total} = O_{Total}$ (Table 3-1).

Nutrient use efficiency in crop production can be defined in a number of ways (e.g. Dobermann, 2007). The same holds for animal production and for the whole food chain. Here, N use efficiency (NUE) and P use efficiency (PUE) in crop and animal productions were defined by the ratio of N (P) output in (main) products and the total N (P) input of crop and animal products.

$$NUEc = (Oc_{Main\ product} / Ic_{Total}) \times 100 \qquad [3\text{-}1]$$

$$NUEa = [(Oa_{Meat} + Oa_{Egg} + Oa_{Milk}) / Ia_{Total}] \times 100 \qquad [3\text{-}2]$$

Where Oc = output from crop production, Ic = input to crop production, Oa = output from animal production, Ia = input to animal production. These equations provide lower estimates of NUE and PUE, as by-products and residues are excluded. Including the nutrients contained in utilized by-products and residues provides higher estimates, and these were also estimated (indicated by NUEc(2), NUEa(2) PUEc(2) and PUEa(2), respectively).

NUE and PUE estimated at the food chain level (NUEf and PUEf) include the effects of by-products and residues and were estimated as follows:

$$NUEf = [(Ih_{Plant\ food} + Ih_{Animal\ food} + If_{Export} - If_{Import}) / (Ic_{Fertilizer} + Ic_{Irrigation} + Ic_{Deposition} + Ic_{BNF} + Ic_{Seed} + Ia_{Grass} + Ia_{Residue\ feed} + If_{Fish})] \times 100 \qquad [3\text{-}3]$$

Where Ih = input from household.

3.3 Results

3.3.1 Nitrogen flows at national level in 2005

The total input of ‘new’ N into the food chain at national level was 48.8 Tg (Figure 3-1). Main inputs were fertilizer (27 Tg), imported animal feed (14.3 Tg), BNF (4 Tg) and atmospheric deposition (2 Tg). Output of N occurred via export of agricultural products to the non - food sector, to other countries (only small amounts) and via losses to air and waters. The losses to air, groundwater and surface waters were the main output and were estimated at 42.8 Tg. The export of useful products from the food chain included 1.9 Tg N in grain for the production of industrial alcohol, 2.1 Tg in residues from the food processing comportment for the production of industrial alcohol, and 0.6 Tg N in straw used for the production of compressed board. Export of agricultural products to other countries was less than 0.1 Tg.

Total N input into the crop production compartment was 44 Tg in 2005 (Table 3-2). Roughly 70% of the total N input was ‘new’ N, from fertilizers (27 Tg) and biological N_2 fixation (4 Tg), and roughly 30% was ‘recycled’ N, from animal manure (5.6 Tg), crop residues (2.0 Tg), atmospheric deposition (2 Tg), irrigation, (1 Tg), human excreta (1.3 Tg) and seeds (0.3 Tg), The N output via crop products from the crop production compartment was estimated at 19 Tg, including 12 Tg in main crop products, 6 Tg in crop residues and 1 Tg in herbage from managed grasslands. Total N losses were estimated at 24 Tg, i.e., 15 Tg as gaseous N emissions and 9 Tg via leaching, erosion and runoff to groundwater and surface waters. The net accumulation of N in soil was estimated at 1 Tg (Table 3-2).

Table 3-2 Nitrogen budget of the crop production compartment at national level in 2005.

Inputs	Total (Tg)	Mean (kg ha^{-1})	Proportion (%)	Outputs	Total (Tg)	Mean (kg ha^{-1})	Proportion (%)
Fertilizer	27	231	61	Main products	12	100	26
Animal manure	6	49	13	Crop residues	6	51	13
Human wastes	1	12	3	Managed grass	1	8	2
Residues to field	2	17	4	NH_3 emission	8	73	19
Irrigation	1	4	2	N_2O emission	<0.5	3	1
Atm. deposition	2	21	5	Denitrification	7	60	16
BNF	4	38	10	Surface runoff	4	36	10
Seed	<0.5	3	1	Leaching	5	39	10
By-production of food	<0.5	4	1	Erosion	<0.5	3	1
				Accumulation	1	5	1
Total	44	378	100	Total	44	378	100

The total N input into the animal production compartment was 23 Tg, including 3 Tg from crop residues, 3 Tg from grain, 7 Tg from grass and 8 Tg N from various other residues (Table 3-3). The uncertainty in the latter number is large. In 2005, 86% of animal production was from traditional rural farming systems, where about 50% of the feed originates from various residues, including tree leaves, potato vines, peanuts shells, wild plants, and household wastes. However, it is difficult to make accurate estimates as the regional variations in the use of residues are large. The total N output was estimated at 23 Tg, including 4 Tg in meat, milk and egg, and 19 Tg animal excreta. A large part of the animal excreta was lost, i.e. 6 Tg N to the atmosphere, and 7 Tg was discharged into surface waters (Table 3-3).

Table 3-3 Nitrogen budget of the animal production compartment at national level in 2005.

Input	Total (Tg)	Mean (kg AU^{-1})	Proportion (%)	Output	Total (Tg)	Mean (kg AU^{-1})	Proportion (%)
Main crop products	3	10	12	Main products	3	9	11
By-products of plant food processing	3	9	11	Animal residues	1	4	5
Straw	1	5	6	NH_3 emission from manure	5	18	22
Grass	7	26	32	N_2O emission from manure	<0.5	<1	<1
By-products of animal food processing	<0.5	2	2	Denitrification from manure	1	3	4
Kitchen residue	<0.5	1	1	Manure to natural grassland	<0.5	2	2
Others (residue)	8	29	36	Manure to crop land	6	21	25
				Manure discharge to surface waters	7	24	30
Total	23	82	100	Total	23	82	100

AU—An animal unit is one mature cow of approximately 500 kg and a calf up to weaning, usually 6 months of age, or their equivalent.

Total N input into the food processing compartment was 11 Tg. The N output via plant and animal food was 3 and 1 Tg, respectively. About 3 Tg N in residues was utilized in animal feed and 0.4 Tg in residues was used as soil amendment. About 2 Tg was exported to the non-food chain sector, including cotton and animal fur. Another 1 Tg was lost to surface water, via discharge of wastes and cleaning water during food processing (Table 3-4).

Table 3-4 Nitrogen budget of the food processing compartment at national level in 2005

Inputs	Total (Tg)	Mean (kg $person^{-1}$)	Proportion (%)	Ouput	Total (Tg)	Mean (kg $person^{-1}$)	Proportion (%)
Crop products	7	5	63	Food from crop products	3	3	30
Animal products	4	3	34	Food from animal products	1	1	10
Fish	<0.5	<1	2	Residues discharge to water	1	1	8
Food import	<0.5	<1	<1	Residues to non-food sector	2	2	20
				Residues to animal feed	3	2	28
				Residues return to field	<0.5	<1	4
Total	11	8	100	Total	11	8	100

The total N input to the household compartment was 4.4Tg (Table 3-5). Roughly one third of the N output from households was recycled in the crop and animal production compartments; another third was lost to surface waters.

Table 3-5 Nitrogen budget of the household compartment at national level in 2005.

Input	Total (Tg)	Mean (kg $person^{-1}$)	Proportion (%)	Output	Total (Tg)	Mean (kg $person^{-1}$)	Proportion (%)
Plant food	3	3	75	Retained in body mass	<0.5	<1	2
Animal food	1	1	25	Excreta applied to cropland	1	1	31
				Food residue to animal	<0.5	<1	4
				Emission to atmosphere	1	1	26
				Discharges to surface waters	1	1	32
				Residues to landfill	<0.5	<1	5
Total input	4	3	100	Total	4	3	100

Figure 3-2 shows the relative partitioning of nutrient flow of the crop and animal production sectors, the food processing sector and the households. The crop production sector is by far the largest source of gaseous N losses (NH_3, N_2O and N_2) to air (68%) and also of N losses to waters (56%). Animal production is the second largest contributor; in contrast to crop production, its contribution of N losses to waters (33%) are larger than those to air (27%).

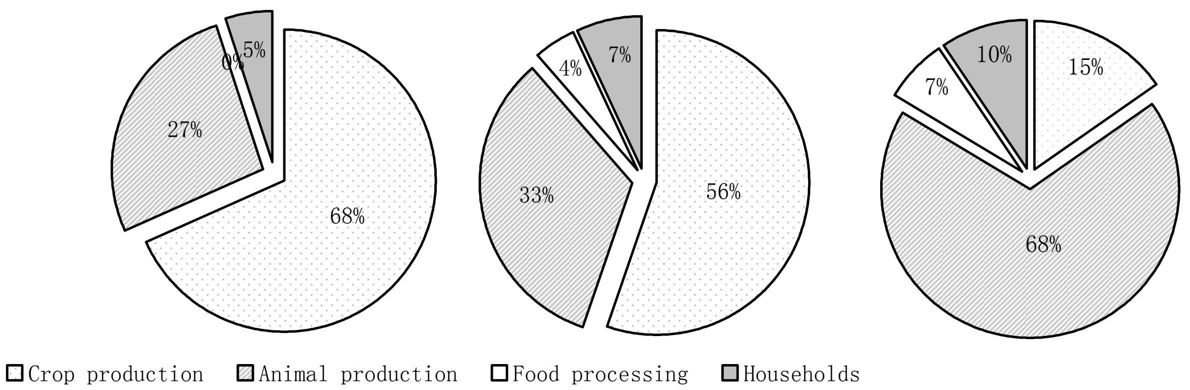

Figure 3-2 Contributions of the crop production, animal production, food processing and household compartments to the total losses of N to atmosphere (left figure), to waters (middle figure) and P to waters (right figure) at national level in 2005, %.

3.3.2 Nitrogen use efficiency at national level in 2005

The N use efficiency in the food chain (NUEf) was 8.9%. Hence, for the delivery of food to households with 1 kg of N, the crop and animal production and food processing compartments used 11 kg of N and wasted 10 kg. To be able to understand these numbers, a further look is necessary into the transfer, transformation and utilization of N in the food chain. In the crop production compartment, the mean N use efficiency (NUEc) was 26.4% and in the animal production 11.1%. These efficiencies are based on the recovery of N in the main products (equations 1 and 2). When the N in the utilized by-products and residues are included in the estimation, the N use efficiency of crop production increases to 39% (=NUEc(2)) and that of animal production to 16% (NUEa(2)).

3.3.3 Phosphorus flows and use efficiency at national level in 2005

The total P input into the food chain was 7.8 Tg (Figure 3-1). The inputs via fertilizer, irrigation and imported seeds were 5.2 Tg and via imported animal feed 2.6 Tg. The P output to the non-food sector was 1.4 Tg. About 3.4 Tg accumulated in soil and 3.0 Tg was lost to surface waters via discharges (mainly manure), runoff, erosion and leaching.

The total P input into the crop production compartment was 7 Tg (Table 3-6). Main output was via harvested crop products (3 Tg). Total input into the animal production compartment was 5 Tg. The output via animal production (pork, egg, beef, milk) was only 1 Tg; most of the P was excreted by animals and was returned as manure to crop land (2 Tg) or discharged to surface waters (2 Tg). Total input into the food processing compartment was 2 Tg; the output was less than 1 Tg (Table 3-6).

The P use efficiencies in crop and animal production were 36 and 5%, respectively (Table 3-6). When the P in the utilized by-products and residues are included in the estimation, the P use efficiency of crop production increases to 48% (=PUEc(2)) and that of animal production to 17% (PUEa(2)). The P use efficiency (PUEf) in the whole food chain was only 7%. Hence, for the delivery of food to households with 1 kg of P, the crop and animal production and food processing sectors used 13 kg of P, and wasted 12 kg P.

Table 3-6 Phosphorus budgets of the crop production, animal production and household compartments at national level in 2005.

Input	Total (Tg)	Mean (kg ha^{-1})	Proportion (%)	Output	Total (Tg)	Mean (kg ha^{-1})	Proportion (%)
Crop production(soil)							
Fertilizer	5	45	69	Main crop products	3	23	36
Manure	2	16	25	Residues	1	8	12
Others	<0.5	3	4	Leaching and runoff	<0.5	1	2
				Erosion	<0.5	3	5
				Accumulation	3	29	46
Total	7	64	100	Total	7	64	100
Animal production							
Grain feed	1	6	14	Main products	<0.5	2	5
Grass	1	7	17	Animal residues	1	5	12
Residues	3	29	69	Manure to grassland	<0.5	1	2
				Manure to crop land	2	14	36
				Manure discharge to surface waters	2	18	45
Total	5	42	100	Total	5	40	100
Food processing							
Crop products	2	13	60	Food from crop products	1	4	18
Animal products	1	9	40	Food from animal products	<0.5	1	4
				Residues discharge to water	<0.5	2	8
				Residues to non-food sector	1	4	19
				Residues to animal feed	1	11	49
				Residues return to field	<0.5	<1	2
Total	3	22	100	Total	3	22	100
Household							
Plant food	<0.5	4	81	Retained in body mass	<0.5	<1	2
Animal food	<0.5	1	19	Excreta applied to cropland	<0.5	2	32
				Food residue to animal	<0.5	<1	4
				Discharges to surface waters	<0.5	3	51
				Residues to landfill	<0.5	1	11
Total	1	5	100	Total	1	5	100

Figure 3-2 shows the relative partitioning of P flow of the crop and animal production sectors, the food processing sector and the households. The animal production sector is by far the largest source of P losses to waters (68%). Crop production is the second largest contributor; in contrast to crop production, its contribution of P losses to waters (15%). There are some relationship of N losses from crop and animal production. 28% main and residue N output from crop production were fed to livestock, which means this part N losses from crop production are tied to animal production. On the other hand, 5.6 Tg animal excreta were as manure to the field, and 25%, 1% and 10% animal manure N via NH_3, N_2O losses to atmosphere and runoff to surface waters, that mean 2 Tg N losses via animal manure and accounted for 8% of N losses from crop production.

3.4 Discussion

3.4.1 Main findings

This study provides the first comprehensive analysis of the N and P costs of plant and animal food production and consumption in China. It shows that for the delivery of the ‘average’ Chinese diet with 1 kg of protein N to households, the crop and animal production and food processing compartments used on average 11 kg of N and wasted 10 kg in the year 2005. Similarly, for the delivery of food to households with 1 kg of P, the crop and animal production and food processing sectors used 13 kg of P, and wasted 12 kg P. Indeed, the N economy of the food chain may be perceived as a pyramid; many N atoms have to support the few that are consumed in the top of the chain. However, the slope of these pyramids may vary considerably due to differences in diets and production technologies and managements, as discussed further below.

NUFER is the first model that allows the assessment of the N and P costs of food production and of the NH_3, N_2, N_2O, NO_3, N_{total} and P_{total} losses to air and waters in a uniform and integrated way for all regions in China. The model synthesizes the results of numerous field and farm studies and surveys. Results of scenario and optimization analyses at regional scale are discussed elsewhere. Further, regional variations in agro-ecosystems, NUE and PUE, N and P surpluses and N and P losses are very large, suggesting that monitoring schemes need specific designs (Gruijter et al., 2006) for which models like NUFER can be instrumental.

3.4.2 Nitrogen use efficiency of food chain in China

Globally, harvested crop biomass (main products and residues) contains on average 50% of the total N input (Smil, 2002). In China, mean NUEc(2) was 39%, and only 26% (NUEc) when the main harvested crop products are considered. This indicates that NUEc in China in 2005 was less than the world average. For the 27 Member States of the European Union (EU-27), mean NUEc for the main harvested crops in the year 2000 has been estimated at 44% (Oenema et al., 2009), while NUEc for the United States (US) in 2000 has been estimated at 56% (Howarth et al., 2002). While these differences are in part related to intrinsic differences in cropping systems and management methods, there are also slight methodological differences in the estimation of NUEc, which may obscure true differences. Yet, the trend is clear; NUEc is low in China, mainly because of the large fertilizer N input and large N losses. The same holds for PUEc (The proportion of main crop products in the table 3-6).

Concomitant with the increasing use of fertilizer during the last two to three decades, there has been an increasing neglect of N in by-products, residues and wastes. Our analyses indicate that only 33 Tg N (the sum of recycle N of Figure 3-1) in by-products, residues and wastes was used effectively out of a total of 82 Tg (the sum of total input of Tables 2-5). Hence, 60% of the N was not used and ended up unaccounted in soils or was lost to the environment. This amount (49 Tg) is much larger than the total N fertilizer use (27 Tg) in 2005. Though the effectiveness of N fertilizers is larger than that of residues and wastes, these massive amounts of unused / unaccounted for N indicate that there is scope for improving NUEc.

Commonly, N use efficiency in animal production (NUEa) is less than NUEc, when the main harvested products are considered only. In 2005, NUEa(2) was 11% when based on the production of meat, egg and milk, and 16% (NUEa) when the utilization of by-products was included, and the NUEa is related to the size of the sector: poultry>prok>beef. When the recycling of N from animal manure also is included, NUEa increases to 41% (Table 3-3). These values are relatively low compared to world average NUEa of 15%, based on main products (Zhang et al., 2005; Smil, 2002) and 16% in US (Howarth et al., 2002). However, the efficiency varies considerably between animal species. According to estimates by Van der Hoek (1998) global N efficiency (main product and by-product) was around 20% for pigs and 34% for poultry, while for beef it is commonly below 10%. For the United States, the protein conversion efficiency of dairy production has been estimated at 40 percent, which is high (Smil, 2002).

Our results indicate that only 40% of the N in crop and animal products sold to the processing compartment were indeed further transferred to households (Table 3-4). Another 20% of N in products was used by the non-food sector. The food processing compartment as perceived in this study is a heterogeneous agglomeration of transport, storage, processing and retail of the products from the crop and animal production compartments. It adds economic value to the crop and animal products and it connects primary producers to household consumers. Although only 40% of the N in crop and animal products was transferred to consumers, our data suggest that much of the remainder was effectively utilized by other sectors and that relatively little was wasted in this compartment. The overall N efficiency in the food chain (NUEf) was defined as the ratio between protein-N in food delivered to households and input of ‘new’ N into the pyramid; it was on average 9% in 2005. This value is intermediate of the estimated world average of 14% for plant food and of 4% for animal food (Galloway and Cowling, 2002). It compares also reasonable with the 10% efficiency estimated for the Norwegian society (Bleken and Bakken, 1997). Though the average Chinese diet is still relatively low in animal protein compared to the diets in northern America and Europe, the N cost of producing this diet is relatively high, and as a consequence, the losses of N to air and water are high.

3.4.3 Losses of N to air and waters

The N surplus is a key environmental pressure indicator, because it expresses the potential N loss to air and waters per unit surface area and year. The mean N surplus of cropland was 221 kg N ha^{-1} in 2005 (Table 3-2), which is one of the highest in the world (Vitousek et al., 2009; Shindo et al., 2003). Apart from a small, but highly uncertain accumulation in soil, the total N surplus of cropland (25 Tg) was dissipated into the atmosphere (56%), mainly in the form of NH_3, N_2 and N_2O, surface waters (30%) and groundwater (14%). Additional losses occurred from point sources, i.e., manure management, food processing and households. The overall mean N losses from agriculture (crop and animal production) via NH_3 volatilization, leaching (including erosion and runoff) to groundwater and surface waters, and denitrification were equivalent to 117, 153 and 73 kg N ha^{-1} agricultural land in 2005. These results contrast with those of for example the EU-27, where mean losses via NH_3 volatilization, leaching and denitrification were 17, 16 and 48 kg N ha^{-1} agricultural land in 2000 (Velthof et al., 2009). Apart from the more that 4 times higher total losses, there were significant differences in the dominant loss pathways, i.e., NH_3 volatilization and leaching are more dominant than denitrification in China, while the opposite seems to be true for EU-27. These differences are related to differences in population, cropping systems (double and triple in China versus one crop per year in EU-27), governmental policy measures and management practices to reduce N and P losses in EU-27 and as yet none in China, environmental conditions, and also to model perceptions and uncertainties. While there is a relative wealth of monitoring data as regards N and P losses from agriculture in EU-27, there is scarcity of systematic monitoring data in China, which complicates the validation of NUFER.

3.4.4 Management options for enhancing NUE and decreasing N losses

There are various reasons for the astonishing high N losses in various regions in China. The N application to soil has a strong impact on N losses to atmosphere via NH_3, N_2O and N surplus, runoff factors and leaching factors affect N losses to underground water and surface waters and N_2 losses from crop production. For animal production, the animal intensity and radio of animal excreta discharge decide on the N losses via NH_3, N_2O and N_2 to atmosphere and to waters respectively. These losses have been measured also in field experiments in various agro-ecosystems (Ju et al., 2009), and have been ascribed to a variety of reasons (Ma and Zhang, 2003; Zhang et al., 2005). A first reason is overfertilization, mainly due to the subsidies on fertilizers and the common conviction that more fertilizer gives higher yields. Also, other sources of N (manure, crop residues, irrigation water) are not properly considered when defining the N fertilizer application rate. Second reason is the high NH_3 emission potential of the commonly used fertilizers urea (60%) and ammonium bicarbonate (27% of total N fertilizer use). A third reason is the intensification of animal production and the establishment of landless farms with little or no opportunity for recycling of nutrients from the animal manure. 47%, 50%, 75% and 65% of the total pork production, dairy and beef production, layer chicken and broiler chicken shifted from land-based to landless over the past ~20 years. A fourth reason is unbalanced fertilization; until recently other essential nutrients like P, K, Zn were in part neglected. A fifth reason is the lack of incentives and regulations to store, handle and use fertilizers, animal manure, and other residues effectively and to minimize nutrient losses. Apart from these and other rather technical reasons, also institutional, educational and behavioral reasons have been put forwards. These latter include the breakdown of cultural practices to use resources and especially organic wastes effectively, the pressure to produce more food for the growing human population, the low education of rural people, and urbanization and the establishment of part-time farmers with little time to manage the land properly. Evidently, there is a variety of possible reasons for the high N and P losses, which are farm and region specific, suggesting that there is no ‘one fix for all cases’. Yet, it seems unfeasible to establish and implement farm-specific nutrient management on all ~0.8 billion farms in China in short term.

Based on our modeling exercises, literature data and forecasts of demographic and agricultural developments, it will be clear that improved nutrient management strategies will have to include the following basic elements (i) increased crop and animal productivity to feed the growing population, (ii) balanced fertilization, i.e., matching crop nutrient demands in the proper ratios, and (iii) manure management focused on full recycling of all animal excrements. Such integrated nutrient management strategies (INM) will have to be implemented step-wise. Experiences with INM so far indicate that N fertilizer input can be reduced by 5-30% and that grain yield can be increased by 10-15% compared to traditional practices (Ju et al., 2009; Zhang et al., 2005; Zhang et al., 2007). The potential of INM has been recognized by policy makers now. For example, a national program for Soil Testing and Fertilizer Recommendation has been set up to help farmers to implementing balanced fertilization. At the same time, unbalanced economic development and income disparities have led to the co-existence of over-nutrition and undernourishment among different demographic groups (Zhang et al., 2005). Therefore, INM strategies should also address human diets and increasing its nutritional value.

Emphasis should go also to improving animal production and manure management. The animal production sector is transforming rapidly like in many other countries in SE Asia. This transition has been termed 'Livestock Revolution' (Delgado et al., 1999), and has profound implications for the environment, but also for human health and livelihoods. The traditional animal production systems are small-scale, land-based, mixed systems with a relatively low productivity but with effective recycling and utilization of nutrients and carbon. The modern systems are large-scale, landless, specialized systems with a high productivity but with little or no opportunities for effective recycling and utilization of nutrients carbon. Here, a large part of the produced manure is discharged into surface waters and not properly used as fertilizer. Improved manure storage, handling and use may greatly contribute to increasing NUE and decreasing nutrient losses. Evidently, the potentials of INM has to be explored further through modeling studies, field experimentation and on-farm demonstrations.

3.4.5 The differences between N and P flow in food chain in China

There are various relationships between N and P flow in food chain in China. Firstly, the activity of N was higher than P during the soil system, crop and animal production, losses to environment. Secondly, the N/P in crop production, animal production, food processing and households compartment were 5.9, 4.6, 4.2 and 7.7 respectively. The food N is main demand of human and the P is accompanying with food N, so the N/P of households is higher than the other compartment. Thirdly, NUEc was lower than PUEc and NUEa was higher than PUEa. Fourthly, the crop production sector is by far the largest source of gaseous N losses (NH_3, N_2O and N_2) to air (68%) and also of N losses to waters (56%), but the animal production sector is by far the largest source of P losses to waters (68%).

3.4.6 Uncertainties

For the model research, variables with the highest level of data uncertainty will be result in the uncertainty of result, and the further testing and validation should be necessary. But in this study, it is difficult to test and validate for the regional and national scale. This paper cannot include the uncertainty analysis for every parameter.

The uncertainty of the result would come from several resources and be controlled by several ways. Firstly, statistical data have some uncertainties themselves. For example, the meat production could not be compared to the meat consumption according to the statistical data. This problem could be resolved by calibration of the N flow from animal production to households using literature about food consumption outside the home, which percentage is about 20% (Ma, 2000). Secondly, the N contents were based on literature data, which also have some uncertainty. There are some methods for uncertainty analysis at regional and national scale, which can be used in future.

3.5 Conclusions

NUFER is the first model that allows a quantitative assessment of the N and P cost of food production and N and P losses to air and waters at regional and national scale in China. The model is able to explore options and scenarios for improving nutrient management in crop production, animal production, food processing and households.

Our comprehensive analyses of the food chain indicate that the mean N cost of food production in China was 11 kg of 1 kg food N in 2005. Similarly, the mean P cost of food production was 13 kg of 1 kg food P.

These high costs were related to the low N and P use efficiencies in crop production (NUEc = 26%; PUEc = 36%) and animal production (NUEa = 11%; PUEa = 5%). Losses of N to air, groundwater and surface waters and of P to surface waters were high. The large NH_3 emissions (13 Tg N) were related to the type of N fertilizer (urea and NH_4HCO_3) and manure management. The large leaching losses of N and P to surface waters were related to discharges of manure into surface waters and to leaching, surface runoff and erosion. Losses of N through denitrification were estimated to be relatively small.

A number of management measures have been identified that should be explored and quantified further. Key measures are (i) increasing crop and animal production, (ii) balanced fertilization, and (iii) improved manure management.

Acknowledgement

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CHAPTER 4

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

This chapter is published in Science of the Total Environment 2012, 434: 51-61. Supplementary information and tables S1, S2, S3, S4, S5, S6, S7 and S8 can be found in the link http://www.sciencedirect.com/science/article/pii/S0048969712003890#ec0005.

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 1980-2005.

4.1 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 has 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 (Bouwman et al., 2009; Conley et al., 2009; Galloway et al., 2008; Smil, 2000; Tilman, 1999; Townsend et al., 2003; 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 (Cui et al., 2008a, 2008b; Zhen et al., 2006). 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 inefficiencies in food processing, retail and households. In 2005, a total 11 kg of N were needed to provide 1 kg of protein N on the plate of the Chinese consumers, while 10 kg of N were 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).

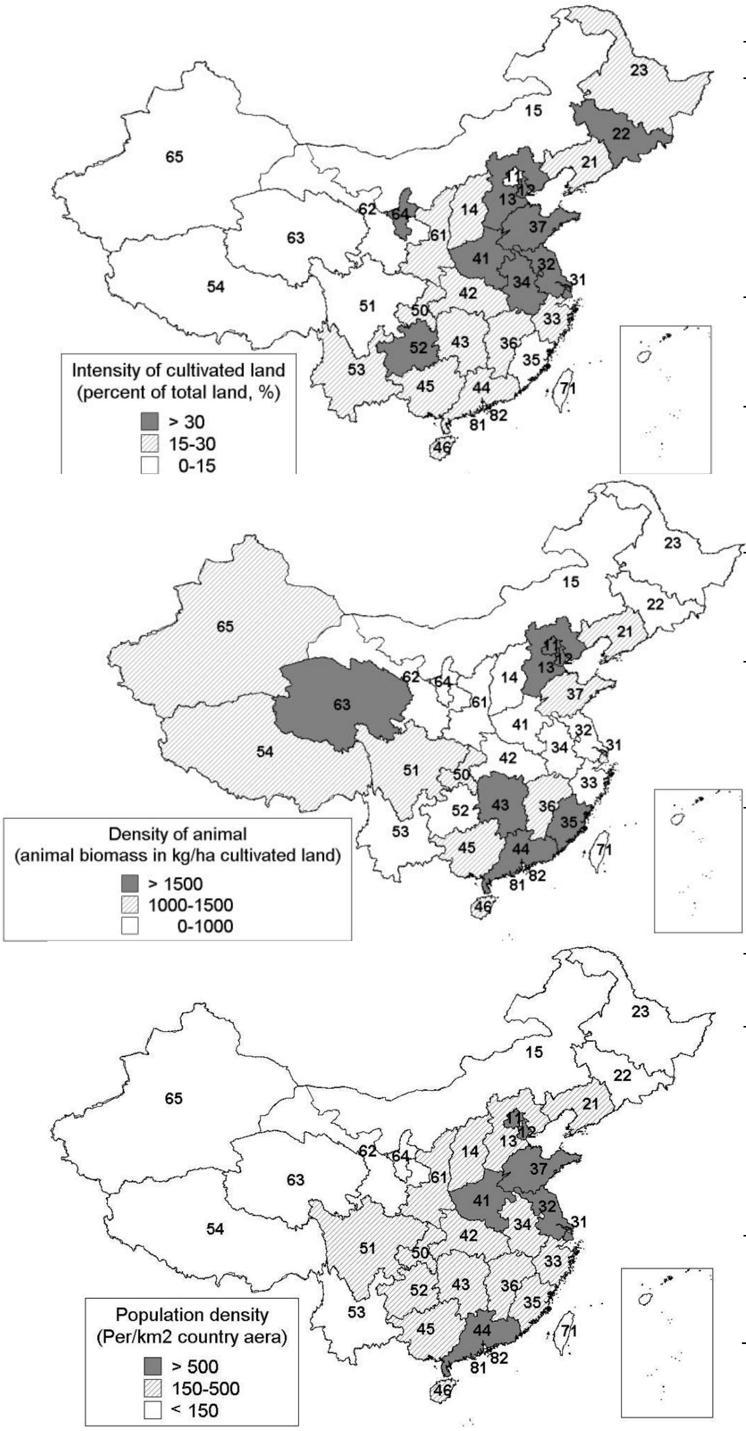
Though the general picture is rather clear, there are large regional differences, which are less quantified and understood. For example, in western China, fertilizer use is much lower than in the eastern. In some areas, crop residues are used for animal feed or fuel, while animal manure is also used 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 estimates 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.

4.2 Materials and methods

4.2.1 Brief description of agriculture in the 31 provinces

Figure 4-1 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.



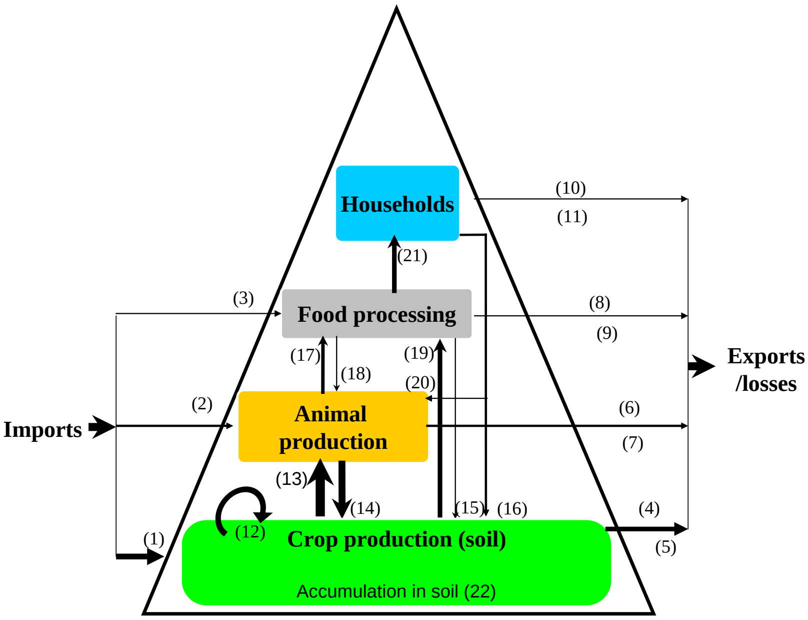
Region	Code	Name
North	11	Beijing
	12	Tianjin
	13	Hebei
	14	Shanxi
	37	Shandong
	41	Henan
Northeast	21	Liaoning
	22	Jilin
	23	Heilongjiang
East	31	Shanghai
	32	Jiangsu
	33	Zhejiang
	34	Anhui
Central	36	Jiangxi
	42	Hubei
	43	Hunan
South	44	Guangdong
	45	Guangxi
	46	Hainan
	35	Fujian
Southwest	50	Chongqing
	51	Sichuan
	52	Guizhou
	53	Yunnan
Plateau	54	Tibet
	63	Qinghai
Northwest	61	Shaanxi
	62	Gansu
	64	Ningxia
	65	Xinjiang
	15	Inner-mongolia
	71	Taiwan
	81	Hongkong
	82	Macao

Figure 4-1 Maps of the utilized agricultural area (in percent), livestock density (in biomass per unit of agricultural land), and human population density (in capita per km^2) in 31 provinces of China in 2005. The regional clustering of provinces in the Table is based on similarities in economic growth, demographic development and land use (Fischer et al., 2010).

4.2.2 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 meter of soil), (ii) animal production (including managed aquaculture), (iii) food processing and retail, and (iv) households (Figure 4-2). New N and P enters 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 efficiency 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).



Item	Code	N (in Tg)		P (in Tg)	
		1980	2005	1980	2005
	Input				
Import to crop production	(1)	11.9	34.2	1.3	5.2
Import to animal production	(2)	4.9	14.3	0.6	2.6
Import to food processing	(3)	0.4	0.3	<0.05	<0.05
	Output				
Export from crop production	(4)	<0.05	2.5	0.2	0.8
Losses from crop production	(5)	9.4	26.5	0.1	0.4
Export from animal production	(6)	0.7	0.5	0.2	0.8
Losses from animal production	(7)	2.5	12.8	<0.05	2.1
Export from food processing	(8)	1.7	2.1	0.6	0.5
Losses from food processing	(9)	0.9	0.9	0.2	0.2
Export from household	(10)	0.1	0.3	<0.05	0.1
Losses from household	(11)	1.5	2.6	0.2	0.3
	Production→consumption				
Crop production→animal production	(13)	1.5	5.1	0.3	1
Crop production →food processing	(19)	5.3	6.8	1.3	1.5
Animal production →food processing	(17)	0.7	3.7	0.2	1.1
Food processing→households	(21)	2.8	4.4	0.4	0.6
	Cycling				
Cycling in crop production	(12)	0.8	2	0.1	0.3
Animal production →crop production	(14)	3.5	5.6	0.8	1.7
Food processing →crop production	(15)	0.1	0.4	<0.05	<0.05
Households→crop production	(16)	1.1	1.3	0.1	0.2
Food processing→animal production	(18)	0.9	3	0.3	1.3
Households→animal production	(20)	0.1	0.2	<0.05	<0.05
Accumulation in soil	(22)	0.4	0.6	0.4	3.4

Figure 4-2 Flows of N and P in the food pyramid in China at national level in 1980 and 2005 (Unit: Tg = 10^{15} g). Arrows in the food pyramid represent N and P flows, which are further explained in the Table. Numbers between brackets refer to the codes in the Table.

4.2.3 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):

$$NUEc = (Oc_{Main\ product} / Ic_{Total}) \times 100\% \quad [4\text{-}1]$$
$$NUEa = [(Oa_{Meat} + Oa_{Egg} + Oa_{Milk}) / Ia_{Total}] \times 100\% \quad [4\text{-}2]$$

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

Equations [4-1] and [4-2] were also used the calculation of P use efficiency in crop production (PUEc) and animal production (PUEa).

The N and P use efficiencies in food processing (NUEfp and PUEfp) were estimated as follows:

$$N(P)UEfp = [(Ofp_{Plant\ food} + Ofp_{Animal\ food}) / (Ifp_{Crop\ production} + Ifp_{Animal\ production})] \times 100\% \quad [4\text{-}3]$$

Where
Ofp = output of N or P from food processing,
Ifp = input of N or P to food processing,
$Ifp_{Crop\ production} = Oc_{main\ product}$,
$Ifp_{Animal\ production} = Oa_{Meat} + Oa_{Egg} + Oa_{Milk} + Oa_{Bone} + Oa_{By\text{-}product} + Ifp_{Fish}$,
Oa_{Meat} = output from animal production as meat,
Oa_{Egg} = output from animal production as egg,
Oa_{Millk} = output from animal production as milk,
Oa_{Bone} = output from animal production as bones,
$Oa_{By\text{-}product}$ = output from animal production as by-products, and
Oa_{Fish} = output from animal production as fish.

Nutrient use efficiency in crop and animal production combined (NUEc+a and PUEc+a) were estimated as follows:

$$N(P)UEc{+}a = [(Oc_{Main\ product} + Oa_{meat} + Oa_{Egg} + Oa_{Millk} + Oa_{Fish}) / (Ic_{Fertilizer} + Ic_{Irrigation} + Ic_{Dposition} + Ic_{BNF} + Ia_{Grass} + Ia_{Residue\ feed})] \times 100\% \quad [4\text{-}4]$$

Nutrient use efficiency in the whole food chain (NUEf and PUEf) was estimated as follows:

$$N(P)UEf = [(Ih_{Plant\ food} + Ih_{Animal\ food} + Ifp_{Export} - Ifp_{Import}) / (Ic_{Fertilizer} + Ic_{Irrigation} + Ic_{Deposition} + Ic_{BNF} + Ia_{Grass} + Ia_{Residue\ feed} + Ifp_{Fish})] \times 100\% \quad [4\text{-}5]$$

Where
Ih = input to household, and
Ifp = input to food processing.

Balances of N and P were calculated at sector, regional and national levels, and in that order. For each compartment, an input-output balance was made, constrained by $I_{Total} = O_{Total}$, where I_{Total} is the total N input and O_{total} is the total N output to the compartment. The N and P surpluses represent the difference between total N and P inputs and the outputs in harvested (main) products.

Losses of N via NH_3 volatilization and N_2O emissions were calculated as N-source specific fractions of the N input, while losses via denitrification and N leaching (including erosion and runoff) to groundwater and surface waters as soil and climate specific fractions of the N surplus. Losses of P leaching (including erosion and runoff) to surface waters were estimated via soil type, climate and geomorphology specific fractions of the total P input and soil P (See Ma et al., 2010 and Supplementary information).

4.2.4 Data sources and analysis

Four main data sources were used for deriving input data of NUFER. Firstly, authoritative statistical sources (ECCAP, 2006; MOA, 2006) for records about fertilizer use, crop yields, cultivated areas and number of animals at regional levels. Fertilizer applications at regional level calculated by the input via single and compound fertilizers, according to the China Agricultural Yearbook. The crop yields and cultivated areas included 18 crops (rice, wheat, maize, sorghum, millet, other cereal, beans, potato, peanut, rape seed, cotton, flax, sugar cane, sugar beet, tobacco, vegetable, fruit tree and managed grassland) per region. The sown areas of these 18 crops accounted for more than 95% of the total sown area. The animal numbers considered 11 animal categories (pig, dairy cattle, dairy cattle, beef cattle, draught cattle, laying hen, broilers, sheep, horse, mule and donkey, rabbit).

Secondly, farm survey reports of the China Agricultural University and National Agriculture Technique Science Center (NATESC) for the period 1999 to 2008. These reports were used to derive farm management activity data. The farm survey reports where based on the results of questionnaires, and provided information about farm structure and management. The surveys used a stratified random sampling approach to choose survey areas and households. A total of 48,613 farmers in 219 counties of all 31 provinces have been interviewed about farm structure, resources uses, farm income, and farm activities. The interviews addressed household composition, soil cultivation, fertilization practices, partitioning of harvested crops over main product and crop residue, animal husbandry, and manure management. The data of all questionnaires have been processed and analyzed statistically. About 5% of the questionnaires were disregarded because of illogical data.

Thirdly, literature data for N and P concentrations in harvested crop and animal products, N and P excretion values per animal category and the partitioning of animal products in edible and other parts. Most of them are measurement data. These parameters were not differentiated between regions.

Fourthly parameters for N and P loss factors from crop production and animal production were derived from literature data and surveys, directly or indirectly following interpretation and initial model calculations and assessments. The following N losses were considered:

- Volatilization of ammonia (NH_3)
- Surface runoff and erosion
- Emissions of nitrous oxide (N_2O), nitric oxide (NO), and nitrogen (N_2) from nitrification and denitrification processes from chemical fertilizer and manure application in the crop production, and
- Downward leaching of nitrates.

Emissions of gaseous N were estimated from manure produced in housing systems, manure in storage and processing, and from droppings by grazing animals. Emission factors and transfer parameters were derived from literature. Further, leaching, run off and erosion of N and P to groundwater and surface waters may occur from uncovered and unsealed manure storage and processing systems, discharges of animal manures, and from agricultural land (diffuse sources). The transfer coefficients and emission factors were estimated from temperature, slope, soil texture, land use, rainfall (intensity), soil depth and crop information (Ma et al., 2010). As a result, N loss pathways differed sharply among regions due to differences in climate, soils, nutrient application, land uses and crop management practices (Ju et al., 2009). A detailed description of emission factors and transfer coefficients are presented in the supplementary information accompanying this paper.

4.3 Results

4.3.1 Main inputs and outputs of N and P in the food chain of China

The amount of ‘new’ N imported into the food chain at national level increased from 17.2 Tg in 1980 to 48.8 Tg in 2005. Main inputs were chemical fertilizer, imported animal feed, biological N_2 fixation (BNF) and atmospheric deposition (Figure 4-2). For comparison, the human population increased from roughly 1.0 billion in 1980 to 1.3 billion in 2005.

Export of N from the food chain occurred via export of agricultural products to the non-food sector, to other countries (only small amounts) and via losses to air and waters. The export of useful products from the food chain included grains and residues of the food processing sector for the production of industrial alcohol, and straw used for the production of compressed board. Total export was 2.5 Tg in 1980 and 5.4 Tg in 2005. However, the largest output occurred through losses of N to air, groundwater and surface waters. Total N losses were estimated at 14.3 Tg in 1980 and at 42.8 Tg in 2005 (Figure 4-2). Hence, total N losses almost tripled.

Between 1980 and 2005, N flows (in animal feed) from the crop production sector to the animal production sector increased by a factor of 3.4. Similarly, N flows from crop production to the food processing sector (cereals, vegetables, fruits) and from animal production to food processing (meat, milk and egg) increased by a factor of 1.3 and 5.3, respectively. Further, N flows from food processing to households (plant and animal food) increased by a factor of 1.6 between 1980 and 2005. Hence, animal-derived food consumption increased much faster than the consumption of plant-derived food.

The 'return' of N via residues and wastes from the household sector to the crop production sector, and from animal production to crop production via animal manure also increased, but less than the 'upward' flows. The total amount of N recycled amounted to 6.5 Tg in 1980 and 12.5 Tg in 2005 (Figure 4-2).

Total import of 'new' P into the food chain was 1.9 Tg in 1980 (P import to crop production, animal production and food processing were 1.3, 0.6 and <0.05 Tg, respectively; see Figure 4-2). In 2005, total import of 'new' P into the food chain was 7.8 Tg (P import to crop production, animal production and food processing were 5.2, 2.6 and <0.05 Tg, respectively). Imports of fertilizer P into the crop production sector and of feed P into the animal production sector increased both by a factor of four. Total P export from the food chain to the non-food sector and to other countries was 1.0 Tg in 1980 and 2.1 Tg in 2005 (see Figure 4-2). Estimated P losses to surface waters via discharges (mainly manure), runoff, erosion and leaching were 0.5 Tg in 1980 and 3.0 Tg in 2005. The return of P via residues and wastes from household, food processing and animal production also increased, but less than the 'upward' flows of P in the food chain. Total amounts of P recycled [flows 12, 14, 15, 16, 18 and 20 in Figure 4-2] amounted to 1.4 Tg in 1980 and 3.5 Tg in 2005. Accumulation of soil P increased from 0.4 Tg in 1980 to 3.4 Tg in 2005.

4.3.2 N and P balances in crop production

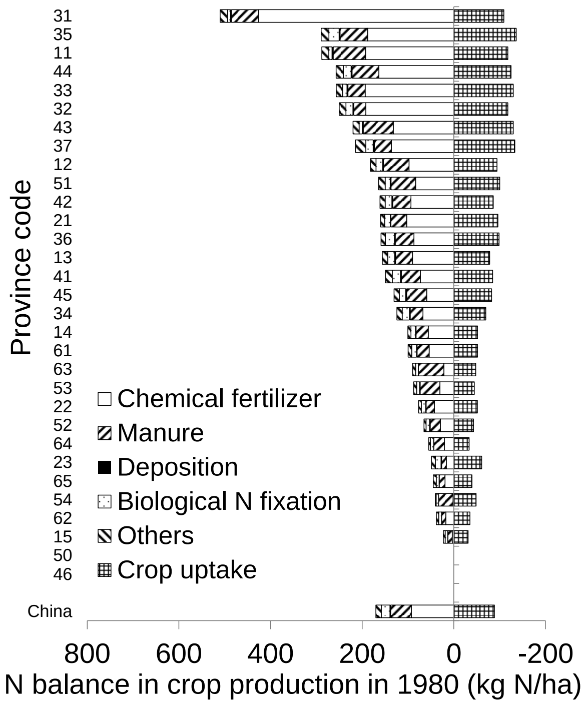
Fertilizer N contributed 54% in 1980 and 61% in 2005 to the total N input into the crop production sector at national level. The contribution of manure N decreased from 27% in 1980 to 16% in 2005. However, there were large differences between provinces. Mean total N input to cropland in the 31 provinces ranged from 23 to 510 kg $ha^{-1}yr^{-1}$ in 1980 and from 63 to 673 kg $ha^{-1}yr^{-1}$ in 2005. In 1980, there were 8 provinces, and in 2005, 22 provinces with mean N inputs of more than 200 kg ha^{-1} (Figure 4-3). Provinces with high N input in 1980 also had high N input in 2005, but changes in mean N input greatly differed and hence the order of the province with highest N input changed (Figure 4-3). Increases were largest in the south, east and central parts of China. Mean N yield in harvested crop at national level increased from 89 kg ha^{-1} in 1980 to 158 kg ha^{-1} in 2005. Mean N surplus increased from 81 to 220 kg ha^{-1}. Again, regional differences were large, but less than in total N input (Figure 4-3).

Mean total P input ranged from 3 to 51 kg ha^{-1} in 1980 and from 13 to 116 kg ha^{-1} in 2005. In 1980, there were 5 provinces [Guangdong (44), Fujian (35), Hunan (43), Beijing (11) and Shanghai (31)] with total P inputs of more than 30 kg ha^{-1} and in 2005 there were 24 provinces (Figure 4-3). Mean P yield in harvested crop ranged from 5 to 27 kg ha^{-1} in 1980 and from 10 to 47 kg ha^{-1} in 2005. Mean P surplus was less than 10 kg ha^{-1} in 1980 and about 35 kg ha^{-1} in 2005. In Fujian (35), mean P surplus in 2005 was even more than 70 kg ha^{-1}.

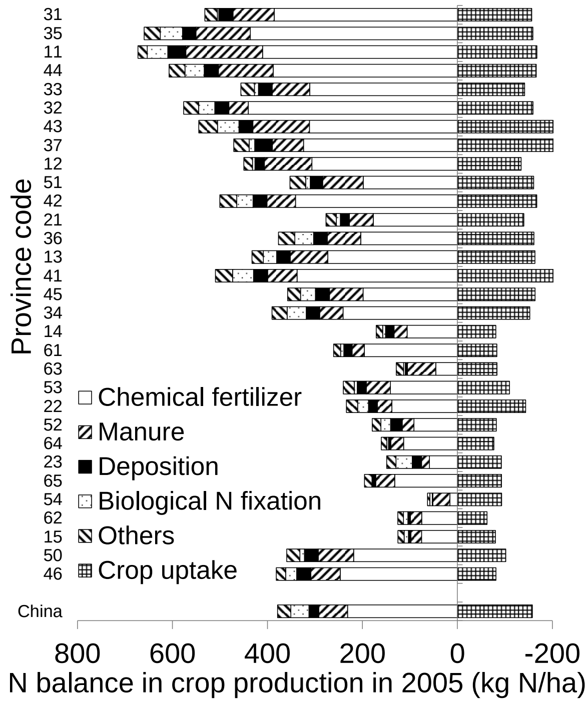
4.3.3 NUE and PUE in the food chain

At national level, mean N use efficiency in crop production (NUEc) was 32% in 1980 and 26% in 2005. In animal production, mean NUEa increased from 8% in 1980 to 16% in 2005. At the whole food chain level, NUEf was 16% in 1980 and 9% in 2005 (Table 4-1). Similarly, mean P use efficiencies in crop production (PUEc) were 59 and 23%, in animal production (PUEa) 16 and 17%, and in the whole food chain 19 and 7% in 1980 and 2005, respectively (Table 4-2).

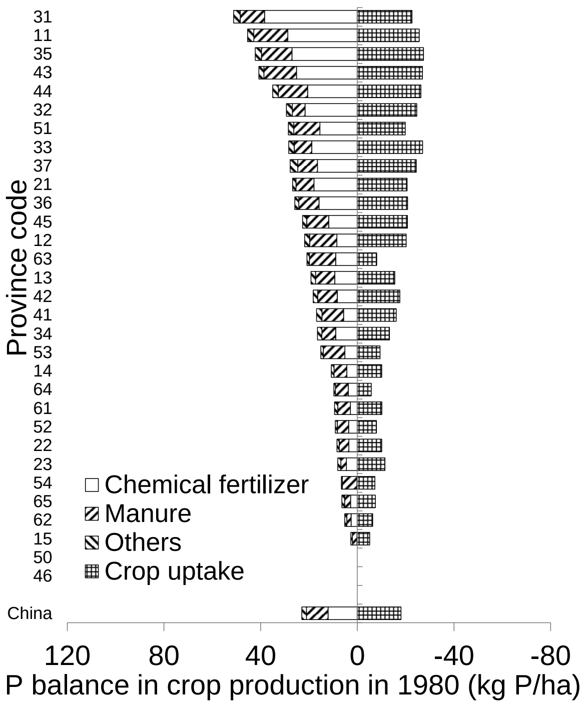
Regional differences in NUE and PUE were large. In crop production, regional mean NUEc in 2005 ranged from 12% in Hainan (46) to 45% in Tibet, while PUEc ranged from 19% in Fujian (35) to 67% in Jilin (Tables 4-1, 4-2). All provinces exhibit decreases in NUEc and PUEc between 1980 and 2005. Interestingly, NUEa and PUEa increased in almost all provinces between 1980 to 2005. The increases in NUEa and PUEa at herd level are related to the strong increase in the number of modern, large livestock operations. These farms have genetically improved herds and use high-quality feeds, and thereby have lower feed conversion rates than the traditional smallholder farms.



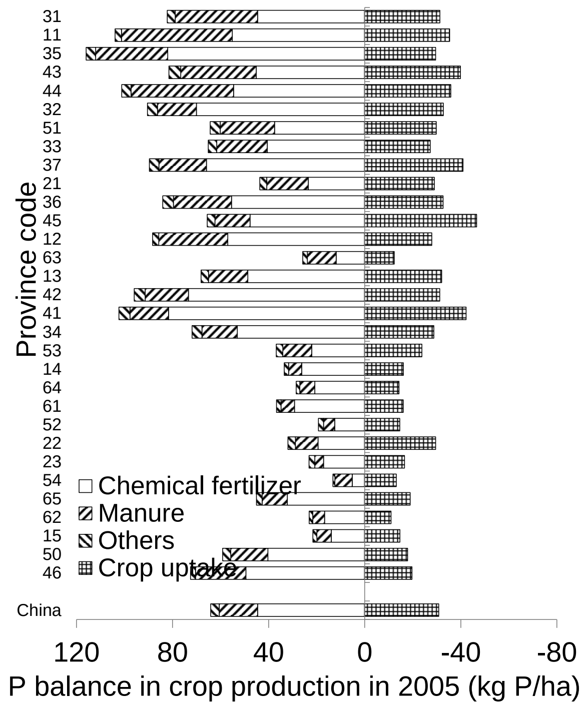
(Fig 4-3a)



(Fig 4-3b)



(Fig 4-3c)



(Fig 4-3d)

Figure 4-3 Input-output balances for N (upper panel) and P (lower panel) of cropland in 31 provinces of China in 1980 and 2005. Inputs are plotted on the left hand side of the Y-axis, outputs on the right hand side. Provinces are ordered according to N and P balances in 1980. For province code see Figure 1. There are no data of province 46 and 50 in 1980 (kg ha^{-1}).

Table 4-1 NUE in crop production, animal production, food processing and food chain in 31 provinces of China between 1980 and 2005 (*: no data).

Province	NUEc (%)			NUEa (%)			NUEfp (%)			NUEf (%)		
code/name	1980	2005	Change	1980	2005	Change	1980	2005	Change	1980	2005	Change
11/Beijing	27	19	-8	9	20	10	83	70	-12	9	4	-6
12/Tianjin	33	21	-11	12	20	9	81	70	-11	14	6	-8
13/Hebei	31	27	-4	11	17	7	75	62	-13	15	8	-7
14/Shanxi	29	29	0	7	12	6	78	59	-19	13	6	-7
15/Inner Mongolia	65	33	-31	5	10	5	66	53	-13	14	6	-8
21/Liaoning	35	33	-2	10	24	14	79	70	-9	16	8	-8
22/Jilin	40	38	-2	8	18	10	70	53	-17	16	8	-9
23/Heilongjiang	80	40	-40	8	17	9	67	47	-20	49	14	-35
31/Shanghai	13	21	8	11	23	13	78	70	-7	5	7	2
32/Jiangsu	30	18	-12	9	23	14	84	72	-11	15	10	-5
33/Zhejiang	31	21	-10	9	20	11	85	71	-14	17	9	-7
34/Anhui	34	26	-8	8	19	11	76	58	-18	16	12	-4
35/Fujian	28	15	-12	10	23	13	84	76	-9	15	8	-7
36/Jiangxi	38	27	-11	8	17	9	87	71	-17	18	14	-4
37/Shandong	40	33	-7	11	21	10	67	61	-6	18	10	-8
41/Henan	37	31	-6	8	15	6	73	57	-16	16	11	-5
42/Hubei	33	22	-11	8	19	11	82	58	-23	15	9	-7
43/Hunan	36	23	-12	9	14	6	85	64	-21	18	10	-8
44/Guangdong	29	17	-12	7	22	15	82	70	-12	14	8	-6
45/Guangxi	35	24	-11	6	14	8	78	58	-21	16	8	-7
46/Hainan	*	12	*	*	17	*	*	72	*	*	6	*
50/Chongqing	*	17	*	*	11	0	*	44	*	*	3	*
51/Sichuan	36	27	-8	7	14	7	80	56	-24	17	9	-8
52/Guizhou	35	24	-11	3	13	10	79	51	-28	16	7	-9
53/Yunnan	30	26	-4	5	11	5	73	56	-17	12	9	-3
54/Tibet	33	45	12	4	10	5	79	60	-19	6	12	6
61/Shaanxi	30	20	-10	5	9	4	79	53	-26	13	5	-8
62/Gansu	50	25	-24	5	9	4	76	51	-25	15	6	-9
63/Qinghai	26	29	3	4	10	6	71	44	-27	5	5	0
64/Ningxia	27	23	-4	8	13	5	79	67	-13	15	8	-7
65/Xinjiang	53	25	-27	6	10	4	67	57	-10	11	6	-5
China	32	26	-6	8	16	8	79	60	-19	16	9	-7

Table 4-2 PUE in crop production, animal production, food processing and food chain in 31 provinces of China between 1980 and 2005 (*: no data).

Province	PUEc (%)			PUEa (%)			PUEfp (%)			PUEf (%)		
code/name	1980	2005	Change	1980	2005	Change	1980	2005	Change	1980	2005	Change
11/Beijing	43	28	-15	12	16	3	82	49	-34	11	3	-8
12/Tianjin	70	26	-45	14	16	2	81	50	-32	22	4	-18
13/Hebei	60	38	-22	17	24	7	75	50	-26	23	7	-16
14/Shanxi	65	35	-31	22	21	-1	73	43	-29	26	4	-22
15/Inner Mongolia	108	44	-64	21	23	1	56	32	-24	16	4	-12
21/Liaoning	55	49	-6	11	17	6	82	50	-31	19	6	-13
22/Jilin	85	67	-18	12	17	5	75	40	-34	36	7	-29
23/Heilongjiang	107	53	-54	13	23	10	73	46	-27	58	12	-46
31/Shanghai	33	31	-2	16	9	-6	78	65	-13	8	5	-3
32/Jiangsu	64	28	-36	18	10	-7	83	68	-15	25	8	-18
33/Zhejiang	70	32	-38	15	12	-3	86	65	-21	30	8	-22
34/Anhui	59	30	-29	13	15	3	79	57	-23	23	8	-15
35/Fujian	47	19	-28	10	13	4	87	69	-19	18	6	-12
36/Jiangxi	59	29	-31	7	10	3	90	69	-21	23	9	-14
37/Shandong	65	37	-28	17	20	3	73	49	-24	25	6	-19
41/Henan	72	33	-39	14	15	2	76	56	-20	29	7	-22
42/Hubei	72	24	-48	8	11	3	84	61	-23	28	6	-22
43/Hunan	49	36	-13	8	12	4	88	63	-25	18	10	-9
44/Guangdong	55	27	-28	6	9	3	83	55	-29	20	5	-14
45/Guangxi	70	55	-14	6	15	8	62	32	-30	24	11	-13
46/Hainan	*	21	*	*	12	*	*	42	*	*	4	*
50/Chongqing	*	21	*	*	11	*	*	39	*	*	2	*
51/Sichuan	50	33	-17	11	13	2	81	53	-28	19	7	-11
52/Guizhou	58	49	-9	9	40	31	80	30	-50	23	8	-15
53/Yunnan	45	48	2	11	14	3	67	46	-21	15	10	-4
54/Tibet	37	37	-1	22	32	11	45	25	-20	7	7	-1
61/Shaanxi	77	32	-45	17	15	-2	76	48	-27	33	5	-28
62/Gansu	81	30	-50	20	20	0	68	37	-31	17	4	-13
63/Qinghai	24	25	1	19	33	14	46	18	-27	5	4	-2
64/Ningxia	36	32	-4	23	23	0	69	47	-22	15	6	-9
65/Xinjiang	85	29	-56	24	25	1	57	29	-28	14	4	-10
China	59	36	-23	16	17	2	77	49	-28	19	7	-12

Nutrient use efficiency in the food processing and retail sector also decreased between 1980 and 2005. Mean NUEfp decreased from 79 to 60% and mean PUEfp from 77 to 49%, indicating that food products were increasingly disregard for consumption. Overall, mean N use efficiency in the whole food chain (NUEf) decreased from 16 to 9% and PUEf from 19 to 7% (Tables 4-1 and 4-2). This indicates that 1 kg of N in food consumed required 11 kg of 'new' N and that 1 kg of P in food consumed required on average 14 kg of 'new' P. Regional variations in NUEf and PUEf were large and related in part to the type of food produced and consumed, to the production methods and to 'outsourcing' of crop and animal production. Importing plant and animal derived food from other regions (and countries) instead of producing the food itself leads to relatively high apparent NUEf and PUEf.

4.3.4 N and P losses from the food chain

The total mean N loss via ammonia (NH_3) emissions was 117 kg ha^{-1} in 2005. Losses via nitrous oxide (N_2O) emissions and N leaching (including runoff, erosion and direct discharges) were 4 and 116 kg ha^{-1}, respectively. Total P losses via leaching, runoff, erosion and direct discharges were 21 kg ha^{-1} in 2005. Losses of N and P to surface waters increased more than losses to air and groundwater between 1980 and 2005, mainly because of an increase of direct discharges of animal manures to surface waters.

There were significant regional differences in NH_3 emissions (Figure 4-4a). High NH_3 emissions occurred in the Beijing and Tianjin metropolitans (Beijing, Tianjin, Hebei, Henan and Shandong), Pearl River Delta (Guandong, Guangxi, Fujian, Hunan, Hubei, Jiangxi and Hainan), Yangzi River Delta (Shanghai, Zhejiang, Jiangsu and Anhui), Sichuan and Chongqing. These provinces also had high N_2O emissions (Figure 4-4b) and large N leaching (Figure 4-4c) and P leaching (Figure 4-4d) losses. In 1980, mean N leaching losses (including runoff and erosion) were less than 50 kg ha^{-1}, except for Shanghai and Fujian. In 2005, mean N leaching losses were higher than 100 kg ha^{-1}yr^{-1} in 18 provinces. Mean N leaching losses increased more than 5 times in the provinces in south, east and central China (Figure 4-4c). Mean P losses to surface waters increased even more than five times between 1980 and 2005. Note that mean N and P leaching losses are low in west and north China, especially in Gansu, Inner Mongolia, Xinjiang, Qinghai and Tibet (Figure 4-4c, d).

The fate of N and P residues are presented in the supplementary information accompanying this paper.

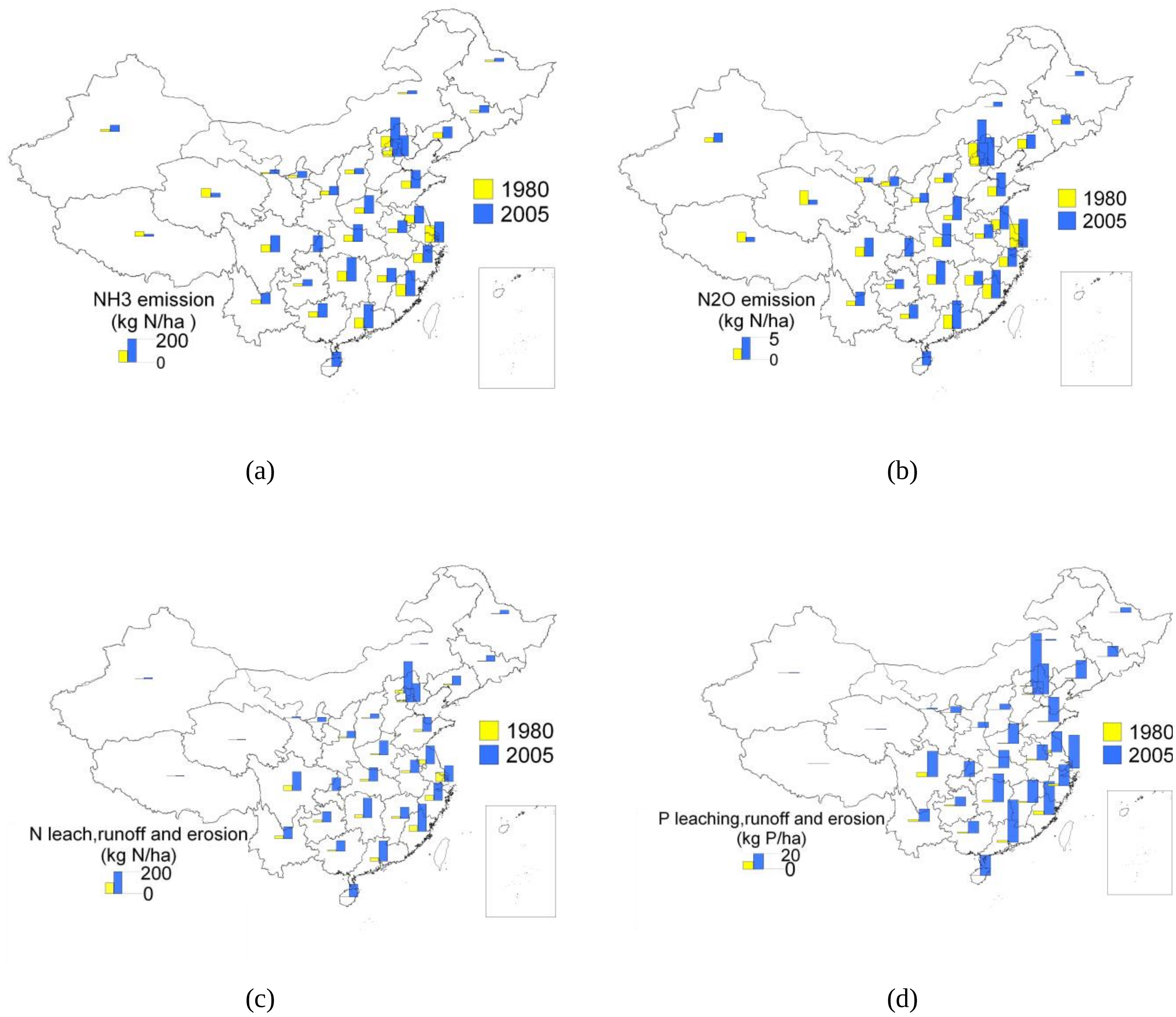


Figure 4-4 Maps of the mean total agricultural emissions of NH_3 and N_2O to air and of N and P leaching (include erosion and surface runoff) to groundwater and surface for the 31 provinces of China in 1980 and 2005, in kg N or P per ha agriculture land.

4.3.5 Relative changes in NUE and PUE

Figure 4-5 relates NUE to PUE in crop production, animal production, food processing and in the whole food chain for 31 provinces and for 1980 and 2005. Evidently, PUEc decreased more than NEUc between 1980 and 2005, but with large regional differences (Figure 4-5a). Further, NUEa increased by a factor of two, while PUEa increased slightly (Figure 4-5b). Overall, NUEf was halved and PUEf was even more than halved between 1980 and 2005, but again with large regional differences (Figure 4-5d). In general, the N and P cost of the food consumed were lower in the west and north parts of China than in the south, west and central parts.

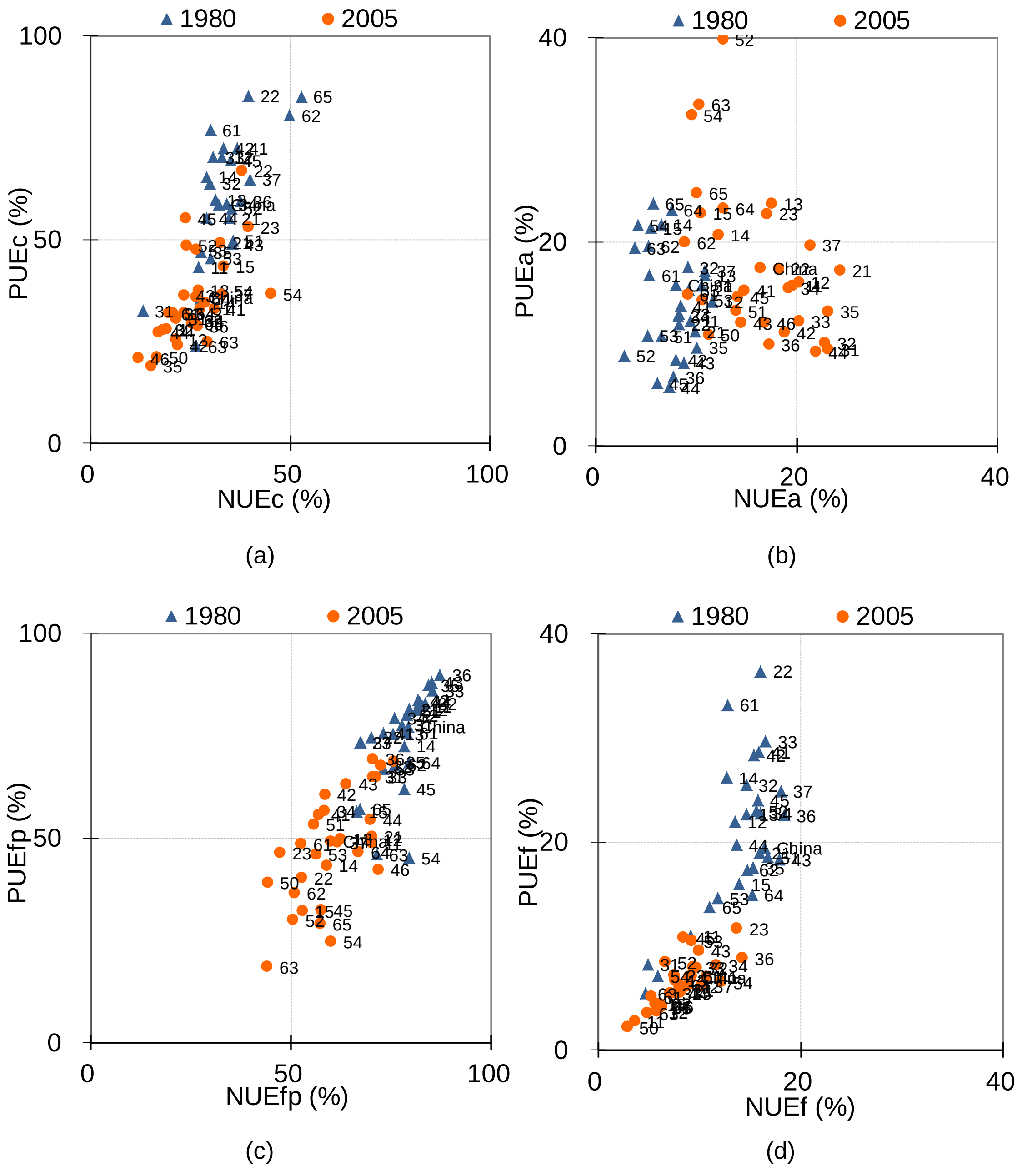


Figure 4-5 Relationships between NUE and PUE in crop production, animal production, food processing and the whole food chain for 31 provinces of China in 1980 and 2005 (For province code see Figure 4-1. There are no data for province 46 and 50 in 1980).

4.4 Discussion

This study is the first integrated assessment of the changes in N and P use efficiencies in the food production - consumption chain in China at regional level between 1980 and 2005. It is also the first integrated assessment of N losses from agriculture to air via emissions of NH_3 and N_2O and of N and P losses to groundwater and surface waters at regional scale. Our result shows that NUE and PUE decreased, and that N and P surpluses and losses increased between 1980 to 2005. The N and P cost of the food consumed increased greatly, which is related to both the increased consumption of animal products and the concomitant expansion of the livestock production sector, and the decreases in NEU and PEU in crop production and food processing.

Our results indicate that the N and P outputs of the animal production sector to the food processing sector increased by a factor of five (figure 4-2), which is much stronger that the output of the crop production sector. Interestingly, the strong increase in animal production was associated with increases in NUE and PUE in animal production (Figure 4-5b). However, N and P losses from animal production also increased strongly, because the N and P in manure were largely disregarded, since farmers do not have the knowledge or means (i.e., equipment) to better utilize manures (Figure 4-2).

Differences between regions in N and P use, outputs and losses were large. In general, provinces with a high mean N input also have a high mean P input, in both 1980 and 2005. However, the order of the provinces changed between 1980 and 2005 (Figure 4-3). Changes in mean N and P use, outputs and losses were largest in the populous south east and least in the sparsely populated west and north.

4.4.1 Mean N and P costs of Chinese food

Between 1980 and 2005, the N cost of the Chinese food increased dramatically from 6 to 11 kg kg^{-1}. Mean P cost increased even more, from 5 to 13 kg kg-1. Hence, 11 kg of N and 13 kg of P were needed in 2005 to deliver food with 1 kg of N and 1 kg of P, respectively. The compliments (10 kg N per kg N in food and 12 kg P per kg P in food) were lost to air or water bodies or accumulated in agricultural soils (mainly P). The N cost of the Chinese food is relatively high compared to estimates for the whole world (Galloway and Cowling, 2002) and the US society (Suh and Yee, 2011). The P cost of the Chinese food is higher than the world average (Smil, 2000). The three main reasons for the increasing N and P cost of the Chinese food are further discussed below.

One reason originates from the need to provide sufficient food for the rapidly increasing Chinese population (Figure 4-1), and the governmental incentives (subsidies) to use N and P fertilizers to boost crop yields. Total annual grain production increased from 300 to 500 million tons (70% increase) during 1980-2005, while N fertilizer use increased from 9 to 27 million tons (~200% increase) and P fertilizer use from 1.3 to 5.2 million tons per year (300% increase). As a result, N recovery efficiency in grain production decreased from 30-35% in the 1980s (Zhu,

1998) to less than 20% today (Cui et al., 2008a; Cui et al., 2008b), much lower than the global average of 33% (Raun and Johnson, 1999). Fertilizer N inputs in cash crops (vegetables, fruits and flowers) increased even more than in grain production, according to a nationwide survey (Miao et al., 2010). The fertilizer P recovery efficiency also decreased dramatically during 1980-2005, but much of the surplus P has been accumulated in soil, also to increase soil P test levels, and this soil bound P may be utilized in part in future (Li et al., 2011).

Another reason is the increasing prosperity of at least a part of the Chinese population and the associated increase in the consumption of animal derived food. As the N and P cost of animal-derived food is higher than that of plant-derived food, the total N and P cost of the food increases. An increase in prosperity has been accompanied also with an increase in fastidiousness and rejection of lower quality food, which has contributed to a decrease in the NUE and PUE of the food processing and retail (Figure 4-2) (Ma et al., 2008; Ma et al., 2011).

A third reason is the growth and specialization of animal production and the decoupling of crop production and animal production. During 1980-2005, the production of meat, egg and milk increased 5, 13, and 10 times, respectively. This huge increase was realized through the establishment of new ‘confined-animal-feeding-operations’ (CAFOs). These CAFOs rely on imported feed, and are therefore situated near big cities and harbors. The improved animal breeds and improved animal feed and herd management in CAFOs have increased the efficiency of animal production at herd level. As a result, a larger fraction of protein-N in animal feed ended up in edible products; from 6% in the 1950s to 9% in the 1980s and to 13% in 2006 (Wang et al., 2010).

Although NUEa and PUEa increased significantly during 1980-2005 (Tables 4-1 and 4-2), the recycling of N and P from animal manure in crop production decreased dramatically, and thereby the NUE and PUE at the whole food chain level. The animal manures produced contain most of the N and P originating from the feed, but the economic cost of manure transport to crop land is found to be too high. As a consequence, a large fraction of the manures from CAFOs are dumped in landfills or discharged into surface waters almost untreated. Livestock manures are now responsible for 38% and 56% of the total N and P discharges into surface waters, respectively (Qiu, 2010). The CAFO practice is in sharp contrast with smallholder farms in rural areas, where large efforts are made to recycle all nutrients from animal manure and residues. Though the NUEa and PUEa is low in rural areas, the NUEf and

PUEf at the food chain level are higher in rural areas than in the urbanized areas in the south and east.

4.4.2 Regional variations in NUE and PUE

Regional variations in NUEf and PUEf are related to the type and efficiency of production and consumption, and to export and import of products between regions. Unfortunately, accurate statistical information about the import and export of crop and animal products is only available at national level and is largely lacking at the regional level. Import of food will lead to high apparent NUEf and PUEf, because the N and P cost of the food production are outsourced to other regions. On the hand, export of food lead to a low apparent NUEf and PUEf, because only a fraction of the food produced will end up in the household sector of that region. Due to the lack of accurate import and export data, some of the actual differences between regions in NUEf and PUEf are nullified; the differences between provinces shown here mainly result from differences in the type and efficiency of production and consumption. For example, regions with a relative high prosperity like Beijing, Tianjin and Shanghai have relatively low NUEf and PUEf, because of the large proportions of animal derived food that is produced and consumed. In contrast, regions dominated by crop production like Heilongjiang, Henan, Hubei and Shandong have a relatively high NUEf and PUEf.

Regional variations in NUEc and PUEc are mainly related to differences in cropping patterns and fertilizer management practices (Chen et al., 2002). Vegetable production has lower NUEc and PUEc than cereal production, and wheat and rice have lower NUEc and PUEc than maize. Further, there are regional differences in soil fertility; the relatively high NUEc in Heilongjiang in the north east is in part related to the high native soil fertility (Wang, 2010).

Regional variations in NUEa and PUEa are related to (i) the dominant farming system (traditional mixed smallholder versus the new landless CAFO), and (ii) the dominant animal species. Pork and poultry production have higher NUEa and PUEa than beef and sheep production, with dairy production in between. The ranges of mean NUEa (9-24%) and PUEa (9-40%) do reflect both factors. However, the high mean PUEa (40%) in Guizhou does suggest that some of the observed regional variation should be related to errors in statistical databases.

4.4.3 Losses of N and P from the food chain

The nutrient surplus of input-output balances represent the fraction of the total nutrient input not utilized for crop and animal production. Hence a negative relationship is expected between the surplus of N and P and NUE and PUE, respectively. Figure 4-6 presents plots of the regional mean N and P surpluses versus the regional mean NUEc+a and PUEc+a, respectively, in which NUEc+a and PUEc+a represent the NUE and PUE of both crop and animal production. The N surplus is negatively related to NUEc+a, but the regression is relatively low with much scatter and did not change much between 1980 and 2005; the increase of the N surplus and decrease of NUEc+a between 1980 and 2005 followed more or less the same trend line. In contrast, the regression of PUEc+a to P surplus decreased greatly between 1980 and 2005, and the scatter also increased. Changes in west China like Qinghai were relatively small, while changes in the south east were large.

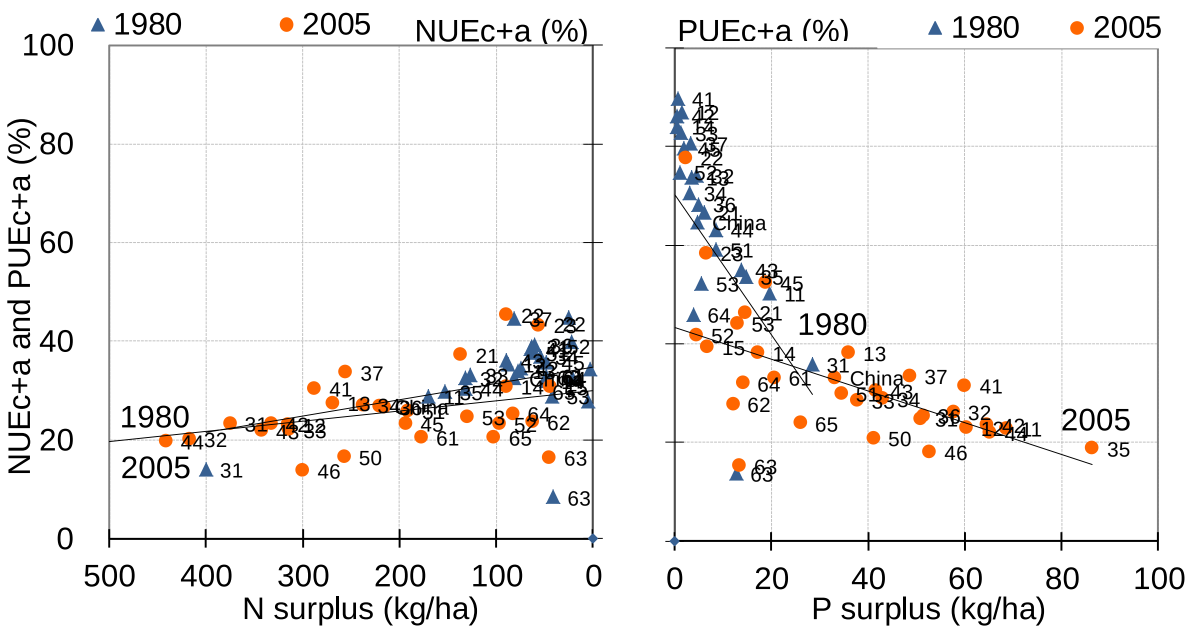


Figure 4-6 Relationship between N surplus and NUEc+a, and between P surplus and PUEc+a for 31 provinces of China in 1980 and 2005. For province code see Figure 4-1. There are no data for province 46 and 50 in 1980.

Regions with low NUEc+a and PUEc+a are associated with high N and P surpluses, high N losses to air and groundwater, and with high N and P losses to surface waters. Regions with large nutrient losses include the Beijing and Tianjin metropolitan areas, Pearl River Delta (South China) and Yangzi River Delta, which are the main crop and animal production areas. Our results differ from estimates of some other studies (e.g. Fischer et al., 2010; Qu and Kroeze, 2010). For example, our estimates for NH_3 and

N_2O emissions are lower and for N leaching higher than those of Fischer et al. (2010). Our estimates for N and P losses to surface waters are higher than those of Qu and Kroeze (2010).

Major sources of NH_3 emission are urea and ammonium-based fertilizers and animal manures. Figure 4-4a shows that highest emissions occurred in Beijing and Tianjin metropolitans, the Yangtze River Delta and the Pearl River Delta. Clearly, these emissions are mainly associated with vegetables, fruits, and animal production. In NUFER, NH_3 emissions from N fertilizer application are different for different crops and fertilizer types. For example, NH3 emissions from crop land in the North China plain accounted for 19.4% and 24.7% of applied N to winter wheat and summer maize, respectively. NH_3 emissions from paddy rice were estimated at 11.6%. There is a reasonable agreement between the estimated N_2O emission by NUFER (Figure 4-4.b) and estimates by the DNDC (DeNitrification-DeComposition) model (Li et al., 2001) and the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model (Li et al., 2010). These estimates are also in line with measured values (Gu et al., 2007).

For cropland, Zhu and Chen (2002) and Wang et al. (2007) estimated the mean N losses via NH3 emissions, denitrification, runoff, and leaching at 11%, 34%, 5%, and 2% of the applied N fertilizer. For rice and wheat cropping systems in south China, Ju et al. (2009) estimated N leaching losses at 0.3 to 3.4% of applied N fertilizer. For wheat - maize cropping systems in the North China Plain, Ju et al. (2009) estimated N leaching losses at 2.7 and 12.1% of applied fertilizer N, respectively. Our estimates for N leaching losses from cropland are much higher and those for denitrification lower. Differences in estimated N losses via leaching and denitrification may be related to a difference in the interpretation of nitrate accumulation in the subsoil. In the NUFER model, all nitrate in soil below a depth of 1 m is considered to be leached. Our NO_3-N leaching estimates agree reasonably well with those of Ju et al. (2006), Li et al. (2007) and Liu et al. (2005) for wheat-maize cropping systems in the North China Plain (6-149 kg ha^{-1} yr^{-1}). There is also a reasonable agreement for rice-rice and rice-wheat cropping systems in south China with N leaching losses ranging from 21 to 46 kg N ha^{-1} (Chen and Mulder, 2007; Sun et al., 2008a; Tian et al., 2007; Xie et al., 2007).

In general, P losses from cropland occur mainly via erosion and runoff (Liu et al., 2008). Our estimates indicate that the discharge of manure in surface waters is a much bigger P loss pathway than erosion and runoff. Our estimates indicate that the P losses from animal production to surface waters (2.1 Tg in 2005) exceed the P application via animal manure to crop land (1.7 Tg in 2005). These estimates agree with results derived from the 1st National census of pollution sources in China, indicating that 56% of the P in animal manure was lost, especially in intensive animal production regions. Rather similar results were provided by the PHOSFLOW (Phosphorus flow model) and AgiphosFA (Agricultural Phosphorus Flow Analysis) models (Chen et al., 2008; Liu, 2005). It has also been estimated that the dissolved P export via the six major rivers in China has increased significantly between 1970 and 2000 (Qu and Kroeze, 2010).

4.5 Conclusions

This is the first integrated assessment of changes of NUE and PUE in the food production and consumption chain in China, and of N losses via NH_3 and N_2O emissions to air and of N and P leaching to groundwater and surface waters from agriculture during 1980-2005.

Our analyses show that the N and P costs of the food has increased greatly. The NUEf and PUEf decreased from ~20% to less than 10% in most regions between 1980 and 2005. NUEc and especially PUEc decreased also, but NUEa and PUEa increased. Further, NUEfp and PUEfp (of the food processing sector) decreased from 75% to 50%.

Losses of NH_3 and N_2O to air and N and P to groundwater and surface waters increased greatly, especially in south, east and central China. Changes over time were relatively small for the west and north. Regions with high N and P losses are in the Beijing and Tianjin metropolitans, Pearl River Delta, and Yangzi River Delta.

Our food chain analysis approach provides insights in the strengths and weaknesses in N and P use in the whole food production consumption chain. Our results indicate that the changes in NUE and PUE in crop and animal production are complex. Increases of NUE and PUE over time in animal production may be completely nullified when the necessary recycling of N and P in animal manure are neglected.

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CHAPTER 5

Urban expansion and it impacts on nitrogen and phosphorus flows in the food chain: A case study of Beijing, China, period 1978 - 2008

This chapter is submitted to Global Environmental Change.

Abstract

Rapid growth of metropolitans is associated with increased flows of nitrogen (N) and phosphorus (P) in the food production- consumption chain. However, quantitative analyses of these flows during urban expansion and information about their controlling factors are scarce.

Here, we report on N and P flows in the food chain of Beijing, which experienced a remarkable growth in population number between especially 1978 – 2008, using a combination of statistical data bases, surveys and the NUFER model. The N (or P) cost of food is defined as the amount of ‘new’ N (or P) used in food production for the delivery of 1 kg N (or P) in the food entering household. New N includes fertilizer N, biological N fixation, atmospheric N deposition, and imports of N via feed and food. Recycled N includes N in crop residues, manures and wastes.

We found that the rapid increase in temporary migrants greatly increased food imports and thereby led to an apparent decrease of the N and P cost of food. The input of new N to the food chain of Beijing metropolitan increased from 180 to 281 Gg, and for P from 33.5 to 50.4 Gg during 1978-2008, as a result of increases in population and changes in food consumption patterns per capita. The food and feed imports in per cent of total ‘new’ N and P inputs increased from 31 to 63% for N and from 18 to 46% for P during 1978 to 2008. The N and P cost of the food was relatively low compared to the mean of China, and decreased over time. In the food chain, 66% of the new N input and 85% of the new P input was not recycled but diffusively accumulated as wastes in 2008 (in crop residues, animal excreta, and human excreta and household wastes). In the combined crop and animal production system, only 49% of N and 55% of P were recycled in 2008, which contributed to low N and P use efficiencies in crop and animal production. Total losses of NH_3 and N_2O to air and of N to groundwater and surface waters increased by a factor of about 3, and losses of P to groundwater and surface waters increased by a factor of 37 in the period 1978 - 2008.

Key measure for decreasing N and P in wastes accumulation and losses are (i) developing satellite towns for temporary migrant, (2) expelling animal production to rural areas, and (3) effective collection and utilization of the wastes and animal manure in rural areas outside Beijing.

5.1 Introduction

Urbanization is a primary driver for altering biogeochemical cycles (Grimm et al., 2008b). This holds especially for nitrogen (N) and phosphorus (P), which are key elements for food production. Several studies have tried to link urbanization to socio-economic growth and national wealth (Bloom et al., 2008), and to changes in the cycling of N and P between urban and rural ecosystems (Deluca, 2009; Grimm et al., 2008a). Urban areas are sinks for nutrients, and in an increasingly urbanized world, cities become 'hotpots' of N and P, which contribute to environmental effects (Marzluff et al., 2008).

The global trend of urbanization has shifting from Europe and North America (first urban transition, 1750–1950) to Africa and Asia (second urban transition, 1950–2030) (Ramalho and Hobbs, 2012). Especially China has witnessed a rapid urban expansion during the last few decades, due to the rapid economic development. Both the economic development and urbanisation had significant impacts on food consumption pattern. For example, mean food protein consumption went up from 9 to 26 kg capita^{-1} year^{-1}, and the percentage of animal-derived protein in the diet increased from 9 to 35% between 1961 and 2007 (FAO, 2010). These changes in food consumption had also large impacts on agriculture. For example, (1) animal production increased through the establishment of large-scale confined animal feeding operations (Wang et al., 2010), (ii) the area used for vegetables and fruit production increased by 31% (FAO, 2010), and (3) intensive vegetable, fruit and livestock production increased near urban areas at the expense of cereal production (Wolf et al., 2003). These changes have also greatly increased nutrient inputs to urban areas.

Beijing is a typical case of the second urbanization. A rapid urban expansion occurred between 1978 and 2008, facilitated by rapid economic growth (Figure 5-1). During this period the population nearly doubled, but about 90% (7.5 million in 2008) of the population increase were temporary migrants from rural areas working in industry and construction. The urbanization rate of the county in Beijing increased from 55 to 85% (Figure 5-1). The rapid urbanization and economic growth have led to a range of environmental problems, that are threatening human health and human well-being, through especially depletion of water resources, degradation of water quality, traffic jams, smog, and sandstorms (Liang et al., 2013; Qi et al., 2007; Wang et al., 2013; Zhang et al., 2007).

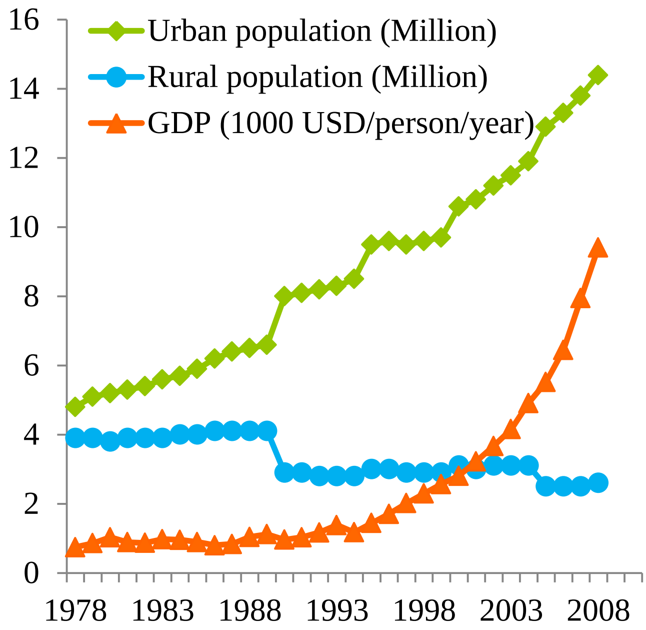


Figure 5-1 Changes in the population of urban and rural areas, and in gross domestic production (GDP) of Beijing metropolitan between 1978 and 2008.

Urban metabolism is a concept used to quantify exchanges of water, energy and elements (including nutrients) in urban areas and compartments, using material flow analysis (Bai, 2007; Kennedy et al., 2007). Analyses of N and P metabolism were undertaken in the food production and consumption chain of for example Paris (Barles, 2007), Toronto (Forkes, 2007), Bangkok (Færge et al., 2001), and Sweden (Neset et al., 2008). Also, several cities in China (Li et al., 2011) were examined, including Beijing and Tianjin (Irie et al., 2013; Qiao et al., 2011), Shanghai (Gu et al., 2012), Hong Kong (Warren-Rhodes and Koenig, 2001) and Suzhou (Liang and Zhang, 2011). These studies quantified N and P flows in the food production and consumption in urban areas, as well as its influences on the regional ecosystem. However, all studies considered cities as static research object, and did not make a link with urban expansion. Moreover, flows of N and P were analysed separately. As a result, our understanding of the impacts of urban expansion on N and P flows and losses in the food chain at sub-regional levels is still limited.

Here, we address the question ‘how did urban expansion change the N and P flows in the food production and consumption chain of Beijing during the past 30 years’. We used a food chain approach and the NUFER model (Nutrient flow in the food chain, environment and resource; Ma et al., 2010) to analyse the changes in N and P flows in the food production and consumption chain over time. The aims of this study are (1) to quantify the changes of the N and P flows and losses in the food chain during the main metropolitan expansion period (1978 to 2008); and (2) to analyse the relationships between urban expansion, economic development and the N and P flows in the food chain.

5.2 Materials and methods

5.2.1 Description of Beijing metropolitan

Beijing in northern China is one of the twenty largest metropolitan areas in the world (Forstall et al., 2009). It is defined here by its administrative boundaries, and includes central Beijing and its 14 counties, with a total area of 1.6 million ha (Figure 5-2). Following the economic reforms in the 1970s and 1980s, the urban area of Beijing has expanded greatly. Following the change in food purchase policy, which made the prices of cereals, vegetables, meat and sugar for residents and migrants similar, a rapid influx of temporary migrants from rural regions to the urban and peri-urban areas of Beijing occurred.

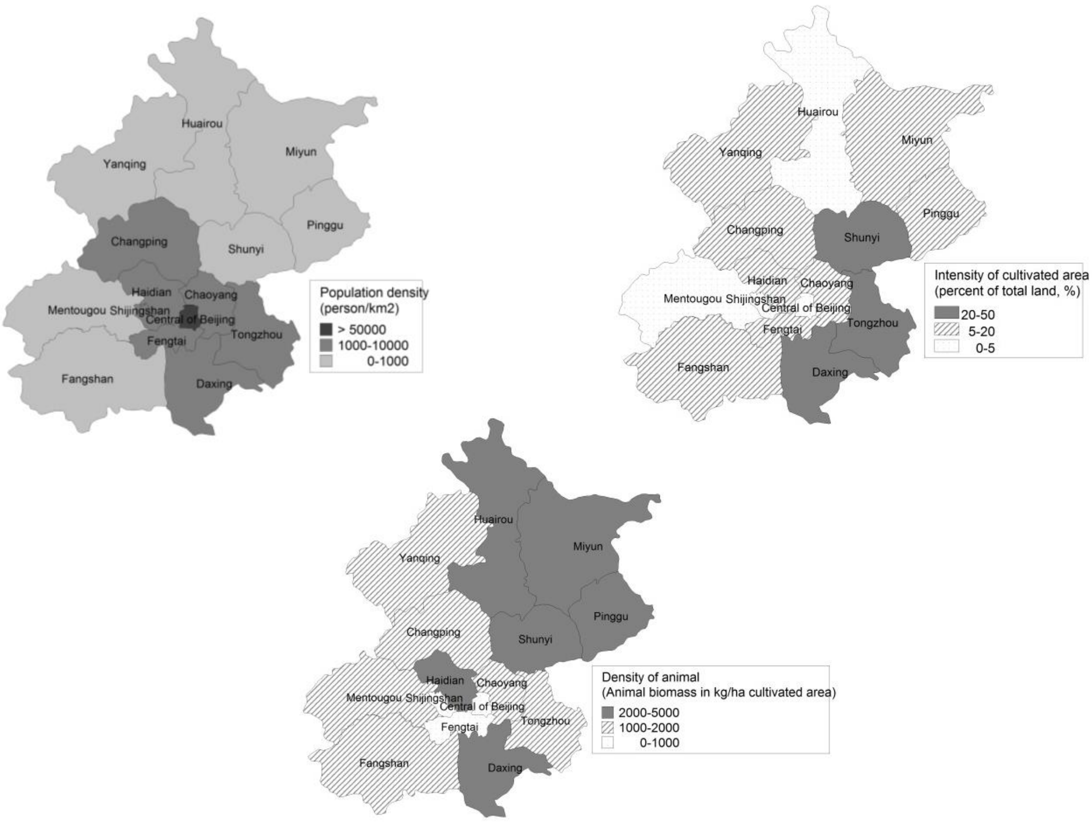


Figure 5-2 Sizes of the human and animal populations and the areas of cultivated land in the 14 counties and centre of Beijing in 2008.

About 21% of the total land area is urban and infrastructural area. Approximately 14% is used for intensive crop production (range 0 to 38% for the 14 counties). The main crops are maize, wheat, fruits and vegetables. A very high animal density in terms of biomass per hectare cultivated land is found in some counties (i.e. Haidian, Shunyi, Daxing, Huairou, Pinggu, and Miyun). About 53% of the total land area is a mixture of extensively used farm land and forest, and 12% is non-utilized mountainous land.

5.2.2 Data sources

Basic data and information (e.g., fertilizer use, crop yields, cultivated areas and number of animals, population and food consumption) were derived from governmental statistical yearbooks and bulletins (BMSB, 2009a, b) and additional model calculations. Crops were aggregated into three main categories (cereals, vegetables, and fruit) per region. The sown areas of these crops accounted for more than 95% of the total sown area. Farm animals were aggregated into six animal categories (pigs, dairy cattle, beef cattle, laying hen, broilers, and sheep).

Data about N and P contents in harvested crop and animal products, N and P excretion values per animal category and the partitioning of animal products into edible food and other parts were obtained from literature (Ma et al., 2010 and 2012, BMSB, 2009a, b). Parameters for N and P loss factors from crop production and animal production were derived from literature data and surveys (Ma et al., 2010 and 2012).

5.2.3 Nutrient flow analyses

A material flow analysis (MFA) of N and P in the food chain in Beijing metropolitan was conducted, using an adjusted version of the NUFER model. NUFER is a deterministic and static model, that enables the calculation of N and P flows in the food chain at regional scale on an annual basis (Ma et al., 2010). The food chain system of Beijing metropolitan is presented in Figure 5-3; it includes 4 compartments: crop production, animal production, households, and wastes (e.g. crop residues, animal and human excreta and household wastes). Inputs of ‘new’ N and P entering the food production and consumption chain occur via (1) biological N fixation, (2) atmospheric deposition, (3) fertilizers, (4) net animal feed import, (5) net plant food import and, (6) net animal food import (from other regions or countries). Outputs of N and P leaving the food production and consumption chain occur via (7) NH_3 emissions, (8) N_2O emissions, (9) leaching, runoff, and erosion and, and (10) N_2 emissions from denitrification. In addition, there are internal N and P flows between the compartments through (12) plant-derived food, (13) feed, (14) animal-derived food, (15) straw, (16) animal excrements, (17) human wastes including food wastes and excrements, (18) animal manure returned to field, and (19) straw used as feed. Accumulation of wastes N and P (11) is the difference between total input and total output (see Figure 5-3 and Table 5-1, including N and P retention in humans). N and P retention in humans increased with the growing population. However this is not a significant amount (<1%) compared to the total N and P inputs in the food chain, and are therefore not considered in this study.

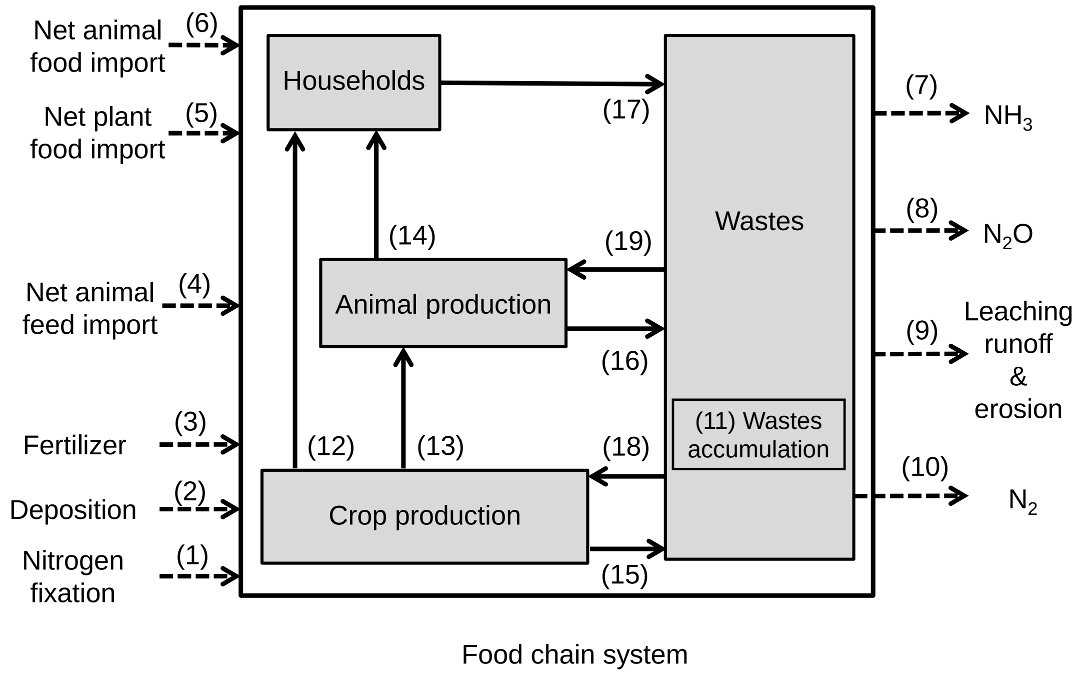


Figure 5-3 The food chain system of Beijing, including crop production, animal production, households and wastes. Inputs are shown on the left-hand side, outputs/losses on the right-hand side. Net import is the difference between import and export. Numbers between brackets refer to the codes which are further explained in Table 5-1.

The net import of N and P via animal feed, plant-derived food and animal-derived food (from other regions or countries) was calculated as (in Gg and in kg ha^{-1} agricultural land):

Net animal feed import = Animal feed consumption – Animal feed production (5-1)

Net plant food import = Plant food consumption – Plant food production (5-2)

Net animal food import = Animal food consumption – Animal food production (5-3)

Accumulation of N and P in wastes was calculated as:

Wastes accumulation = Total input – Total output (5-4)

Where: total input includes biological N fixation, atmospheric deposition, fertilizers, net animal feed import, net plant food import, and net animal food import Total output includes ammonia (NH_3) emissions, emissions of nitrogen oxides (NO_x), nitrous oxide (N_2O) and di-nitrogen (N_2) from nitrification and denitrification processes, and losses via leaching, runoff, erosion and discharge (see also Ma et al. 2010 and 2012).

5.2.4 Nutrient use efficiency indicators

The following nutrient use efficiency indicators (Table 5-2) were used:

- The N (P) cost of food, defined as the amount (in kg) of 'new' N (P) used in crop and animal production for the delivery of 1 kg N (P) in the food entering households (Ma et al., 2010).
- Nutrient use efficiency in crop production (NUEc and PUEc, %), defined as the ratio of N (and P) output in marketed crop products and the total N (and P) input into crop production (Ma et al., 2012). Nutrient use efficiency in animal production (NUEa and PUEa, %), defined as the ratio of N (and P) output in marketed animal products and the total N (and P) input into animal production (Ma et al., 2012).
- Nutrient use efficiency in crop and animal production combined (NUEc+a and PUEc+a, %), defined as the ratio of N (and P) output in marketed crop and animal products and the 'new' N (and P) input into crop and animal production (Ma et al., 2012).
- Ratio of animal food – to – plant food in the diet (APFR in %), defined as the percentage of N (P) in the diet derived from animal food (Ma et al., 2013).

- Loss – to – input ratio (LIR in %), defined as total N (and P) losses from the food chain in per cent of the 'new' N (and P) entering the food chain (Ma et al., 2013).
- Rate of residue recycling (RRR, %), defined as the percentage of total N (and P) in crop residues and animal excreta that were recycled effectively in crop and animal production (%).
- Import ratio (ITR, %), defined as the percentage of total 'new' N (and P) inputs to the food chain that was imported in food and feed from other regions (%).
- Wastes accumulation of N (P) (kg ha^{-1} yr^{-1}), defined as the amount of N (P) in wastes (e.g., crop residues, animal and human excrete, and household wastes) accumulated in the food chain system per unit agricultural area.

Table 5-1 Total N and P inputs and outputs in the food chain in Beijing in 1978, 1988, 1998, and 2008. Codes refer to the input flows in the food chain, shown in Figure 5-3.

Item	Code	Total, in Gg							
		N (Gg N =10^9 g N)				P (Gg P =10^9 g P)			
		1978	1988	1998	2008	1978	1988	1998	2008
Input									
Nitrogen fixation	(1)	11	9	8	4	*	*	*	*
Deposition	(2)	25	22	20	12	*	*	*	*
Fertilizer	(3)	87	88	139	87	27.7	17.3	29.7	27.3
Feed import	(4)	40	59	79	100	5.5	11.4	11.6	15.0
Plant food import	(5)	15	12	12	53	0.4	-0.6	-0.3	6.2
Animal food import	(6)	1	0	8	24	0.0	0.0	0.5	1.8
Total input		180	191	266	281	33.5	28.1	41.5	50.4
Output									
Ammonia emissions	(7)	42	47	68	53	*	*	*	*
Nitrous oxide emissions	(8)	1	1	2	1	*	*	*	*
Runoff, erosion and leaching	(9)	17	21	38	41	0.4	2.3	4.7	7.4
N_2 emissions	(10)	10	8	12	9	*	*	*	*
Wastes accumulation	(11)	109	114	146	176	33.2	25.8	36.8	42.9
Total output		180	191	266	281	33.5	28.1	41.5	50.4
Inter-flows									
Plant food	(12)	25	30	27	13	5.9	7.2	6.3	3.0
Feed	(13)	6	13	19	13	1.4	3.2	4.6	3.1
Animal food	(14)	3	10	13	21	0.3	0.7	1.1	1.5
Straws	(15)	13	18	19	10	1.7	2.3	2.3	1.2
Animal excretion	(16)	45	62	83	83	6.7	13.7	14.3	15.1
Human wastes	(17)	43	52	60	111	6.6	7.3	7.6	12.5
Animal manure and straw to field	(18)	37	46	48	38	7.2	12.3	10.7	8.5
Straw feed	(19)	4	5	7	4	0.5	0.7	0.9	0.5

Note: * no data.

5.3. Results

5.3.1 Changes in food production and consumption

Table 5-2 Nutrient use indicators for the food chain (see text).

Element	Category	Indictors	1978	1988	1998	2008
N	Nutrient use efficiencies	NUEc+a (%)	17	22	16	17
		N cost of food (kg kg^{-1})	4.1	3.7	4.5	2.5
		NUEc (%)	27	36	30	26
		NUEa (%)	7	17	16	25
	Indicators of percentage	APFR (%)	8	19	35	41
		LIR (%)	34	36	41	34
		RRR (%)	70	64	55	49
		ITR (%)	31	37	37	63
	Indicators of per capita	Plant food consumption (kg $capita^{-1}$)	4.6	4.0	3.1	3.9
		Animal food consumption (kg $capita^{-1}$)	0.4	0.9	1.7	2.7
		Net import of plant food (kg $capita^{-1}$)	1.7	1.1	1.0	3.1
		Net import of animal food (kg $capita^{-1}$)	0.1	0.0	0.7	1.4
	Indicators of per unit agricultural land	'New' N input (kg N ha^{-1})	419	463	781	1211
		Wastes accumulation (kg N ha^{-1})	254	277	428	761
P	Nutrient use efficiencies	PUEc+a (%)	19	28	18	11
		P cost of food (kg kg^{-1})	5.1	3.8	5.5	4.0
		PUEc (%)	30	48	38	24
		PUEa (%)	5	6	7	10
	Indicators of percentage	APFR (%)	4	10	21	27
		LIR (%)	1	8	11	15
		RRR (%)	92	82	70	55
		ITR (%)	18	38	28	46
	Indicators of per capita	Plant food consumption (kg $capita^{-1}$)	0.7	0.6	0.5	0.5
		Animal food consumption (kg $capita^{-1}$)	0.0	0.1	0.1	0.2
		Net import of plant food (kg $capita^{-1}$)	0.0	-0.1	0.0	0.4
		Net import of animal food (kg $capita^{-1}$)	0.0	0.0	0.0	0.1
	Indicators of per unit agricultural land	'New' P input (kg P ha^{-1})	78	68	122	217
		Wastes accumulation (kg P ha^{-1})	77	63	108	185

Changes in the production, consumption and net import of food and animal feed in Beijing between 1978 to 2008 are shown in Figure 5-4. All flows are expressed in amounts of N and P in Gg $year^{-1}$. Mean food consumption per capita increased from 5.0 to 6.6 kg $capita^{-1}$ for N and from 0.7 to 0.8 kg $capita^{-1}$ for P. Consumption of plant-derived food decreased from 4.6 to 3.9 kg $capita^{-1}$

for N, and from 0.7 to 0.5 kg capita^{-1} for P between 1978 to 2008. Consumption of animal-derived food increased from 0.4 to 2.7 kg capita^{-1} for N and from 0.03 to 0.2 kg capita^{-1} for P. The percentage of the diet derived from animal food (APFR) increased from 8 to 41% for N and from 4 to 27% for P between 1978 and 2008 (Table 5-2).

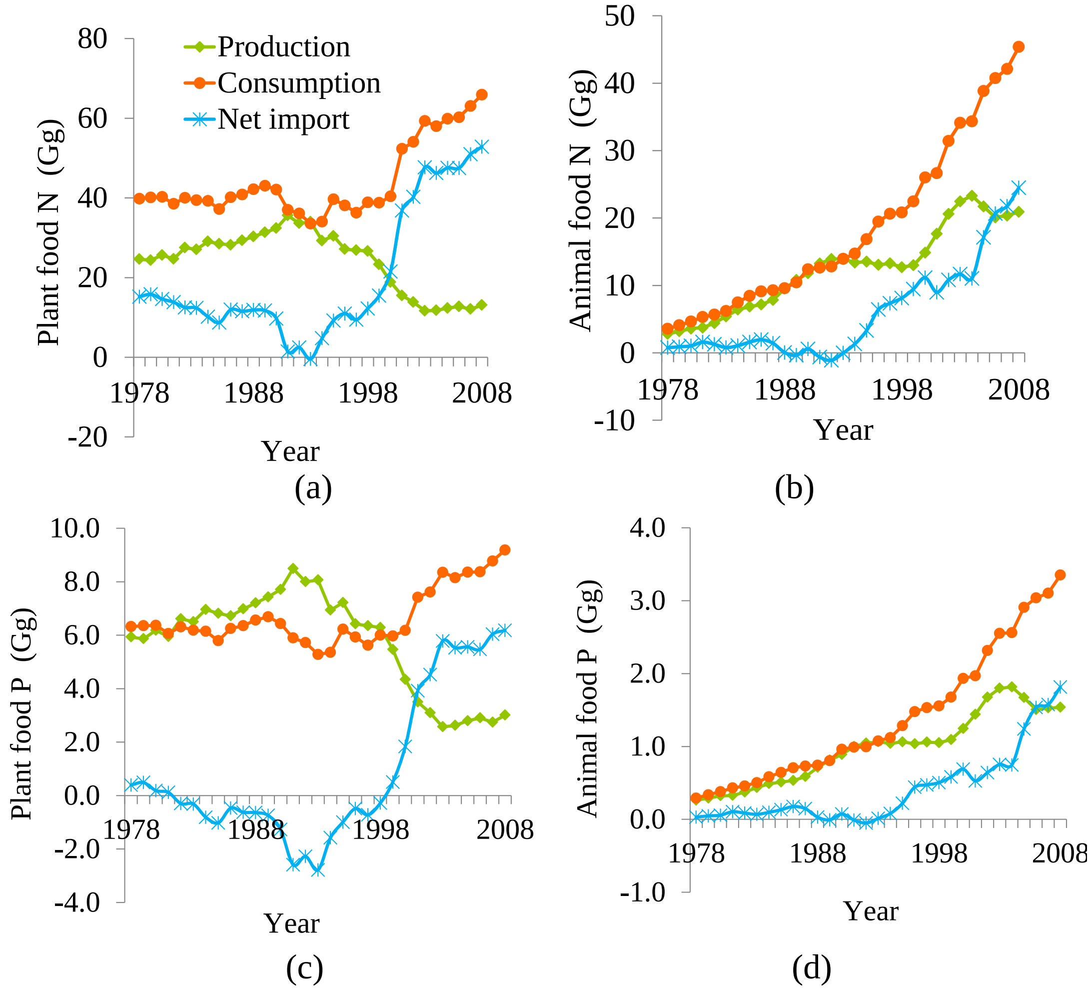


Figure 5-4 Changes in total production, consumption and net import of (a) N in plant food, (b) N in animal food, (c) P in plant food, and (d) P in animal food, in Beijing during the period 1978 to 2008. Note that the export of food N and P were likely overestimated (and hence the net import underestimated) , because losses of food N and P during food processing step were not considered due to lack of data.

Three distinct phases (1978-1988, 1988-1998, and 1998-2008) have been distinguished. The period 1978 to 1988 (phase I) is typified here as ‘food gap reduction’. Before 1978, there was serious malnutrition in Beijing, up to starvation, especially during the 1960s and early 1970s. Between 1978 to 1988, animal food production and consumption became in balance; the gap between plant food production and consumption decreased gradually. Four counties (Miyun, Shunyi, Fangshan and Daxing) transformed from food importing to food exporting counties, while food import in Haidian increased (Figure 5-5).

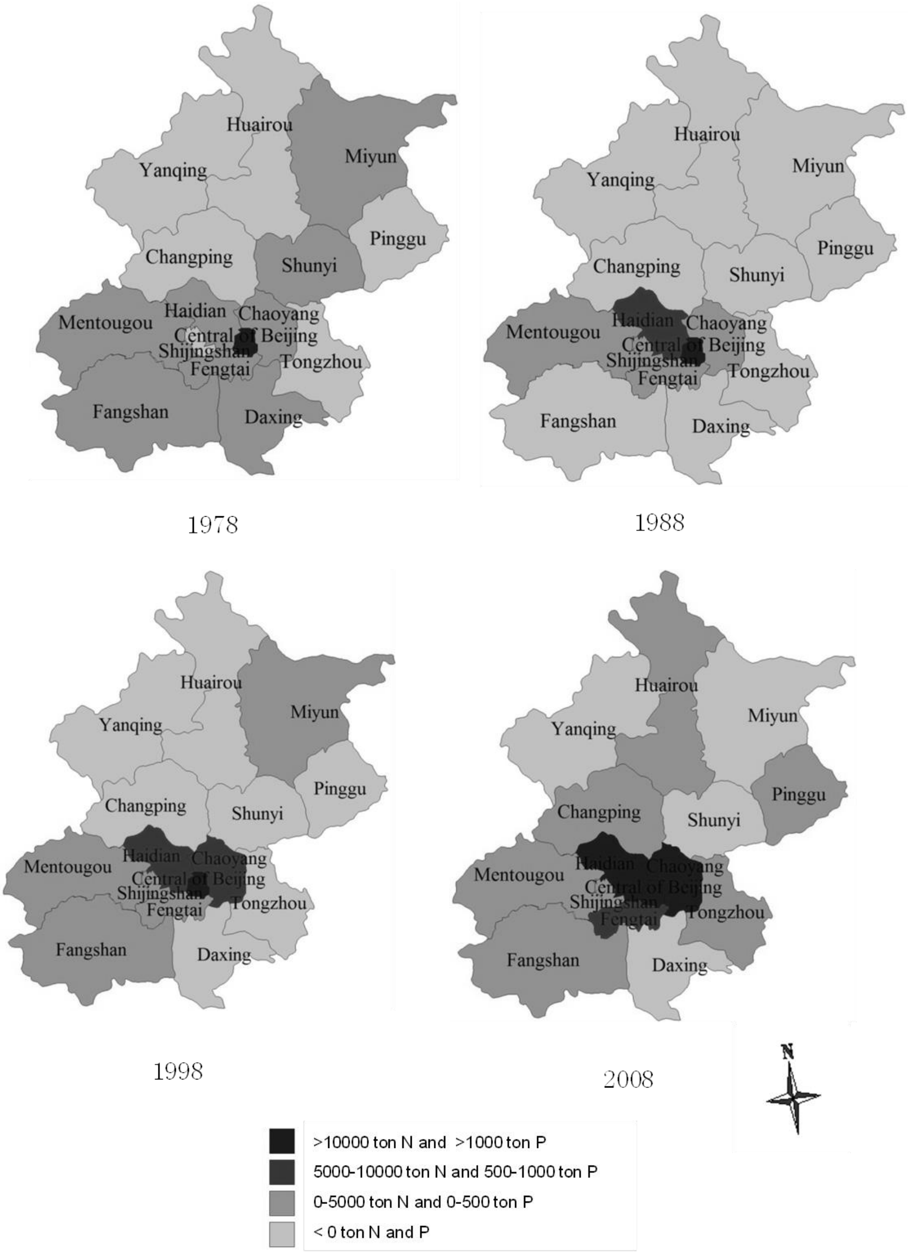


Figure 5-5 Changes in the difference between food consumption and production (expressed in N and P) in Beijing in 1978, 1988, 1998 and 2008. Positive values indicate that consumption of food is higher than production and that import of food is needed (in ton N and P). Red means importing areas and grey means exporting areas.

The period 1988 to 1998 (phase II) can be considered as 'transitional period'. Increasingly, agricultural land was converted to urban land. Plant-derived food production decreased (from 32 to 27 Gg for N and from 7.4 to 6.3 Gg for P), while the consumption of plant-derived food remained at a level of 40 Gg for N and 6 Gg for P. Animal-derived food production slightly increased (from 12 to 13 Gg N and from 0.8 to 1.1 Gg for P), while the consumption of animal-derived food nearly doubled (from 12 to 22 Gg N and from 0.8 to 1.6 Gg P; Figure 5-4). The food import increased especially in Chaoyang, Fangshan and Miyun (Figure 5-5).

The period 1998 to 2008 (phase III) can be considered as the period in which the gap between food production and consumption increased again, as food import greatly increased. This rapid increase of food import coincided with the rapid increase of the population (Figure 5-1), due to temporary migrants. The consumption of plant-derived food N and P increased with 70 and 54%, respectively, and the consumption of animal-derived food N and P with 102 and 100%, respectively. The gap between food production and consumption, expressed in mass of N and P, increased greatly (Figure 5-4). Regions with food import enlarged from central Beijing to the suburbs gradually, while food exporting regions contracted in the peri-urban counties (Figure 5-5).

5.3.2 Changes in total N and P inputs and outputs

The total input of 'new' N into the food chain in Beijing increased from 180 Gg (equivalent to 419 kg N ha^{-1} of agricultural land) in 1978, to 281 Gg (equivalent to 1211 kg N ha^{-1} of agricultural land) in 2008. Main 'new' N inputs were fertilizer, imported animal feed, and plant- and animal-derived food (Tables 5-1 and 5-2). The amounts of N in imported food and feed relative to the total N input (the import ratio ITR) increased from 31 to 63% between 1978 and 2008 (Table 5-2). Our calculations indicate that most of the imported N accumulated; 254 kg in 1978 and 761 kg N ha^{-1} of agricultural land in 2008 (Tables 5-1 and 5-2). The cumulative N accumulation in wastes during the last 30 years was estimated at 4186 Gg (equivalent to12, 766 kg ha^{-1} of agricultural land). The fate of the N in wastes is not known, because NUFER does not consider the fate of accumulated wastes in subsequent years. Likely, a significant part will have been further dissipated into the environment via NO_3 leaching to the subsoil and via NH_3, N_2O, and N_2 emissions to the atmosphere.

Total 'new' P input into the food chain in Beijing increased from 34 Gg (equivalent to 78 kg P ha^{-1}) in 1978, to 50 Gg (217 kg P ha^{-1} of agricultural land) in 2008 (Tables 5-1 and 5-2). Phosphorus import ratio (ITR) increased from 18 to 46% between 1978 and 2008 (Table 5-2). The largest P output item was in the accumulation of wastes (landfill); 77 kg P ha^{-1} in 1978 and 185 kg P ha^{-1} of agricultural land in 2008 (Tables 5-1 and 5-2).

5.3.3 N and P use efficiencies

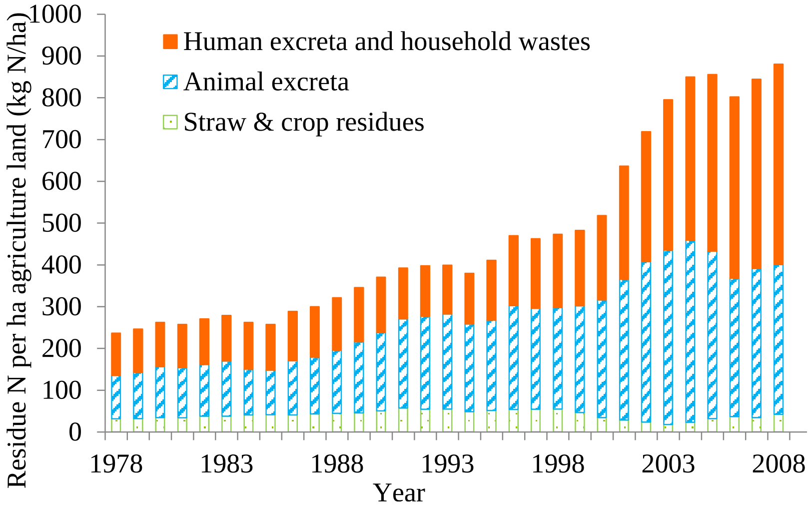
Mean N use efficiency in crop production (NUEc) increased from 27% in 1978 to 36% in 1988. From 1988 to 2008, NUEc decreased to 26%, because N input increased much stronger than the N yield. Mean NUEa steadily increased from 7% in 1978 to 25% in 2008. When considering crop and animal production as a combined system, NUEc+a was 17% in 1978, 22% in 1988, and 17% in 2008. NUEc+a was relatively low, despite the strong increase of NUEa, because the N and P in manure and crop residues were not recycled effectively, while 'new' N and P inputs increased in both crop and animal production (Table 5-1). The total N cost of food remained at the level of 2.5 to 4 kg kg^{-1} (Table 5-2).

Trends for P use efficiency (PUE) were similar as the trends for NUE. Mean PUEc increased from 30% in 1978 to 48% in 1988 and then decreased again to 24% in 2008. Mean PUEa increased from 4% in 1978 to 10% in 2008. The increasing trend of PUEa was weaker than NUEa, mainly because of the strong increased use of P additives in feed. Mean PUEc+a was 19% in 1978, 28% in 1988, and only 11% in 2008. Total P cost of food remained at the level of 4 to 5 kg kg^{-1} (Table 5-2).

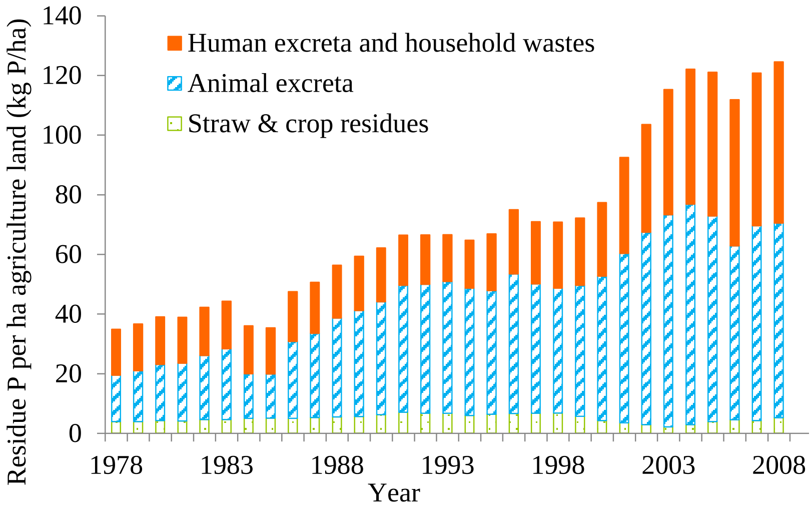
5.3.4 Total N and P losses

Between 1978 and 2008, the amounts of residues increased by a factor of 3.7 (Figure 5-6). The residues recycling rate in agricultural land decreased from 70 to 49% for N and from 92 to 55% for P between 1978 and 2008 (Table 5-2).

Total mean N losses from agriculture via NH_3, N_2O and N_2 emissions to the atmosphere, and via leaching (including runoff, erosion and direct discharges) to surface waters and groundwater were 450 kg ha^{-1} of agricultural land in 2008 (Figure 5-7). Losses increased by a factor of 2.4 for NH_3, 1.9 for N_2O, 1.6 for N_2 and 4.3 for leaching compared to 1978 (Figure 5-7). The N loss-to-input ratio (LIR) increased from 34% in 1978 to 41% in 1998, and decreased again to 34% in 2008 (Table 5-2).



(a)



(b)

Figure 5-6 Amounts of nitrogen (upper panel, a) and phosphorus (lower panel, b) in straw and other crop residues, animal excreta, and human excreta and household wastes in Beijing from 1978 to 2008, in kg ha^{-1} $year^{-1}$.

The total mean P losses via leaching (including runoff, erosion and direct discharges) were 32.1 kg ha^{-1} of agricultural land in 2008. Losses increased 37 times compared to 1978 (Figure 5-7). The loss-to-input ratio (LIR) for P increased from 1% in 1978 to 15% in 2008 (Table 5-2).

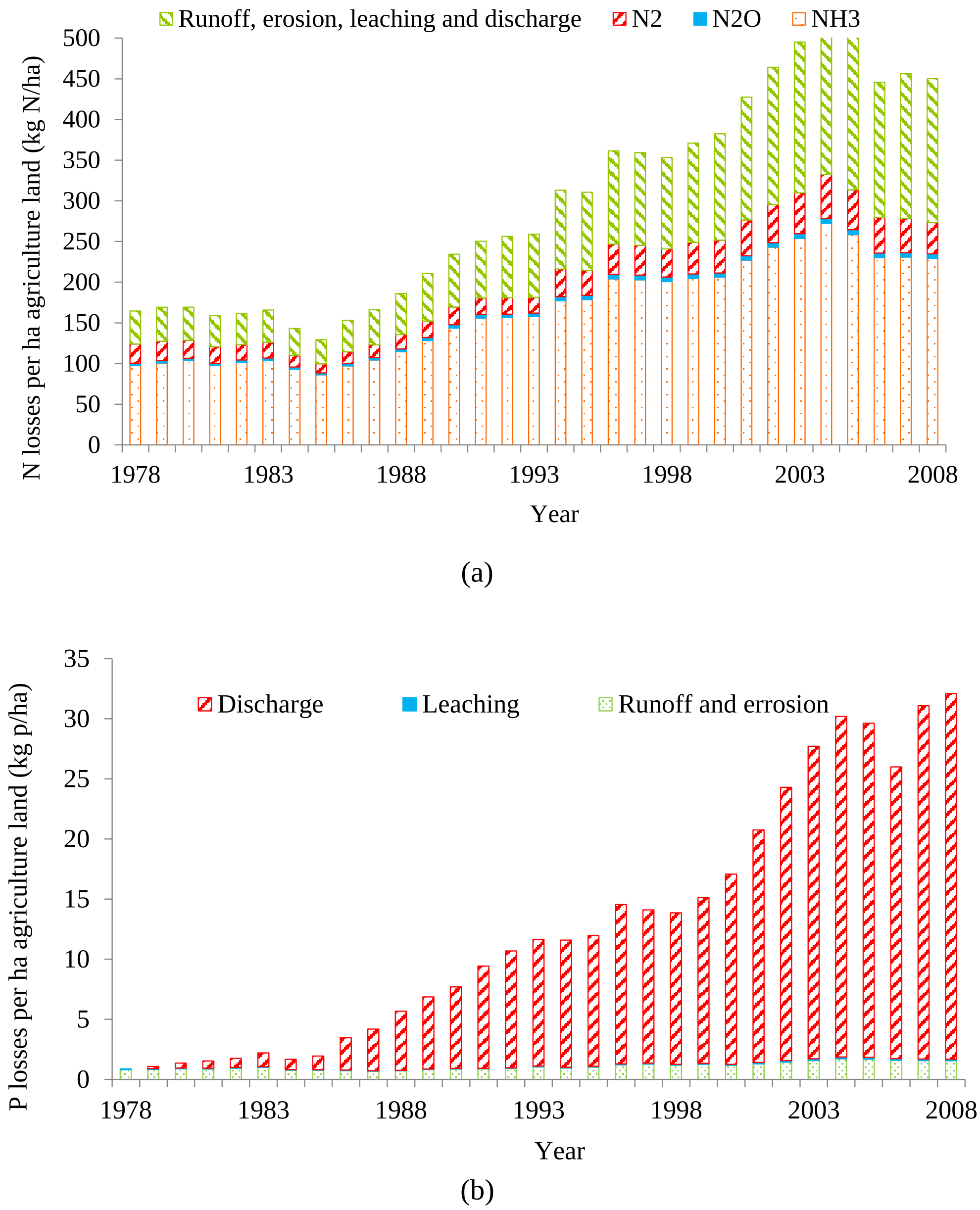


Figure 5-7 Nitrogen losses via ammonia (NH_3), nitrous oxide (N_2O) and di-nitrogen (N_2) emissions to the atmosphere and via runoff, erosion, leaching and discharge to water bodies (upper panel, a), and phosphorus losses via runoff, erosion, leaching and discharge to water bodies (lower panel, b) in Beijing from 1978 to 2008, in kg ha^{-1}.

5.4. Discussion

5.4.1 Main findings

This is the first detailed analysis of the changes in N and P flows and losses in the food chain of a large peri-urban area during a period of rapid urbanization and economic growth. The main changes were: (1) the population density and built-area increased, at the expense of agricultural land, (2) the consumption of animal-derived protein increased, (3) the areas used for vegetables and fruit production increased, at the expense of cereal crops, (4) rapid increases in animal production, based on imported animal feed, (5) rapid increases in food imports, (6) a rapid decoupling of N and P cycling between (i) food production and food consumption areas, and (ii) feed production and feed consumption areas, (7) rapid decreases in the recycling of nutrients in residues and animal manure, and (8) rapid increases in total N and P losses.

We found that the urban expansion through especially temporary migrants from the mid-1990s onwards have contributed to increased food imports and have led to an apparent low N and P cost of food. We found that the N and P cost of food in Beijing in 2008 (2.5 kg kg^{-1} for N and 4.0 kg kg^{-1} for P in 2008) were much lower than the average N and P cost in China (11 kg kg^{-1} for N and 13 kg kg^{-1} for P in 2005) (Ma et al., 2010). The main reason is that the imports of feed and food in Beijing (63% for N and 46% for P) were much higher than on average for China (less than 1%) (Ma et al., 2010). In contrast, nutrient use efficiency in crop and animal production in Beijing (NUEc+a=17% and PUEc+a=11%) was much lower than the average for China (27% for N and 33% for P in 2005) (Ma et al., 2012). The low NUEc+a and PUEc+a in Beijing were related to the low recycling and reuse of nutrients in crop residues and animal excreta in crop production.

These results are not without uncertainties. Firstly, statistical data have intrinsic uncertainties, which are difficult to assess without further information. Secondly, mean N and P contents and emission factors are derived from various literature sources; these contents and emission factors do not consider the large spatial variability within the area. It is difficult to quantitatively assess the overall uncertainty in our results. Tentatively, we estimate the uncertainties in N and P inputs and outputs at regional levels at 10 to 30%, and the uncertainties in individual N and P loss pathways at 50 to 100%. Further studies are needed to verify these estimates.

5.4.2 Driving forces of urban expansion

Urban expansion accelerated in Beijing in the past three decades, driven by economic development, change of policy and population growth. Economic development is a key driver. The mean income per capita increased by a factor of 61 between 1978 and 2008. Mean income per capita in Beijing (27678 Ren Min Bi $year^{-1}$) was 3 times higher than the average income in rural China (6700 Ren Min Bi $year^{-1}$) in 2008 (BMSB, 2009a, b; NBSC, 2010). The differences in income promote the migration of young people from rural areas to Beijing (Hessler, 2010), and has accelerated the expansion of Beijing metropolitan. At the same time, a major barrier for migration was removed, i.e., the 'ration stamp'(Keung Wong et al., 2007). Before the mid-1990s, the 'food ration stamp' policy provided low-priced rationing of foods to each individual residing in his or her place of residence. It was almost impossible for an individual to move from the place of residence to another place, because the food price was very high without local 'food ration stamp' (Keung Wong et al., 2007). Both, economic growth and the change in policy, have greatly contributed to the making of Beijing as a 'huge hotel', where more than 40% of the population is 'migrant', i.e., without permanent residency ('Hukou') in Beijing. Additionally, the natural growth of the population is another driver for the urban expansion.

The urban expansion of Beijing has accelerated economic growth, but has also contributed to a range of huge challenges: (i) increased dependency on imported food (this paper) and imported water resources (Zhang et al., 2011), (ii) strong smog and sandstorms, which affect human health (Zhang et al., 2007), (iii) degradation of water quality (Wolf et al., 2003), (iv) crowded traffic and loss of effective working hours (Zhang and Gao, 2008), and (v) increasing inequality between rural and urban people. These challenges are largely interrelated through the growth of the economy and the population. The problems are in part also caused by poor practices. Below, we focus further on the N and P flows associated with food.

5.4.3 Urban expansion and N and P flows

Our research illustrates causal links between urban expansion and N and P flows in the food chain. The rapid increase of migrant population coincided with a rapid increase of gross domestic production (GDP; Figure 5-1), and with changes in food demand and food consumption patterns. The consumption of animal-derived food increased from 8% in 1978 to 41% in 2008 in terms of N, and from 4% to 27% for P (Table 5-2). Also, the percentage of food consumed in restaurants instead of at home increased, because of the increasing income (Dong and Hu, 2010). Food consumption in restaurants is associated with a 'luxury' consumption pattern and with more food waste. These changes likely have contributed to the increased food and feed imports to Beijing metropolitan.

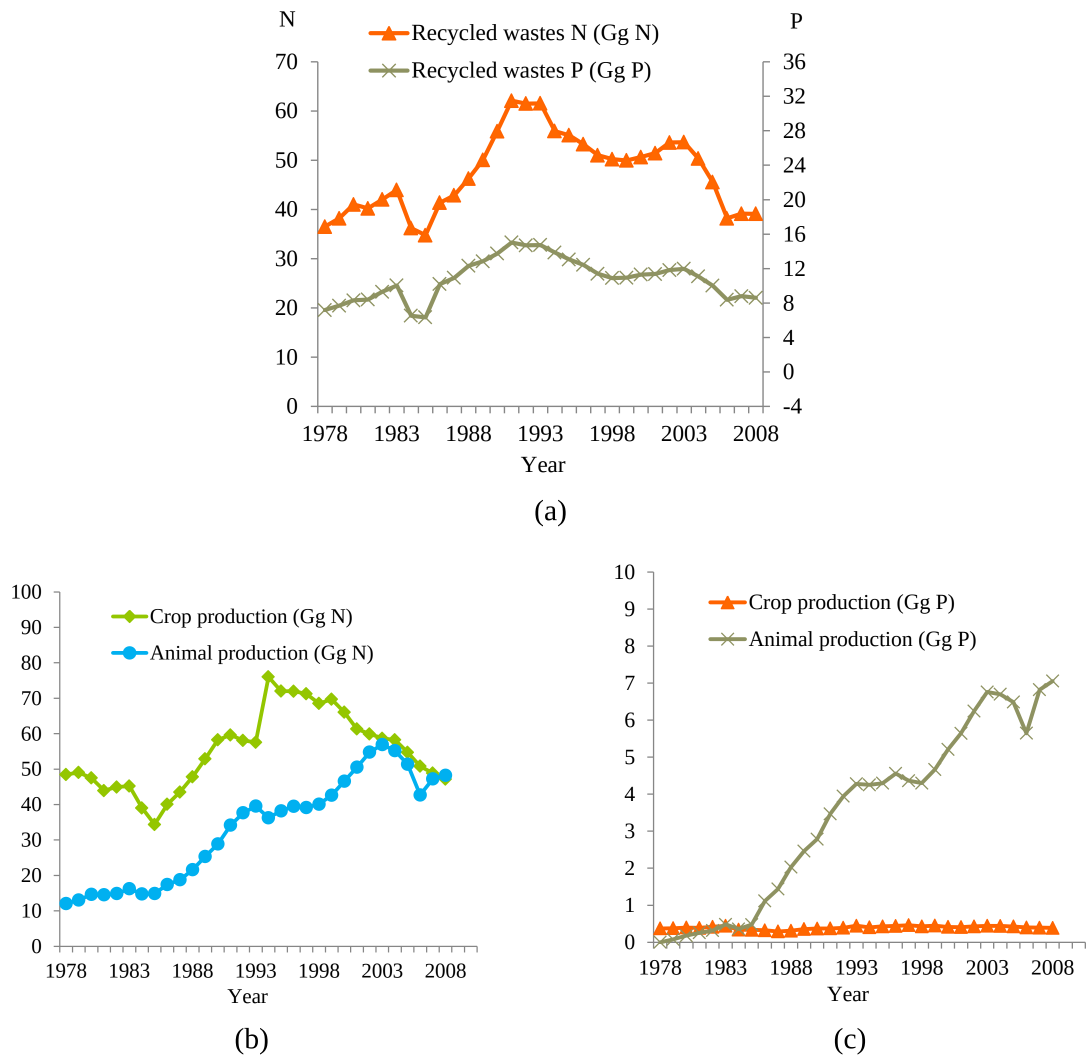


Figure 5-8 Changes in amounts of (a) N and P in recycled wastes, (b) total N losses from crop and animal production, and (c) total P losses from crop and animal production in Beijing metropolitan, between 1978 to 2008. The discharge of manure was included in the N and P losses in animal production (b and c). Note, the drop in animal production in 2003-2006 was due to animal diseases (blue-ear, foot and mouth, and pig pest).

Though the N and P cost of food was relatively low, the N and P losses and accumulation were high and increased dramatically (Figure 5-8). Increased losses occurred especially because of the decreasing recycling of wastes N and P (Figure 5-8a; Li et al., 2011)). In the past, the N and P in food wastes and human excreta were typically recycled in an approximately closed loop, even in 'urban' areas. The food wastes were used as feed in traditional animal farms. Before 1980s, human excrements were collected and used by farmers in rural areas as 'night soil' to fertilize the land (Shiming, 2002). However, the traditional recycling was replaced by poor-functioning sewage waste water collection systems and a poor municipal solid waste collection system, almost without recycling of N and P. In 2008, approximately 90% of municipal solid wastes was landfilled, 8% was incinerated and only 2% was recycled after composting (Li et al., 2009). At the same time, the recycling of sewage sludge decreased substantially, mainly because of the elevated economic cost of transporting and removing unwanted and toxic substances from the sludges (Qiao et al., 2011). The poor recycling of food system N and P in Beijing is not unique; only 7% of N and 10% of P was recycled in Bangkok (Færge et al., 2001) and 4.7% of N in Toronto (Forkes, 2007). In contrast, 20-40% of N was recycled in Paris, following the implementation of an advanced sewage collection and treatment system (Barles, 2007).

Urban expansion induced also structural changes of local agriculture. Cereal-based systems changed into vegetable and fruit production systems, because of the increased demand and much higher value, and also because of the effects of long-distant transport of fresh fruit, vegetables and animal products on quality. The high value of vegetables and fruits have also contributed to large fertilizer N and P applications, up to 1575 kg N $ha^{-1}year^{-1}$ (Hou et al., 2012; Yan et al., 2013). The high fertilizer input is a main reason for the relatively low NUEc and PUEc in Beijing.

Landless, intensive livestock production expanded also rapidly (Liang et al., 2013), due to the increased demands for dairy, meat and egg products. Most of the high-protein and high-P feed (e.g. soybean, maize, alfalfa) had to be imported from elsewhere. However, most of the animal excrements in intensive animal farms were simply flushed out of the animal facility, followed by direct discharge to nearby waters or were stocked piled in lagoons, where it evaporates to air and drains to the subsoil, with little beneficial use (Wang et al., 2011; Wang et al., 2010). Clearly, the decoupling between crop production and animal production is a main reason of the low NUEc+a and PUEc+a in Beijing.

5.4.4 Suggestions for lowering N and P losses

Basically, all large cities face problems with the accumulation of N and P from the food production-consumption chain, which contributes to the deterioration of air and water quality, and human health (Grimm et al., 2008a). Possible remediation strategies include (1) developing satellite towns and spreading or decentralization of government-related activities, and (2) importing all food and expelling animal production to rural areas, and (3) implementation of effective collection, processing and distribution systems for wastes and manures.

In Beijing, all three strategies are being considered currently, and also applicable, combined with halting further urban expansion. The strategy of satellite towns could separate the working and living spaces of the temporary migrants (Shen and Huang, 2003). In that case, food production and consumption could be balanced better and opportunities for recycling of N and P in wastes and manure may increase, especially if the areas between central Beijing and satellites is large enough for waste recycling and food production. This strategy has been implemented to variable degree in some metropolitans, such as London, and Tokyo (Echenique et al., 2012; Gill et al., 2008; Sorensen, 2001). Beijing has already several satellite towns and these are instrumental for pushing people out of Beijing to Baoding, Shijiazhuang, Langfang, and Zhangjiakou (Tan, 2010). An increasing number of high-speed railways connect Beijing with its satellite towns and cities (Tang et al., 2011). However, the cost of commuting is still too high relative to the cost of living in Beijing. Moreover, increased commuting may worsen the traffic jams and smog in the city (Li et al., 2005). A better strategy may be to transfer various central government-related departments and activities out of Beijing to other cities. Stimulating economic growth and improving the living condition in rural areas are also instrumental for stopping or reversing the influx of migrants from the rural area to Beijing.

Expelling livestock production from the peri-urban area to the rural area combined with the import of processed food from the rural area to the city is another option. The intensive peri-urban animal production systems are landless, large-scale, specialized systems and a large part of the produced manure is discharged into surface waters, which has led to a strong decrease of the water quality (Wolf et al., 2003). The amounts of manure N and P produced in Beijing is much higher than the crop N and P requirements (Wang et al., 2010).

Another option is the processing of animal manures from the landless livestock production farms and the subsequent transport of processed manure to crop production areas where these manure can be used effectively. Though technically possible, this option is costly (Chadwick et al., 2012), and a main reason why it has not been implemented. Similarly, the proper collection and processing of household wastes, and the subsequent recycling and re-use of N and P in rural regions has economic barriers. In the progress of urban expansion, wastes N and P must flow back from urban to rural areas (Liu et al., 2013). Theoretically, a near ‘closed’ system at regional level would be possible (Kimura and Hatano, 2007). Achieving the full potential of this strategy requires the establishment of a household wastes sorting and high-technology processing system and the operation of organic waste markets. The return of organic wastes to agricultural land reduces also the amount of wastes to be disposed of (Nunan, 2000).

5.5 Conclusions

Beijing metropolitan has rapidly expanded between 1978 and 2008, due to the rapid economic growth, which attracted a large number of temporary migrants from the rural areas as labourers in industry and construction. The urban expansion and economic growth had large impacts on the whole food production – consumption - recycling chain.

Our analyses show that the current average N and P cost of food are relatively low in Beijing. The main reasons are the relatively large import of food and animal feed. The rapid increase in the number of temporary migrants from the 1990s onwards has greatly contributed to the increasing import of food and to the apparent low food N and P cost.

Yet, nutrient use efficiency in crop and animal production (NUEc+a and PUEc+a) were low and decreased between 1988 and 2008. The main reasons are (i) the importance of animal production relative to crop production, (ii) the importance of vegetable and fruits relative to cereal production, and (iii) the low recycling of crop residues and animal excreta.

Total N and P losses from agriculture to atmosphere and surface waters and groundwater have increased dramatically, mainly because of the poor recycling of N and P in crop residues, animal manures and human wastes back into crop production systems.

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CHAPTER 6

Environmental assessment of management options for nutrient flows in the food chain in China

This chapter is published in Environmental Science & Technology, 2013, 47 (13), 7260-7268. Supplementary information and tables S1, S2, S3, S4, S5, S6 and S7 can be found in the link http://pubs.acs.org/doi/suppl/10.1021/es400456u/suppl_file/es400456u_si_003.pdf .

Abstract:

The Nitrogen (N) and phosphorus (P) costs of food production have increased greatly in China during the last 30 years, leading to eutrophication of surface waters, nitrate leaching to ground water, and greenhouse gas emissions.

Here, we present the results of scenario analyses in which possible changes in food production - consumption in China for the year 2030 were explored. Changes in food chain structure, improvements in technology and management, and combinations of these on food supply and environmental quality were analyzed with the NUFER model.

In the business as usual scenario, N and P fertilizer consumption in 2030 will be driven by population growth and diet changes, and will both increase by 25%. N and P losses will increase by 47 and 71%, respectively, relative to the reference year 2005. Scenarios with increased import of animal products and feed instead of domestic production, and with changes in the human diet indicate reductions in fertilizer consumption and N and P losses relative to the business as usual scenario. Implementation of a package of integrated nutrient management measures may roughly nullify the increases in losses in the business as usual scenario, and may greatly increase the efficiency of N and P throughout the whole food chain.

6.1 Introduction

The rapidly increasing world human population and the concomitant increase in prosperity in some parts of the world will greatly increase the demand for crop and animal derived food during the next few decades (Smil, 2000). The increased use of nitrogen (N) and phosphorus (P) to support the increased food production may lead to increased losses of N to the air via ammonia (NH_3), nitrous oxide (N_2O) and di-nitrogen (N_2) emissions, and of N and P to groundwater and surface waters via leaching, erosion and run-off (Conley et al., 2009). This in turn may further degrade the quality of soil, air and water, and of natural ecosystems (Galloway et al., 2008; Gu et al., 2012). Moreover, there is a risk that we will exhaust the supply of natural resources required for food production, such as land, water and P, especially when bio-fuel production will compete with food production (Gilbert, 2009). There is evidently a great need to reduce food production and nutrient use efficiency, and thereby to decrease N and P losses to the wider environment.

China is an interesting case here, as it is the most populous country in the world and is in transition from a poor agrarian to a prosperous industrial society. Agricultural production is highly intensive with low N and P use efficiencies and the environmental effects of agricultural production and N and P losses are large (Vitousek et al., 2009). Forecasts indicate that the population will increase further from 1.3 billion in 2005 to about 1.4 billion in 2030 (UN, 2008). Over the same period, the ratio of the urban to the rural population will be reversed from 1:2 to 2:1(UN, 2008). These changes in population and urbanization greatly increase the demand for animal-derived food and hence animal feed because the proportion of animal-derived protein in the human diet is much higher in urban than in rural areas . Notwithstanding the huge increase in domestic crop production during the recent decades, there has also been a rapid increases in the imports of soybean and maize because domestic production is insufficient to cover the demand by the expanding animal production (Brown, 2011). Evidently, increasing food production, nutrient use efficiency and environmental quality in China represents an enormous challenge (Fu et al., 2007).

Several studies have assessed N and P losses from food production and consumption during recent years (Bouwman et al., 2009; Cordell et al., 2009; Galloway and Cowling, 2002; Liu et al., 2010; Liu et al., 2008b; Villalba et al., 2008). These studies indicate that N and P losses from food systems have increased in most regions, although there are large differences between countries and between regions (Bleken and Bakken, 1997; Isermann and Isermann, 1998; Ma et al., 2010; Shindo et al., 2003). Various studies have also estimated N_2O and NH_3 emissions, and N and P losses via leaching, runoff and erosion losses at field level for various cropping systems and for agricultural land at national level (Fischer et al., 2010; Ju et al., 2009; Qu and Kroeze, 2010; Zheng et al., 2004; Zhu and Chen, 2002). In a recent study, Ma et al. (2012) quantified the relationships between N and P inputs to agriculture and associated N and P emissions, and N and P use efficiencies (NUE and PUE, respectively) in the food chain at regional scale in China over the last 30 years. The results indicate that the N and P costs of food production and consumption almost doubled between 1980 and 2005 (Ma et al., 2010; Ma et al., 2012). The results also suggested that NUE and PUE were relatively low in China compared to other countries.

Here, we address the question of how the N and P costs of food production and consumption in China may change during the next 20 years for a range of scenarios. In the scenarios, we have made series of assumptions related to feed and food production and imports, the human diet, and nutrient management throughout the whole food production – consumption chain. The main aim of the study was to increase our understanding of the complex relationships between (increased) feed and food production and imports, improvements in nutrient management, and their resulting effects on NUE and PUE and N and P losses in the food chain at regional level in China. The specific objectives were to quantify the effects of (i) structural adjustments in feed and food production and utilization (including dietary changes), (ii) improvements in technology and management (including manure management), and (iii) combinations of (i) and (ii) on N and P use and losses by using the model NUFER (Ma et al., 2010).

6.2 Materials and methods

6.2.1 Scenarios development

The situation in 2005 was used as the reference and that in 2030 as the target year, for which four main scenarios have been analyzed, comprising (0) business as usual (S0 scenario), (1) structural adjustments of the food production – consumption chain, including changes in diet and food and feed imports (S1 scenarios), (2) improvements in technology and management, including balanced fertilization, precision feeding and manure management (S2 scenarios), and (3) combined options (S3 scenarios). The scenarios are summarized briefly below.

6.2.2 General assumptions regarding food requirement in 2030

Total food requirement is based on total population number and mean food demand per capita. The population in China will peak at 1.4 billion in 2030 (UN, 2008). The expected increase in urbanization from 50% to 80% and in mean prosperity will likely increase the average consumption of animal-derived food per person and that of plant-derived food will decrease concomitantly. We therefore assume that the total consumption of protein per person in 2030 will be similar to that in 2005, but that the percentage of animal-derived protein will increase from 34% in 2005 to 50% in 2030 (UNDP, 2010). As a consequence, the demand for crop and animal-derived food will increase by 25% and 80%, respectively, compared with the reference year 2005. The increase in food demand translates mainly into increased demand for maize and soybean (used in animal feeds) rather than for wheat and rice (used as human food see Tables S1 to S6 in the supplementary information). The above assumptions refer to all scenarios described further below, with exception of the diet change scenario (S11) and the combined scenario (S31).

Scenario S0 - Business as usual (BAU). Scenario S0 is based on the assumption that the domestic food production in China will increase significantly following the suggestions of a number of scientists (Cui et al., 2013). In crop production we assume that total yields will increase on average by 25% compared to 2005, by using high yielding crop varieties and better management. Yields of maize and soybeans are assumed to increase by 40% and those of other crops by 10%. Additional data for 2005 and 2030 are listed in Table S3 in the supplementary information.

Scenario S11 - Diet change. This scenario was designed to simulate a slowdown of the increase in animal-derived food consumption, while following the Chinese food dietary guidelines (CDG). The CDG is based on a human nutrition survey by the Chinese Nutrition Society in 2007 and the nutrient requirement standards of WTO. The guidelines recommend the following: 1) eating a range of foods with cereals as the staple, 2) consuming adequate amounts of vegetables, fruits and tubers, 3) consuming milk, beans, or dairy or bean products every day, 4) consuming appropriate amounts of fish, poultry, eggs and lean meat; and 5) reducing the intake of animal fat in the diet. Based on the CDG, the consumption of meat will decrease and that of milk, eggs, beans and fruit will increase compared with 2005. We assume that the changes in consumption will lead to proportional changes in production.

Scenario S12 - Increased import of animal products. In this scenario we assume that the increase in the animal products required, such as meat and milk to feed the population in 2030 in the BAU scenario, will be imported from other countries.

Scenario S13 - Increased import of animal feed. This scenario assumes that all the increased need for animal feed in the BAU scenario in 2030 relative to 2005 will be imported from other countries.

Scenario S21 - Balanced fertilization in cropland. This scenario builds on the BAU scenario but assumes balanced N and P fertilization in crop production (BNFc), i.e. the amount of fertilizers and manures applied to crops are precisely tuned to crop N and P demands while taking other N and P inputs into account (i.e. deposition, mineralization, and biological N_2 fixation). See also supplementary information.

Scenario S22 - Precision feeding. This scenario also builds on the BAU scenario but assumes precision animal feeding, i.e. protein N and P intakes by the animals according to recommended intake levels. We assume, that the protein N and P contents of the animal rations will decrease on average by 20% (but more for industrial systems than for collective animal production systems) compared with scenario S0 (Wang et al., 2010).

Scenario S23 - Improved manure management. This scenario also builds on the BAU scenario but assumes that the percentage of manure applied to croplands increase from 20-75% in 2005 to an average of 80% (Ma et al., 2010; Wang et al., 2010). Massive amounts of animal manure are currently discharged into ponds and rivers (Wang et al., 2010) and only 20 to 75% of the animal excreta are applied to land, with the exact amount s varying from province to province (Ma et al., 2010).

Scenario S24 - Integrated nutrient management (S21+S22+S23). In this scenario balanced fertilization (S21), precision feeding (S22) and improved manure management (S23) are combined.

Scenario S31 – Combination of S11 and S24. In this scenario diet change (S11) and integrated nutrient management (S24) are combined.

Scenario S32 – Combination of S12 and S24. In this scenario, increased imports of animal products (S12) and integrated nutrient management (S24) are combined.

Scenario S33 – Combination of S13 and S24. In this scenario increased imports of animal feeds (S13) and integrated nutrient management (S24) are combined.

6.2.3 Scenario analysis

For each scenario we have applied a food chain approach in which the nutrient transfers between crop production, animal production, food processing and retailing, and food consumption in households and restaurants are quantified at regional level as visualised in Figure 6-1 using the NUFER model (Ma et al., 2010). NUFER is a deterministic mass flow model which can be used to calculate the flows of food, feeds and nutrients, the N and P use efficiencies and emissions in the food chain of China and for 31 regions, on an annual basis. NUFER consists of input modules with activity data and transformation and partitioning coefficients, a calculation module, and an output module. The output module tabulates the N and P flows, use efficiencies, and emissions at compartment level, at regional and national scales. For the study described in this paper, a scenario analysis module was included in NUFER in order to assess the effects of the assumptions in each scenario on the N and P flows, emissions (including the results by both total amount in Tg and the average value in kg per ha of cropland) and use efficiencies (Ma et al., 2010).

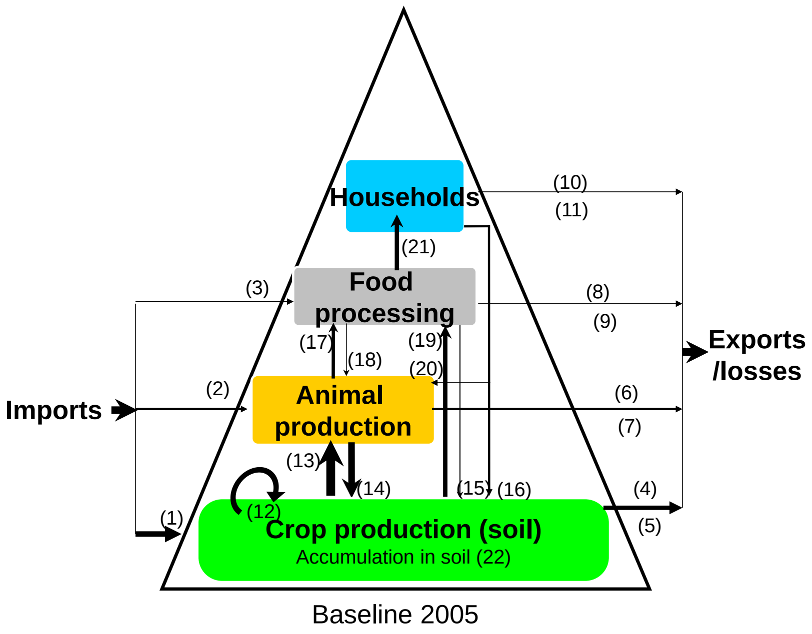


Figure 6-1 Flows of N and P in the food pyramid in China at national level. Arrows in the food pyramid represent N and P flows, and numbers in brackets refer to the codes which are further explained in Tables 6-2 and 6-3.

6.2.4 Indicators for assessing nutrient use efficiency in the food system

A total of six sets of indicators was used to assess nutrient use efficiencies in the food chain (Ma et al., 2010) and the effects of the scenarios.

Nutrient use efficiency in the food chain (NUEf and PUEf) and the N and P cost of food were selected as the two indictors from the food system perspective (Ma et al., 2010). The N (P) cost was defined as the amount (in kg) of 'new' N (P) used in the crop and animal production and food processing compartments for the delivery of 1 kg N (P) in the food entering households (Ma et al., 2010).

The ratio of animal food - to - plant food (APFR) was used as an indirect indicator for the environmental impact of the diet; it was defined as the percentage of N (P) in the diet derived from animal food. An increase in the consumption of animal derived food by households is associated with an increase in total N and P losses and greenhouse gas emission in agriculture (Popp et al., 2010; Xue and Landis, 2010).

Nutrient use efficiency in crop production (NUEc, PUEc) and in animal production (NUEa, PUEa) were used as indicators for nutrient management (Ma et al., 2010).

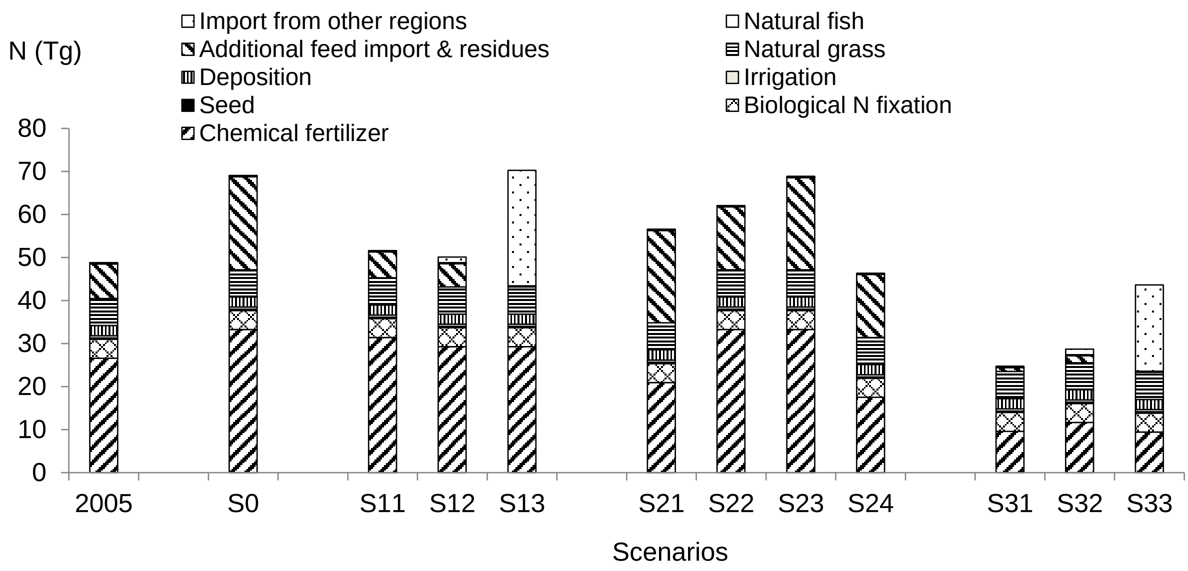
Finally, the loss - to - input ratio (LIR, %) was regarded as a direct indicator for the environmental impact of the whole food chain. It was defined as total N losses from the food chain in per cent of the total N and P input (including 'new' and 'recycled' N and P) entering the food chain.

6.3 Results

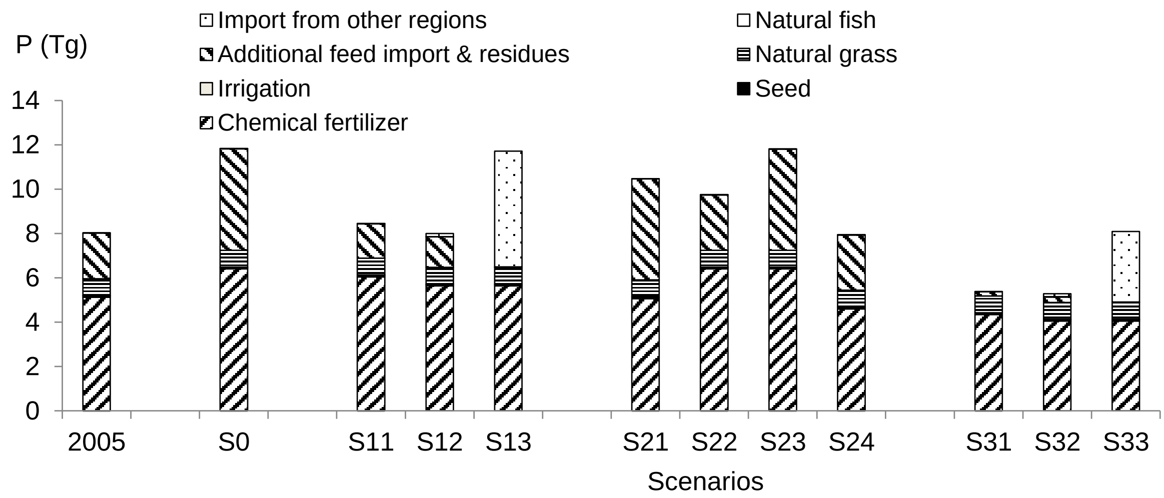
6.3.1 Business as usual scenario

In business as usual scenario for 2030 (BAU; S0) inputs of 'new' N and P increased by 42 and 47%, respectively, compared with 2005. In crop production, fertilizer N and P use increased by 6.6 and 1.3 Tg, respectively (Figure 6-2). In animal production, feed N and P intake increased by 79 and 78%, respectively. However, the domestic feed supply was not sufficient to cover the increased demands for animal feed, resulting in a gap between required and available feed, equivalent to 13.6 Tg N and 2.5 Tg P in S0 (Figure 6-3). We assumed that this gap was covered by increased (additional) imports. Concomitant with the increase in animal production, manure N production also increased significantly; in most provinces mean manure N production per ha of cultivated land increased to more than 200 kg per ha per year.

In the food consumption compartment (households), the animal - to - plant food ratio (APFR, %) increased from 32 to 47% for N and from 35 to 48% for P (Table 6-2). Compared to 2005, the total N and P losses from crop and animal production increased by 47% and 71%, respectively (Table 6-3), due to the increased fertilizer use and animal manure production. The N and P use efficiencies throughout the whole food chain decreased; NUEf decreased from 9 to 8% and PUEf from 7 to 6%. Similarly, the N cost of food increased from 11 to 12 kg per kg and the P cost from 14 to 17 kg per kg (Table 6-2).



(a)

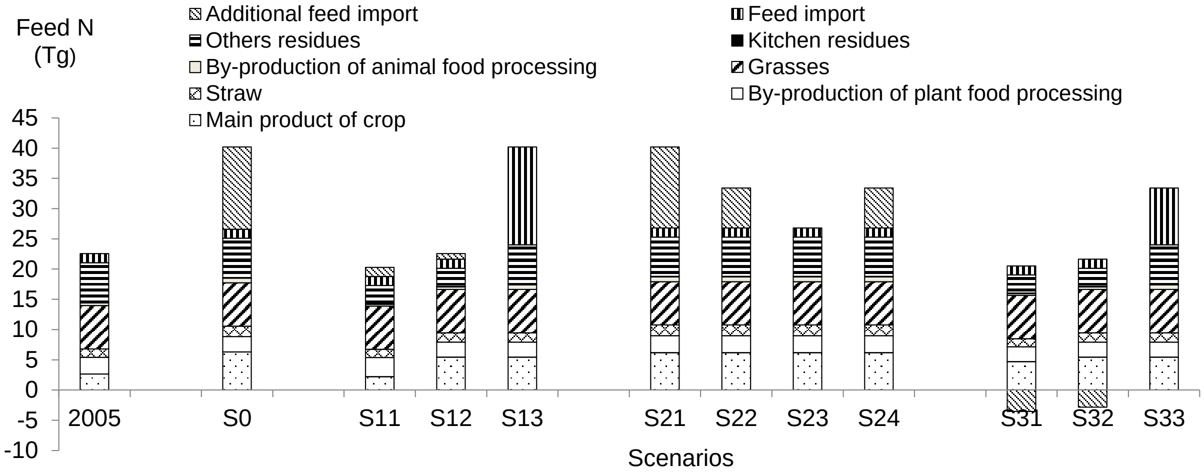


(b)

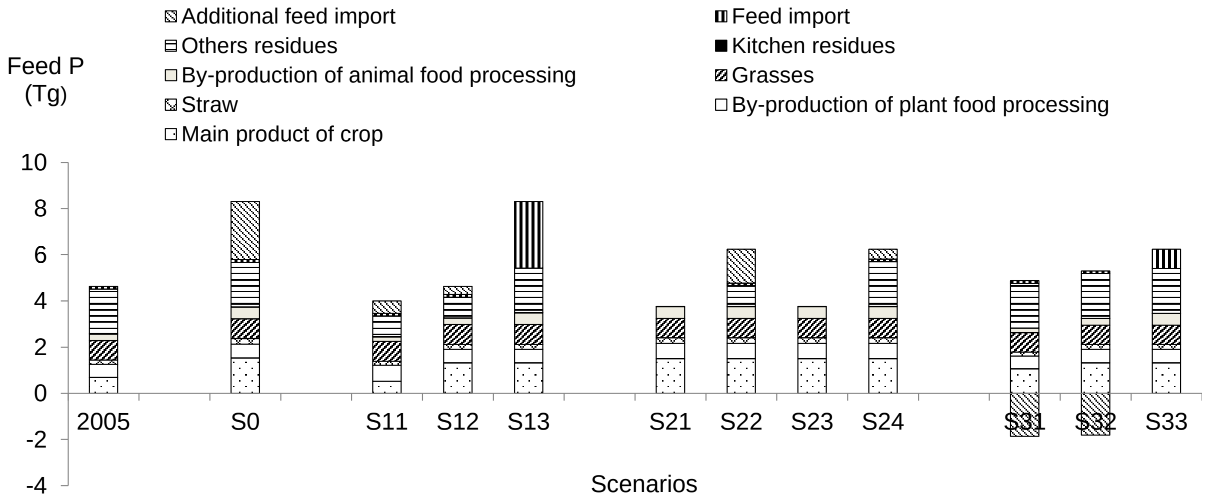
Figure 6-2 Inputs of 'new' N (upper panel) and P (lower panel) in the food chain in China in 2005 and in 2030 for different scenarios. 'New' N and P are defined as N and P inputs from outside the food pyramid (Figure 6-1).

6.3.2 Structural adjustment scenarios

In the structural adjustment scenarios, we explored the effects of changes in the animal food demand (i.e. S11, diet change) and in the ratio of domestic animal food and feed production versus increased imports of animal food (S12) and animal feed (S13) on N and P use and losses.



(a)



(b)

Figure 6-3 Feed N intake (upper panel) and feed P intake (lower panel) in animal production in China in 2005 and in 2030 for different scenarios. Additional feed import is defined as the difference between feed required and total feed supplied, that cannot be provided by domestic production.

In S11 (diet change) the ratio of animal-derived food to plant-derived food (APFR) decreased from 47 to 30% for N and from 48 to 28% for P compared with S0 (Table 6-2). As a consequence, imports of N and P in animal feed were more than halved

(Tables 6-2 and 6-3). Also, the N cost of the food decreased from 12 to 7 and the P cost from 17 to 10 kg per kg (Table 6-2), and total N losses decreased from 482 to 346 kg per ha and total P losses from 36 to 18 kg per ha, relative to scenario S0 (Table 6-3).

In S12 (increased import of animal products), fertilizer N and P consumption decreased by 12% (Figure 6-2), and nutrient losses decreased by 30% for N and 42% for P relative to S0 (Table 6-2). NUEf and PUEf increased to 11% and 9% respectively (Table 6-2).

In S13 (increased import of animal feed), fertilizer N and P consumption decreased by 12% (Figure 6-2), but nutrient losses dropped by only 4% for N and by 1% for P relative to S0 (Table 6-3). Nutrient use efficiencies did not change compared to 2005 (Table 6-2).

6.3.3 Technology and management scenarios

In scenario S21 (balanced fertilization), fertilizer N consumption decreased from 40.8 Tg in S0 to 28.6 Tg (a decrease of 30%, Table 6-1) and fertilizer P from 6.5 Tg in S0 to 5.2 Tg (a decrease of 22%, Table S7). Total N losses in crop production decreased by about 100 kg per ha per year, from 283 kg in S0 to 181 kg per ha per year in S21 (Table 6-3). Total P losses from crop production decreased slightly (1%) as P losses from crop production are mainly determined by erosion of P-rich topsoil which did not change in the scenario.

In scenario S22 (precision feeding), the import of animal feed N decreased from 27.9 to 20.9 Tg (Table 6-1) and that of animal feed P from 5.3 to 3.2 Tg (Table S7). As a consequence, total N losses from animal production decreased by about 40 kg per ha per year, from 199 kg in S0 to 159 kg per ha per year (Table 6-3). Total P losses from animal production decreased from 32 kg in S0 to 23 kg per ha per year (Table 6-3).
In scenario S23 (improved manure management), N and P losses via discharges of animal manures decreased from 104 to 38 kg per ha for N and from 32 to 12 kg per ha for P, relative to S0 (Table 6-3). However, the full potentials of improved manure management was not yet realized in this scenario because the losses in crop production increased due to the increased use of manure; the losses were simply transferred from animal production to crop production.

Table 6-1 Main flows of N in the food pyramid in China at national level in 2005 and in 2030 for all scenarios (Unit: Tg = 10^{12} g). Numbers in brackets refer to the codes in the food pyramid in Figure 6-1.

Item	Code		Business as usual scenario	Structural adjustment scenarios			Technology and management scenarios				Combination scenarios		
		2005	S0	S11	S12	S13	S21	S22	S23	S24	S31	S32	S33
Inputs													
Import to crop production	(1)	34.2	40.8	39.0	36.9	36.9	28.6	40.8	40.8	25.1	17.2	19.2	17.0
Import to animal production	(2)	14.3	27.9	12.3	11.7	29.0	27.7	20.9	27.7	20.9	7.2	7.9	22.2
Import to food processing (including feed processing)	(3)	0.3	0.3	0.3	1.5	4.4	0.3	0.3	0.3	0.3	0.3	1.5	4.4
Outputs													
Export from crop production	(4)	2.5	1.2	1.3	1.1	1.1	1.3	1.3	1.3	1.3	0.9	1.1	1.1
Losses from crop production	(5)	26.5	32.6	29.0	25.9	30.0	20.8	30.1	38.8	21.4	9.1	10.3	15.7
Export from animal production	(6)	0.5	0.8	0.5	0.5	0.8	0.8	0.7	0.8	0.7	0.4	0.4	0.7
Losses from animal production	(7)	12.8	23.0	10.7	12.8	23.0	23.0	18.4	15.4	12.3	5.9	6.8	12.3
Export from food processing	(8)	2.1	3.5	3.4	2.9	3.6	3.3	3.3	3.3	3.3	4.0	2.9	3.6
Losses from food processing	(9)	0.9	1.5	1.5	1.3	1.5	1.4	1.4	1.4	1.4	1.7	1.3	1.5
Export from household	(10)	0.3	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.5
Losses from household	(11)	2.6	4.4	5.8	4.4	4.4	4.4	4.4	4.4	4.4	5.8	4.4	4.4
Production → Consumption													
Crop production→animal production	(13)	5.1	8.0	3.5	7.0	7.0	7.9	7.9	7.9	7.9	6.0	7.0	7.0
Crop production →food processing	(19)	6.8	7.0	8.8	6.8	6.8	7.8	7.8	7.8	7.8	6.7	6.8	6.8
Animal production →food processing	(17)	3.7	6.3	3.7	3.7	6.3	6.3	6.3	6.3	6.3	3.7	3.7	6.3
Food processing→households	(21)	4.4	5.7	7.4	5.7	5.7	5.7	5.7	5.7	5.7	7.4	5.7	5.7
Cycling													
Cycling in crop production	(12)	2	2.3	1.7	2.2	2.2	2.4	2.4	2.4	2.4	1.7	2.2	2.2
Animal production →crop production	(14)	5.6	10.1	5.4	5.6	10.1	10.1	8.1	17.7	14.2	7.0	7.9	14.2
Food processing →crop production	(15)	0.4	0.4	0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Households→crop production	(16)	1.3	0.7	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.7	0.7
Food processing→animal production	(18)	3	3.4	3.5	2.9	3.3	3.6	3.6	3.6	3.6	2.8	2.9	3.3
Households→animal production	(20)	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Accumulation in soil	(22)	0.6	2.4	2.3	1.8	2.2	1.1	2.1	3.0	1.1	0.0	0.0	0.7

Table 6- 2 Indicators for the assessment of the performances of the scenarios for N and P utilization in the food chain (see text)

Indicators		Business as usual scenario	Structural adjustment scenarios			Technology and management scenarios				Combination scenarios		
	2005	S0	S11	S12	S13	S21	S22	S23	S24	S31	S32	S33
N												
NUEf (%)	9	8	14	11	9	10	9	8	12	27	20	14
N cost of food (kg kg^{-1})	11	12	7	9	12	10	11	12	8	4	5	7
APFR (%)	32	47	30	47	48	45	45	45	45	35	47	48
NUEc (%)	26	25	25	28	25	34	27	23	34	43	42	37
NUEa (%)	16	16	18	16	16	16	19	16	19	22	20	19
LIR (%)	51	54	52	52	54	48	51	49	41	35	34	39
P												
PUEf (%)	7	6	10	9	6	7	7	6	9	15	13	9
P cost of food (kg kg^{-1})	14	17	10	12	16	15	14	17	11	6	8	11
APFR (%)	35	48	28	48	49	46	46	46	46	34	48	49
PUEc (%)	36	32	31	37	32	38	37	27	37	38	44	35
PUEa (%)	17	17	18	17	17	17	23	17	23	24	23	23
LIR (%)	20	23	19	21	24	24	21	12	12	14	12	12

Table 6-3 Mean N and P losses from crop and animal production in China in 2005 and in 2030 for all scenarios (kg ha^{-1}). Losses associated with manure application to land are included in crop production.

Compartment	Losses		Business as usual scenario	Structural adjustment scenarios			Technology and management scenarios				Combination scenarios		
		2005	S0	S11	S12	S13	S21	S22	S23	S24	S31	S32	S33
Crop production	NH_3	73	96	82	78	88	70	92	114	71	39	45	54
	N_2O	3	4	3	3	3	3	4	4	3	2	2	2
	N_2	70	91	86	69	85	41	79	114	43	0	0	26
	NOx	15	19	15	17	17	19	19	19	19	15	17	17
	N losses via leaching, runoff and erosion	57	73	65	59	67	48	68	86	49	23	26	37
	Total	218	283	251	226	260	181	262	337	185	79	90	136
Animal production	NH_3	44	79	37	44	79	79	63	79	63	29	35	63
	N_2O	1	1	1	1	1	1	1	1	1	1	1	1
	N_2	8	15	7	8	15	15	12	15	12	6	7	12
	N losses via discharge and leaching	58	104	48	58	104	104	83	38	31	15	17	31
	Total	111	199	93	111	199	199	159	133	107	51	60	107
Total	NH_3	117	175	119	121	167	149	155	193	135	68	80	117
	N_2O	4	5	4	4	5	4	5	6	4	2	3	3
	N_2	78	106	94	77	100	56	91	129	55	6	7	38
	NOx	15	19	15	17	17	19	19	19	19	15	17	17
	N losses via leaching, runoff and erosion	115	177	114	117	172	152	151	124	80	39	43	68
	Total N losses	329	482	344	337	459	380	421	470	292	130	150	243
Crop production	P losses via leaching, runoff and erosion	3	4	4	3	4	4	4	5	4	3	3	4
Animal production	P losses via discharge and leaching	18	32	14	18	32	32	23	12	8	4	5	8
Total	Total P losses	21	36	18	21	36	36	27	17	12	7	8	12

In scenario S24 (S21+S22+S23, integrated nutrient management) we examined combinations of balanced fertilization in crop production, precision feeding in animal production and improved manure management. In S24 fertilizer N and P consumption decreased from 40.8 to 25.1 Tg and from 6.5 to 4.7 Tg, respectively (Tables 6-2 and 6-3). Further, imports of animal feed N and P decreased from 27.9 to 20.9 Tg and from 5.3 to 3.2 Tg, respectively (Tables 6-2 and 6-3). As a result total N losses from crop and animal production combined decreased by almost 200 kg per ha per year, from 482 kg in S0 to 292 kg per ha per year in S24 (Table 6-3). Similarly, total P losses from crop and animal production combined decreased by a factor of 3, from 37 kg in S0 to 12 kg per ha per year in S24 (Table 6-3).

6.3.4 Combination scenarios

Scenario S31 in which structural adjustments of domestic food demand were combined with improvements in technology and management resulted in large decreases in N and P losses and in the N and P costs of food production. These scenarios minimized the need for new N and P inputs and increased NUE and PUE more than the single scenarios.

Scenario S31 combined adjusted diets (S11) and integrated nutrient management (S24). Fertilizer consumption decreased from 40.8 to 17.2 Tg for N and from 6.5 to 4.4 Tg for P, relative to S0 (Tables 6-2 and 6-3). Feed N imports decreased from 27.9 to 7.2 Tg and feed P imports from 5.3 to 0.9 Tg. As a result, total N losses decreased by more than a factor of 3, from 482 kg in S0 to 130 kg per ha per year in S31. Total P losses in animal production decreased by a factor of 8, from 32 kg in S0 to 4 kg per ha per year in S31 (Table 6-3).

Scenario S32 combined increased import of animal products (S12) and integrated nutrient management (S24). Again, large decreases in fertilizer consumption, animal feed imports and total N and P losses were obtained, but imports of animal-derived food increased. There were smaller decreases in N and P losses than in scenario S31.
Scenario S33 combined increased imports of animal feed (S13) and integrated nutrient management (S24). This scenario decreased N and P losses to a lesser extent than scenarios S31 and S32.

6.4 Discussion

This study provides the first scenario analysis of N and P flows in the future food chain in China, and considers structural changes in food production and consumption together with improvements in nutrient management in crop and animal production.

We show that all the changes examined exert some effect on NUE and PUE and on N and P losses to the environment.

The main findings are as follows. Firstly, the business as usual scenario (S0) suggests dramatic increases in (new) N and P inputs and N and P losses for 2030, mainly as a result of the inferred increase in the demand for animal-derived food. Secondly, optimizing the human diet and balanced N and P fertilization are the most effective single measures (scenarios) for increasing the NUE and PUE of the food chain. Improved manure management is the most effective measure to decrease nutrient losses. Thirdly, there is a very large requirement for additional feed imports to support the human demand for animal food in the BAU scenario for 2030. Hence, choices have to be made between changes in diets and/or increased food and/or animal feed imports. Fourthly, implementation of a package of integrated nutrient management measures strongly decreases nutrient losses and roughly nullifies the predicted increases in N and P losses in the BAU scenario. These measures would also greatly increase NUE and PUE throughout the whole food chain.

Clearly, these findings are not without uncertainties. We made various assumptions about possible development pathways of the food production – consumption chain and there are also uncertainties related to the statistical analysis and the coefficients used in the model calculations (see supplementary information). The results can therefore not be used as 'blueprints'.

6.4.1 Potentials for structural optimization

In the past few decades the NUE and PUE of the Chinese food chain have decreased, due to the increased consumption of animal-derived food, increased fertilizer use, and reduced recycling of nutrients from residues, manure and wastes (Ma et al., 2012). It is likely that nutrient use efficiency in the food chain will decrease further during the next two decades in the BAU scenario unless changes are made to the diet, and/or food and feed imports, and/or improvements in nutrient management and animal nutrition. These latter changes and improvements are needed also from a food security perspective because total food and feed production in the BAU scenario is insufficient to meet the increased food demand by 2030, even with our rather optimistic assumptions of a 25% increase in mean crop yield. There is simply not enough land to produce the required amount of plant food and animal feed (Hubacek and Sun, 2001). The difference between the required amount of feed and the domestic feed production is equivalent to more than 10 Tg protein N which has to be provided by additional imports (Figure 6-3).

The change in diet in S11 greatly reduced the animal-derived food and animal feed demands. This in turn reduced the requirement for land (Kastner et al., 2012), water (Liu et al., 2008a) and fertilizer (Howarth et al., 2002) and reduced greenhouse gas emissions (Popp et al., 2010). Although highly effective, a dietary change towards less animal-derived food and more vegetables, fruits, milk and cereals is challenging. Food consumption patterns are closely related to affluence, urbanization and cultural food preferences (Xue and Landis, 2010). Hence, great efforts are needed to make dietary changes happen or to prevent that unwanted changes. Communication of the effects of diets on human health, land requirements and nutrient losses to stakeholders (public, policy makers, regional governments, business) using results from among others, the NUFER model, may facilitate adoption of the Chinese food dietary guidelines (CDG). Additional (economic) instruments will likely be needed to realize changes in food consumption patterns in practice.

Animal-derived food may be imported from other countries than produced domestically. Over recent decades world trade in pig meat and chicken meat has grown at annual rates of 5.6% and 6.8%, respectively (FAO). Imports of animal products greatly reduce the area of land required and the amounts of water and nutrients required in the importing countries (Galloway et al., 2007). However, imports increases dependency and transfer inefficiencies in food production and consumption to the exporting countries. Increasing food trade between countries is a response of competitive advantages and subsequent specialization of food production in certain countries in a globalizing world (Reed, 2001).

Instead of importing animal-derived food, there is the option of importing animal feeds and producing animal-derived food domestically (scenario S13). Maize and soybeans are the main animal feeds in this case because of their high energy and protein contents. However, the increased imports of maize and soybeans have a large effect on the world markets of grain and soya. The total imports of maize and soybeans in the S13 scenario are equivalent to 97% and 87 % of the current total export of all countries in the world combined in 2005. Clearly, an increased demand for animal feed by China will place heavy additional pressure on scarce exportable supplies of cereals (Brown, 2011). This may induce a strong upward trend in world market prices for cereals and in the end will not be very attractive for China or the other cereal importing countries.

6.4.2 Nutrient management options

Our modelling results clearly show that improved nutrient management strategies must include (i) balanced fertilization in crop production, (ii) precision animal feeding, and (iii) improved manure management. Balanced fertilization (S21) is the single most effective measure for increasing NUE and PUE. Balanced fertilization was also identified as an effective strategy to increase nutrient use efficiency in the European Union (Velthof et al., 2009). Supra-optimal fertilization is common in China, especially in and around the Beijing and Tianjin metropolitan regions (North China), the Pearl River Delta (South China) and the Yangzi River Delta (East China) (Ma et al., 2012). Although various initiatives have been launched in recent years such as integrated nutrient management, integrated soil-crop systems management, and soil testing and fertilizer recommendations programs, to increase crop productivity and decrease fertilizer application rates simultaneously (Chen et al., 2011; Wang, 2011; Zhang et al., 2011), the rate of implementation by famers is still limited. The big challenge now is to transfer these technologies and management knowledge from research to practice through education, training, demonstration, extension services and appropriate economic incentives.

Precision feeding (S22) may decrease feed N and P intake by the animal without reducing animal productivity, especially in industrial feedlots which import essentially all feed. However, traditional small-holder animal farms still contribute 20 to 80% of the total livestock production in China, depending on animal species. On these farms there are only few animals housed in the backyard. These are typically fed with household residues and crop residues (straw and stalks) without much prospect of precision feeding.

Current N and P use efficiencies at herd level are much lower in China than in North America and Europe, because of the low genetic potential of the herd, the low feed quality and the relatively poor management. However, there are very large differences between systems. Large industrial animal feed operations around big cities are almost as efficient at herd level in China as in EU-27 and the USA (Bai et al., 2013). In contrast, the so-called backyard animal farming and smallholder farming systems are dominant in rural areas and these systems have low efficiencies at herd level but have high efficiencies at the whole system level (Bai et al., 2013). Hence, precision feeding can be implemented only by switching from subsistence farming systems to modern farming systems which can afford modern feeding technology.

Improved manure management (S23) is the single most effective scenario to decrease nutrient (especially P) losses. Manures are currently the main sources of N and P exports to lakes and rivers in China (Wang et al., 2010). Improved manure management as defined in scenario S23 clearly shows the very large effects of increased recycling of nutrients from manure. Again, implementation of this measure is a huge challenge, because many of the new industrial systems are landless (i.e., purchasing all feeds from elsewhere) and hence lack a nearby land-base for proper recycling of manure nutrients. Achieving the full potentials of this measure requires either high-technology manure processing and transport of processed manures to cropping areas and/or spatial planning of animal production systems amidst crop land (Lesschen et al., 2011; Oenema, 2004; Oenema et al., 2009).

Combinations of structural adjustments and improvements in technology and management provide the best prospects for decreasing nutrient losses, and maximizing nutrient use efficiencies. Yet, there were significant differences between the combinations (Tables 6-3, 6-4 and 6-5). Scenario S31(combination of diet change and integrated nutrient management) had the best indicator values and the lowest N and P losses, emphasizing that a dietary change towards healthy food together with integrated nutrient management is the most promising strategy for simultaneously achieving food security and environmental sustainability. Importing food combined with integrated nutrient management is the second best option and importing animal feeds with integrated nutrient management the third best option.

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CHAPTER 7

General discussion

7.1 Introduction

Increased inputs of ‘new’ nitrogen (N) and phosphorus (P), mainly via fertilizers, biological N_2 fixation, atmospheric deposition, and feed additives, have contributed to increased food production during the last decades but have also led to less recycling of N and P in residues and wastes to soils (Conley et al., 2009). This has led subsequently to lower N and P use efficiencies in the food chain and to larger losses of N and P, and of emission of greenhouse gases per unit of food produced (Galloway et al., 2008). However, the relationships between N and P inputs, food production, N and P use efficiency and N and P losses are complex and poorly understood, especially when considering the whole food production and consumption chain, at regional and national levels. Moreover, the interactions between N and P in the food production and consumption chain have been less analyzed. Therefore, the main questions of my thesis are “How to analyze N and P use efficiency and how to manage N and P flows in the food production – consumption chain at regional and national scales?”

The studies described in Chapters 2 to 6 were each dedicated to a specific theme in order to answer specific research questions. Together they contributed to answer the general research question. All studies were conducted in China, for various reasons, including (i) the country is highly diverse and in a rapid economic, demographic and agricultural transition, (ii) there is as yet very little information about N and P use efficiency in the food production – consumption chain at regional level in China, and (iii), my background and experience, which allowed me to access unique data and information.

The aim of this general discussion chapter is to highlight the main results of my thesis, also in the broader context of the international scientific literature, and thereby to answer the main research questions and to prove my hypotheses. The hypotheses of my thesis are: H1: Lowering the net N and P costs of food requires a food chain approach; H2: Changes in N and P use efficiencies of the food production – consumption chain are large and regionally diverse in China during the last three to four decades, due to changes in human diets and management practices.

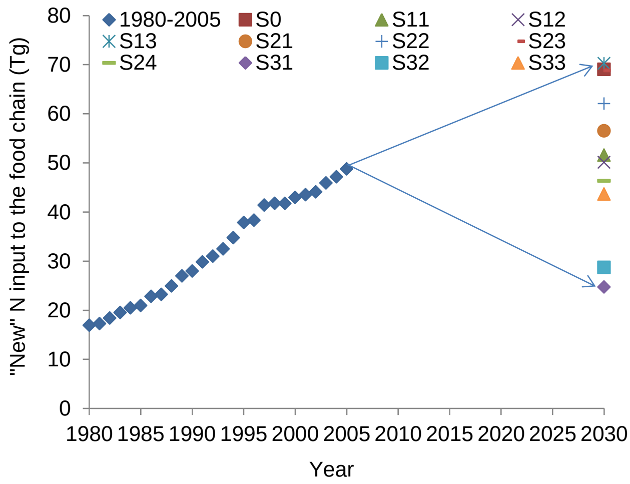
This chapter starts by presenting the main findings of my thesis research. Then, the importance of the food chain approach and the NUFER model (Chapter 3) are discussed. Moreover, the main driving factors for changes in nutrient use efficiency in the food chain of China are discussed, in comparison also with other countries. Options to increase nutrient use efficiency in the food chain are discussed using the results presented in Chapters 2, 3, 4, 5 and 6 and other studies. Finally, the main conclusions and suggestions for future research are presented.

7.2 Main findings

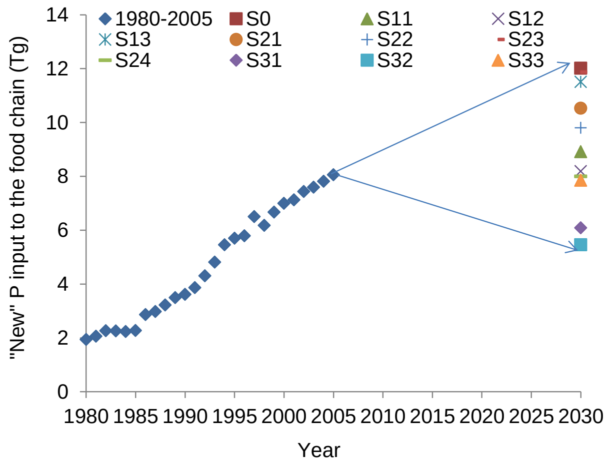
Though various promising nutrient management concepts and technologies have been developed and tested already, especially in crop production, adoption of these concepts and technologies in farmers ‘practice is still negligible in China. This is mainly due to a lack of a coherent strategy for nutrient management, lack of sufficient education, and also due to the numerous small farmers. To develop a coherent nutrient management strategy, there is a need for shifting the research focus from nutrient management in crop production at field and farm level to nutrient management in the whole food production – consumption chain. Especially, a greater focus on the proper collection of nutrients from manure and recycling to crop land is needed (Chapter 2).

The food chain approach (the ‘food pyramid’) developed in this study proved to be a good tool for analyzing N and P flows in the food production and consumption chain. The food pyramid with food production at the base and food consumption by humans at the top helps to visualize and understand the low nutrient use efficiency of the food chain (Chapter 2-6).

The amounts of ‘new’ N and P imported into the food chain at national level nearly tripled for N and more than quadrupled for P in China in 2005 compared with 1980 (Figure 7-1). Main inputs were fertilizers and imported animal feed, biological N fixation, atmospheric N deposition, and feed additives (Chapters 3 and 4).



(a)



(b)

Figure 7-1 Total inputs of N (upper panel) and P (lower panel) in the food chain in China during the period 1980-2005, and in 2030 for different scenarios. 'New' N and P are defined as N and P inputs from outside the food chain (see text). Scenarios for 2030 are defined as follows: S0-business as usual, S11-diet change, S12-increased imports of animal products, S13-increased imports of animal feed, S21-balanced fertilization in cropland, S22-precision feeding, S23-improved manure management, S24-integrated nutrient management, S31-combination of S11 and S24, S32-combination of S12 and S24, S33-combination of S13 and S24 (see Chapter 6).

Total N losses to water and atmosphere almost tripled between 1980 and 2005 (to 42.8 Tg in 2005). Estimated P losses to water systems increased from 0.5 Tg in 1980 to 3.0 Tg in 2005 (Chapters 3 and 4). Mean ammonia (NH_3) emissions and N and P leaching losses (including runoff, erosion and direct discharges) were the major loss pathways (Table 7-1). Losses of N and P to surface waters increased more than losses to air and groundwater between 1980 and 2005, mainly because of an increase of direct discharges of animal manures to surface waters (Chapter 4).

Table 7-1 Estimated mean N and P losses from crop and animal production in China between 1980 and 2005 and for different scenarios in 2030 (all in kg ha^{-1} year^{-1}). Gaseous N losses include ammonia (NH_3), nitrous oxide (N_2O), dinitrogen (N_2), and nitrogen oxides (NOx).

Year and Scenarios*)	NH_3	N_2O	N_2	NO_x	N losses via leaching, runoff and erosion	P losses via leaching, runoff and erosion
1980	55	2	21	15	24	1
1990	90	3	42	21	48	5
2000	115	4	79	17	93	15
2005	117	4	78	15	115	21
S0	175	5	106	19	177	37
S11	119	4	94	15	114	18
S12	121	4	77	17	117	21
S13	167	5	100	17	172	36
S21	149	4	56	19	152	36
S22	155	5	91	19	151	27
S23	193	6	129	19	124	17
S24	135	4	55	19	80	12
S31	68	2	6	15	39	7
S32	80	3	7	17	43	7
S33	117	3	38	17	68	12

*) Scenarios are explained in Figure 7-1 and in Chapter 6.

The N (or P) cost of food is an indicator to get quantitative insight of the amount of N and P needed to produce food for households. The N (or P) cost is defined as the amount (in kg) of new N (or P) used in the crop and animal production and food processing compartments for the delivery of 1 kg N (or P) in the food entering households. Between 1980 and 2005, the mean N cost of food in China increased from 6 to 11 kg kg^{-1} . Mean P cost increased from 5 to 13 kg kg^{-1} (Chapters 3 and 4). Between 1980 and 2005, the N and P use efficiencies decreased in crop production (NUEc and PUEc), increased in animal production (NUEa and PUEa), and decreased in the whole food chain (NUEf and PUEf) (Table 7-2). The main reasons for the decreasing NUEf and PUEf are (i) changes towards a diet with more animal-derived protein, (ii) over fertilization in crop production, and (iii) decoupling of crop and animal production, which has led to less recycling of manure nutrients in crop land (Chapters 3 and 4).

Table 7-2 Nitrogen and phosphorus use efficiencies in crop production, animal production, and in the whole food chain in China between 1980 and 2005 and for different scenarios in 2030 (all in %).

Year and	Nitrogen use efficiencies (%)			Phosphorus use efficiencies (%)		
scenarios	NUEc*	NUEa*	NUEf*	PUEc*	PUEa*	PUEf*
1980	32	8	16	59	16	19
1990	32	11	13	50	14	13
2000	26	16	10	35	15	8
2005	26	16	9	36	17	7
S0	25	16	8	32	17	6
S11	25	18	14	31	18	10
S12	28	16	11	37	17	9
S13	25	16	9	32	17	6
S21	34	16	10	38	17	7
S22	27	19	9	37	23	7
S23	23	16	8	27	17	6
S24	34	19	12	37	23	9
S31	43	22	27	38	24	15
S32	42	20	20	44	23	13
S33	37	19	14	35	23	9

*: NUEc is the N use efficiency in crop production; NUEa is the N use efficiency in animal production; NUEf is the N use efficiency in the food chain; PUEc is the P use efficiency in crop production; PUEa is the P use efficiency in animal production; PUEf is the P use efficiency in the food chain. Scenarios are explained in Figure 7-1 and Chapter 6.

There were significant regional differences in N and P losses to the environment via NH_3 and N_2O emissions to air and N and P leaching to groundwater and surface waters. High emissions occurred in the Beijing and Tianjin metropolitans, Pearl River Delta, and Yangzi River Delta. The N and P losses increased in these regions more than 5 times between 1980 and 2005. Mean N and P losses were relatively low in west and north China (Chapter 4).

The input of ‘new’ N to the food chain of Beijing metropolitan increased from 180 to 281 Gg, and for P from 33.5 to 50.4 Gg during 1978-2008. A total of 66% of the N input and 85% of the P input was not recycled but wasted and diffusively accumulated in soils, landfills and waterways (via crop residues, animal excreta, and human excreta and household wastes) in 2008. Total losses of NH_3 and N_2O to air and of N to groundwater and surface waters increased 2.9 folds, and losses of P to groundwater and surface waters increased 37 folds (Chapter 5).

Following a business as usual (BAU) scenario towards 2030, N and P fertilizer consumption in China will both increase by 25%, and N and P losses will increase by 47 and 71%, respectively, compared to 2005. The main cause for this increase is population growth and the per capita increase of animal-derived food consumption (Chapter 6). Scenarios with changes in human diet and increased imports of animal products result in reductions in fertilizer consumption and N and P losses relative to the BAU scenario. Combination of balanced fertilization in crop production, precision feeding in animal production and improved manure management are the most effective management options for increasing the N and P use efficiency in the food chain (Chapter 6). The scenarios also indicate that if diets would follow the Chinese food dietary guidelines (less meat, more vegetables, fruits and cereals), imports of N and P in animal feed could be halved, and total N and P losses would decrease. If the increase in the animal products would be imported from other countries, fertilizer N and P consumption will decrease by 12%, and nutrient losses by 30% for N and by 42% for P (Chapter 6). However, increased imports of feed and food will increase the N and P losses in other countries.

7.3 Food chain approaches and the food pyramid

The food system concept has been developed by sociologists some years ago (McMichael, 1994). Sobal et al. (1998) identified four major types of model concepts: food chain, food cycles, food webs and food contexts, and developed a more integrated approach, the ‘food and nutrition system’ (Sobal et al., 1998). Recently, a new concept was developed, to examine the complex of food security and its interactions with global environmental change (Ingram, 2011). All these approaches and concepts provide qualitative understanding of the food production – consumption chain, but they do not provide quantitative insight.

Material flow analysis (MFA) has been used to quantitatively analyze resource uses at a wide range of geographical scales and to aid environmental management in the field of (industrial) ecology (Ayres and Ayres, 2002; Brunner and Rechberger, 2004). However, MFA can only assess the physical consequences and changes. Life cycle assessment (LCA) is a well-established, quantitative method to evaluate the use of resources and emissions of pollutants during the entire life cycle of a product (Guinée, 2002), also for agricultural products (de Boer et al., 2011). However, it is difficult to aggregate multiple food categories within the food chain with LCA only.

In food systems, nutrient transfers and transformations take place. To be able to quantify and assess these transfers and transformation, a food chain approach was developed for the whole food production and consumption chain (Chapter 3), using the combined strengths of MFA and LCA. In this approach, (1) all physical N and P inputs, outputs, flows and emissions can be allocated to compartments, and related to N and P input-output budgets in crop production, animal production, food processing, households and the whole food chain,; (2) losses of N and P can be quantified in the entire food chain using the law of mass conservation; and (3) N and P use efficiencies and the N and P cost of food can be analyzed and quantified. The food chain approach allows to analyze the relationships between food production and consumption, environmental impacts and resource uses. The analyses in and results of Chapters in 3 to 6 also proved my first hypothesis (H1; see Chapter 1): 'lowering the net N and P costs of food consumption requires a food chain approach'. The N and P cost of food consumption can only be quantified if the N and P flows in all parts of the food chain are quantified, and priorities for actions can only be made if the effectiveness and efficiency of these actions are known.

The food pyramid concept (Figure 7-2) was developed in my thesis research as a hierarchically structured and multilevel analytic framework. It is a visual and simple tool to analyze N and P flows in the food production – consumption chain and consists of an interrelated set of compartments (i.e. crop production, animal production, food processing and households) that are connected through flows of N and P (Figure 7-2). Each compartment has inputs and outputs of N and P.

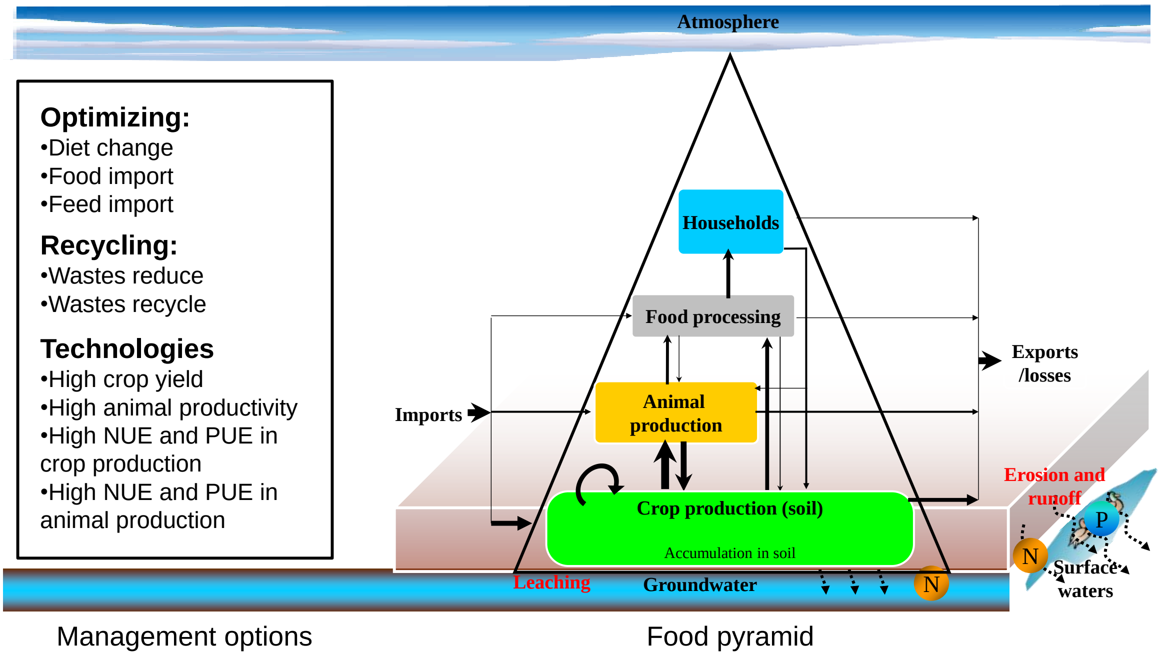


Figure 7-2 The food pyramid or food production – processing - consumption chain (right-hand side), and packages of management options for increasing nutrient use efficiency and for decreasing nutrient losses in the food production – processing - consumption chain. The green, yellow and blues boxes in the left side represent management options.

The food chain approach allowed to calculate the N and P input - output budgets at crop, animal, food processing and retail, and households levels, using national and regional statistics, literature data and additional model calculations.

7.4 NUFER model

To quantify N and P flows in the food pyramid, I developed the NUFER model, which includes the food pyramid approach. NUFER can be used to analyze N and P flows and use efficiencies in the whole food production – consumption chain, and was applied to China.

In Box 7-1 and Table 7-3, I have listed other nutrient cycling and budgets models that have been used recently to simulate nutrient flows at regional and national levels in China. None of these models have a food chain analysis approach. Moreover, there are differences in system boundaries. The boundary of the CHANS model and the national N cycle model is the biosphere, the boundary of National static SFA model and P stock and flow model is the land system, and the boundary of N budget model and AgiPhosFA is the primary agricultural production system. The CHANS model, the national N cycle model and N budget model only consider N flows and budgets in

China, while the National static SFA model, and AgiPhosFA model analysed only the P flows and budgets in China.

Table 7-3 Characteristics of simulation models used for analysing nutrient flows and budgets in China at national and regional levels.

	Method	Elements	Sectors considered	Area involved	Time	Reference
NUFER	Nutrient flows and balance analysis	N and P	Crop production, animal production, food processing and food consumption	China and 31 provinces	1980-2010, and 2030	(Ma et al., 2010; Ma et al., 2012b)
CHANS model	Mass balance	N	Cropland, livestock, aquaculture, grassland, forest, urban, surface water, industry, urban greenland, groundwater, surface waters	China	1980-2010	(Gu et al., 2012)
The national N cycle model	*	N	Land, atmosphere, inland water, coastal subsystems	China	1910-2010, and 2050	(Cui et al., 2013a)
N budget model	Mass balance	N	Land system	National and provincial scales of China	1985-2007	(Ti et al., 2012)
National static SFA model of China	Substance flow analysis	P	Mining, chemical/fertilizer industries, agricultural crops, animal husbandry, food industry, fodder industry, and food consumption	China	1996	(Liu et al., 2004)
P stock and flow model	Substance flow analysis	P	Production, fabrication & manufacturing, use, and waste management & recycling	China	1984-2008	(Ma et al., 2012a)
AgiPhosFA model	Substance flow analysis	P	Agroecosystem	China	2004	(Chen et al., 2008)

Note: * no description

BOX 7-1 Description of the main models on nutrient flows and budgets analysis in China

The CHANS model (Nitrogen cycle in coupled human and natural systems) seeks understanding of the complexity through the integration of knowledge of constituent subsystems and their interactions. This involves linking sub-models to create coupled models capable of representing human (e.g., economic, social) and natural (e.g., hydrologic, atmospheric, biological) subsystems and most importantly the interactions among them. A mass balance approach is used to quantify the nitrogen fluxes for each subsystem (in total, 14 subsystems) in a CHANS of China with over 6000 nitrogen flows. A comprehensive assessment of ammonia (NH_3), nitrogen oxides (NO_x), and nitrous oxide (N_2O) emissions in China based on a full cycle analysis was presented by CHANS model (Gu et al., 2012).

The national N cycle model, divided the environment into four subsystems: atmosphere, land (the surface of the earth excluding the ocean, rivers, and lakes), inland waters, and coastal waters, analyse Nr fate and flux across subsystems throughout the whole country in China. Each subsystem can be viewed as a dynamic system with interaction of biological communities and the physical environment and as an N reservoir (Cui et al., 2013a).

N budget model was established based on the mass balance model. N inputs included biological fixation, chemical fertilizer, atmospheric deposition, and import of food and feed. N output included ammonia (NH_3) volatilization, N export to water bodies, food and feed exports, and biomass burning emissions. The difference between N inputs and outputs was assumed to be denitrification and storage, which both are difficult to quantify directly. The N budget was calculated for the years 1985, 1990, 1995, 2000, 2005 and 2007 for each province, autonomous region or municipality of mainland China. The inputs and outputs were then spatially allocated using 1 km resolution land use maps(Ti et al., 2012).

National static SFA model of China was developed as regarding China's national P flows for 1996, and the relevant data were mainly from the China Statistical Yearbook. Because the static model is based upon the conception that the physical economy operates in a steady state, it is assumed that there was equilibrium between inflow and outflow, that is, the fundamental formula of mass conservation can be further simplified as IN = OUT, regardless of stock and accumulation within the economy. As China becomes increasingly linked with the world economy, import/export of P material was also taken into account in the model. The P exchanges at the interfaces between atmosphere, geosphere, and hydrosphere were not taken into account. It starts from P resources, through mining, chemical/fertilizer industries, agricultural crops, animal husbandry, food industry, fodder industry, food consumption, and environmental industries, to end up in the environment (Liu et al., 2004).

P stock and flow model, which is composed of 4 sub-models (production, fabrication & manufacturing, use, and waste management & recycling), was constructed for China's national P metabolism and subsequently applied to statistical data collected from a variety of sources, including statistical yearbooks, government surveys, research papers and related websites. It was applied to time-series data from 1984 to 2008 to explore the correlation between change traits of anthropogenic phosphorus (P) metabolism in China and socioeconomic variables, quantify the accumulation of P in natural reservoirs and search for man-made stocks with the greatest potential for recovering P (Ma et al., 2012a).

AgiPhosFA is a static, quantitative model based on an emission inventory analysis (EIA) and a nutrient full balance (NFB) calculation. AgiPhosFA model describes the phosphorus (P) flow in the agricultural systems in China and assess the impact of human activities on waters driven by agriculture and rural life (Chen et al., 2008).

The NUFER model distinguishes four main compartments (crop production, animal production, food processing and retail, and households) and within the crop compartment 18 different crops and within the animal compartment 11 different animal categories. It is a flexible framework for studying changes in N and P use efficiency in each compartment, with clear system boundaries. It is a flexible framework for studying changes in N and P use efficiency in each compartment, with clear system boundaries.

An analysis of other modelling studies indicates that system boundaries are not always applied appropriately. For example, Cui et al.(2013) recently estimated the total input of reactive nitrogen (Nr) in China, and presented Nr budgets for the land, atmosphere and water subsystems for the last century. However, their estimations of total Nr accumulation in the land subsystem (17 Tg in 1978 and 45 Tg in 2010) are likely overestimated (factor two) because of unclear definition of the system boundaries. Actually, some Nr will be stored in land/soil (in organic matter of productive croplands), but the annual uptake of N in plants and harvested products in croplands does not represent Nr accumulation. These products are consumed by animals and humans, and most of the N is recycled in urine and faeces and partly dissipated into the wider environment.

The NUFER facilitate assessment of the inter-relationships between N and P. There are significant differences between N and P in their transfer between compartments, dissipation into the environment, their residual effects, and use efficiency. For example, if the animal manure now discharged into surface waters in China (～2 Tg P per year) is used to replace fertilizer P, PUEf would increase from 7 to 11%. Such a huge increase may not be achieved with NUEf because a significant fraction of manure N is already lost during storage and application to land, especially without using low-ammonia emission techniques (Chapter 3). The food pyramid approach of NUFER generates knowledge that enhances decision-making by stakeholders along the food chain regarding nutrient management at regional level.

However, there is also scope for improvement of NUFER. Firstly, the model requires testing at different scales, but so far there is a lack of data to validate and verify the results. Detailed monitoring data of N and P flows and losses are required to verify the model at regional levels. Secondly, NUFER is a static model on annual basis. As a result, residual effects are not addressed explicitly. Crop production is not directly related to inputs of plant-available N and P. Emissions of NH_3 to air are not directly coupled to deposition of atmospheric N to crop land, and the excretion of N and P by the domestic animals is not yet a direct result of the animal feed offered to the animals (but derived from data statistics). Thirdly, the spatial resolution is still low. Many decisions are made at county level (and not at national and province levels), and hence there is a need to downscale and refine the budgets at county levels. However, collection of data and information is more complex at this level than at province level. Finally, NUFER estimates N and P losses to air and water bodies, but does not estimate the resulting environmental quality of the air and water bodies.

Evidently, there are uncertainties in the results of the calculations by the NUFER model. The uncertainties in the results mainly originate from uncertainties in the data sources, coefficients, and emission factors. Firstly, statistical data and future forecasts have intrinsic uncertainties, which are difficult to assess without further information. However, these statistical data are the best available data currently. Secondly, the variables used for N and P contents, and N and P emission factors are taken from the literature and this may also introduce uncertainties. For example, the ideal method for estimating N and P excretion per animal category is the balance method, i.e., the difference between nutrient intake and nutrient retention per animal category (e.g., Bai et al., 2013). However, because of data limitations and uncertainties as regards the nutrient intake and nutrient retention per animal category, N and P excretion per animal category were based on literature data (Wang et al., 2011; Wang et al., 2010). Emission factors to estimate gaseous N losses and leaching fractions to estimate leaching are average emission factors. Application of average emission factor on regional levels is another source of uncertainty as region-specific conditions may affect the emission factor.

Further research at animal category level are needed to cross-check these literature values. A possible option would have been to undertake a Monte Carlo-type of uncertainty analysis, as has been done for example for the N budget in The Netherlands (De Vries et al., 2003).

7.5 Changes of nutrient use efficiency in the food chain of China

I hypothesized that changes in NUE and PUE of the food production – consumption chain are large in the past decades in China, due to changes in human diets and management practices (H2). Therefore, N and P cost of food was used as indicators for assessing N and P use in the food chain at the regional and national levels. By using this approach, I was able to integrate the knowledge about N and P use in crop production, animal production, food processing and households. The NUEf decreased from 16% to 9% and the PUEf from 17% to 7%, and the mean N cost increased from 6 to 11 kg kg^{-1}. The mean P cost increased from 5 to 13 kg kg^{-1} between 1980 and 2005. The results of my studies presented in Chapters 3, 4, 5 and 6 proved that my second hypothesis is true, but that there are more factors involved, as discussed below.

The base of the food pyramid became wider in China between 1980 and 2005, because more N and P were needed to produce the food consumed in the top of the chain (Figure 7-2). The slope of these pyramids visualizes the food N and P costs (Figure 7-2). These changes were influenced by several factors.

Firstly, China's on-going transition from a rural to urban population has been a major driver for changing human diets. The associated changes in lifestyle have led to both quantitative and qualitative shifts in the patterns of food consumption. In most regions, especially in urban regions, hunger is no longer a problem. The steady increase in the consumption of animal products and fast food products is an emerging issue, which is reflected in rising rates of obesity and chronic diseases (Zhai et al., 2009). Also, the N and P cost of animal-derived food are higher than that of plant-derived food (Galloway and Cowling, 2002), and hence, the total N and P costs of the food increased.

Secondly, inefficient nutrient management practices in the food chain contribute to low NUEf and PUEf. Improved technologies of nutrient management in crop production have been developed and have the potential to significantly increase both crop yields and nutrient use efficiency, and thereby to reduce the N and P losses to the environment at field and farm levels (Chen et al., 2011; Cui et al., 2013b; Cui et al., 2013c). However, widespread adoption of these improved nutrient management practices has not occurred yet (Ma et al., 2013). Additionally, current farmers often lack the knowledge base for sound nutrient management. Also, farmers do not gain much by reducing fertilizer application via improving nutrient management practices, because fertilizers are relatively cheap (through subsidies).

Thirdly, the establishment of large-scale confined animal feeding operations has greatly increased animal productivity and has lowered the N and P costs for dairy, meat and egg production in China. However, these systems are completely disconnected spatially from crop production, which makes the proper recycling of manure extremely complicated (Wang et al., 2010). According to my scenario analysis, improved manure management is the single most effective measure to decrease N and P losses in current China. However, implementation of this measure is a huge challenge because many of the new industrial animal farms are landless and hence lack a nearby land-base for recycling of manure in their own farms. Therefore, incentives for recycling of manure N and P among animal farms and arable farms have to be implemented, and livestock farms have to be situated in such a way spatially that recycling of manure N and P is possible indeed.

Finally, metropolitan expansion has significantly increased the N and P losses in the food production – consumption chain. In Chapter 4, the spatial distribution and changes of N and P losses from the food chain at regional level were examined. Losses of NH_3 and N_2O to air and N and P to groundwater and surface waters increased greatly, especially in the three main metropolitans: Beijing and Tianjin, Pearl River Delta, and Yangzi River Delta. My analysis in Chapter 5 indicated that the rapid growth of the Beijing metropolitan has significantly increased the food N and P import to the metropolitan and decreased the recycling of nutrients in crop residues and wastes back to the rural areas. Changes in the N and P use efficiency and losses are complex during metropolitan expansion, due to various co-occurring changes in crop and animal production, food and feed import, relative consumption of plant- and animal-derived food, and in the recycling of residues and wastes. Main driving forces for changes in N and P use efficiencies in Beijing were (i) population growth, (ii) transition from a rural to urban lifestyle, (iii) establishment of large specialized and land-less animal feeding operations, and (iv) shifts from cereal production to highly intensive vegetable and fruit production.

In summary, the factors that drive changes in the food chain of China are not unique; they occur globally. However, the rate and scale of change are unique and unprecedented. It results from a combination of rapid economic growth, and strong governmental policies related to food security, infrastructure and industry, which have facilitated a rapid transition from a largely rural/agrarian to an urban/industrial. . Likely, the food pyramid approach and the driving factors are applicable to other countries as well, including BRIC countries, OECD countries, and low-income, food-deficit countries.. Further studies are needed to be able to understand the relative importance of driving forces and their effects on N and P flows in the food chain of other countries.

7.6 Comparison with other countries

The N and P use efficiency in the food chain (NUEf and PUEf) in China went down from 16% to 9% for N, and from 17% to 7% for P between 1980 and 2005. For comparison, the estimated world average NUEf is 16% (Smil, 2002), while NUEf in USA is 15% (Howarth et al., 2002), in Germany 23% and in Norway 19% (Isermann and Isermann, 1998). Similarly, the world average PUEf is 11% (Cordell et al., 2009; Smil, 2000), while PUEf is 18% for USA (Suh and Yee, 2011) and the Netherlands (Smit et al., 2010). Hence, the NUEf and PUEf in China are at the lower end of the spectrum in the world. Differences between countries likely emanate from differences in diets and food production systems, but also from differences in nutrient use efficiency in crop and animal production, and from differences in the recycling of nutrients in food residues and food wastes.

The study of Bleken and Bakken (1997) in Norway was one of the first studies in which the N cost of the food consumed by humans was assessed at national level. The N-cost, defined as the ratio between total N input (including 'new' N and 'recycled' N) and the N in foodstuff was on average 10. Bleken and Bakken (1997) indicated that for each kg of N used in food production, only 0.1 kg ended up in food consumed while 0.9 kg was dissipated into the wider environment. Isermann and Isermann (1998) estimated the N use and losses in the food chain for Germany. Compared to the basic needs of the population for protein-N in food, N input to the food chain was 2 to 3 times higher than necessary. Howarth et al. (2002) analyzed the fate of N fertilizer in the food chain in the USA for the period 1961-2000, and presented potential future trends. Nitrogen inputs into the USA doubled between 1961 and 1997, largely driven by the consumption of more meat protein. Shindo et al. (2003, 2006) estimated the average N use efficiency in food production and total N losses to groundwater and surface water for 13 countries in East Asia for the period 1961-2020. Total N load increased by a factor of 3.8 between 1961 and 2002, and further by 1.3 to 1.6 times under future scenarios for 2020.

In term of P flows in the food chain, most studies emphasized the low use efficiency. Suh and Yee, 2011) found that only 15% of the total P extracted from nature for the provision of food is eventually ingested by humans in the US; the rest is lost to the environment. Cordell et al (2013) reported that despite being a net food exporter, Australia is a net P importer. The imported P is used to replenish P-deficient soils and to support an intensive agriculture. Matsubae et al (2009 and 2011) reported that the food chain of Japan has relied on imported P not only via fertilizer, yellow phosphorus and phosphorus ore, but also via food and feed. Smit et al (2010) reported that the Netherlands is a net importer of P; there was an accumulation of more than 60 Gg of P in 2005 (31 Gg accumulating in agricultural soils, 3 Gg in the aquatic environment following leaching from agricultural soils, and 25 Gg in landfill and the aquatic environment following sewage waste treatment).

7.7 Options to increase nutrient use efficiency in the food chain of China

In the report 'Our nutrient world' ten main objectives for increasing nutrient use efficiency have been identified (Sutton et al., 2013): (1) Improving nutrient use efficiency in crop production, (2) Improving nutrient use efficiency in animal production, (3) Increasing the fertilizer equivalence value of animal manure, (4) Low-emission combustion and energy-efficient systems, including renewable sources, (5) Development of NO_x capture and utilization technology in energy combustion, (6) Improving nutrient efficiency through reducing food waste, (7) Recycling nitrogen and phosphorus from waste water systems, (8) Energy and transport saving, (9) Lowering personal consumption of animal protein among populations consuming high rates (avoiding excess and voluntary reduction), and (10) Spatial and temporal optimization of nutrient flows (Sutton et al., 2013). Among these actions, there are seven actions specifically related to the food chain.

My results support the aforementioned seven actions related to the food chain. My scenario analyses for the food chain in China suggest that the food pyramid in the business as usual scenario will become wider. Unless actions are undertaken, the N and P food costs will increase further towards 2030 (Figure 7-3). It is therefore essential to understand how management options can increase nutrient recycling and increase nutrient use efficiency in the food chain in China. The possible options have been categorized into three groups (Figure 7-2).

Firstly, structural measures through changes in human diets, and increases in food and feed import (Figure 7-2). A diet change towards less animal-derived protein and increased food and feed import will lead to reductions in fertilizer consumption and nutrient losses in China. Following these structural adjustments, the shape of the food pyramid will become more slender or its shape could become somewhat like a diamond through the increased imports of animal products and feed and the decreased domestic crop production (Figure 7-3). Importing more food and feed may bring benefit to China's environment but will lead to increased environmental pressures for the food exporting countries. In the meanwhile, these changes may introduce a strong upward trend in world market prices for food, due to the demand- and price-inelasticity of food at the short term (Koning et al., 2009). Instead of importing food and feed, there is the option of diet change. However, additional incentives are needed to realize changes in food consumption patterns in practice (Galloway and Cowling, 2002; Xue and Landis, 2010).

Secondly, technological measures related to the so-called ‘Double high agriculture’ can greatly increase NUE and PUE in crop production (Chen et al., 2011). Double high agriculture aims at both high productivity and high resource use efficiency in crop production by integration of nutrient management with sound soil cultivation, use of new crop varieties, crop husbandry, and irrigation management practices (Chen et al., 2011). These technologies were developed for the staple grains (maize, rice and wheat) in 500 experimental plots across 11 provinces in China. So far, they have increased both the yields and the N efficiency by 30-50% (Zhang et al., 2013). However, more research of ‘double high’ technologies for vegetables, fruits, other crops and animal production are needed (Yan et al., 2013). Even so, it remains a challenge to transfer these technologies into farming practice. By implementing ‘Double high agriculture’ technologies in practice, the shape of the food pyramid will become more slender at the base (Figure 7-2).

Thirdly, improved recycling of nutrients from crop residues, manures, food wastes, and residues of food processing can greatly contribute to increasing NUEf and PUEf. (Figure 7-2). In recent decades, the nutrients in by-products, residues, and wastes have been neglected in nutrient management by farmers. Our analyses in Chapter 3 indicate that only 33 Tg N in by-products, residues and wastes was used effectively out of a total of 82 Tg in 2005. Hence, about 60% of the N in residues and wastes was not used and ended up unaccounted for in soils or was lost to the environment. This is especially true for manure in animal production (Chapter 4). The recycling of N and P from animal manure back to crop production decreased greatly during the period 1980 and 2005. Animal manures are now responsible for about 38% and 56% of the total N and P losses into surface wasters, respectively (Qiu, 2010). Therefore, there is need for the implementation of incentives for recycling of nutrients from manures, residues, and wastes in crop production, not only intra-regions but also inter-regions and in ‘rural-metropolitan settings’ (Chapter 6).

The combination of the three group of options mentioned above appeared to be the most effective option for a drastic increase of the use efficiency of N and P throughout the whole food chain (Chapter 6). The shape of the food pyramid in the combined options scenarios (both structural adjustments and improved nutrient managements) is most slender (Figure 7-3).

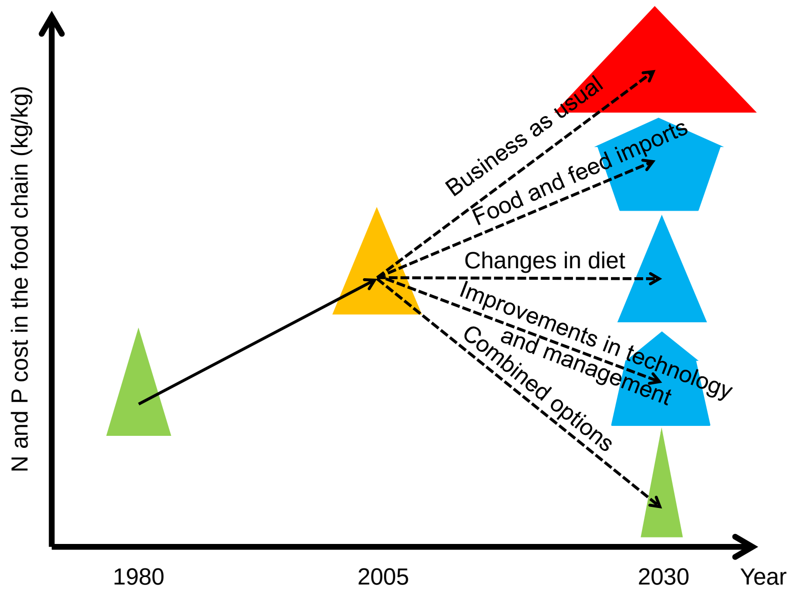


Figure 7-3 The 'shape of nutrient use' in the food pyramid and the relative nitrogen (N) and phosphorus (P) costs of food in China in 1980, 2005 and in scenarios for 2030. The horizontal axis represents time (in years), and the vertical axis represent the N and P cost in the food chain. The shape of nutrient use in the food pyramid reflects the relative magnitudes of inputs of new N and P in crop production, animal production, food processing and retail, and households (see text) .

7.8 Conclusions

The main objective of this thesis was to increase our understanding of the changes in N and P use efficiency (NUE and PUE) and losses in the food production – consumption chain in China at national and regional levels during the past 30 years and in the coming 20 years. In order to meet this objective five specific objectives were formulated (Chapter 1). My conclusions regarding the five specific objectives and the main conclusions are presented here.

A food chain approach for analyzing nutrient flows at regional and national levels is needed to quantify the N and P flows and losses in the whole of food production-consumption chain. In this thesis, a food pyramid approach was developed as an integrated framework for analyzing N and P management at regional and national levels.

The NUFER model has been developed to quantitative assess the N and P costs of food and of N and P losses to air and waters at national and regional scales in China. A set of indicators was developed for assessing N and P flows in the food chain.

The N and P use efficiencies decreased in crop production, increased in animal production, and decreased in the whole food chain between 1980 and 2005. Total losses to water and atmosphere increased almost three times for N and six times for P between 1980 and 2005. Losses of N and P to surface waters increased more than losses to air and groundwater. Mean NH_3 emissions and N and P leaching (including runoff, erosion and direct discharges) were the major loss pathways.

The regional variations in NUE and PUE in the food chain were large; lowest NUE and PUE, and highest N and P losses in the food chain occurred in the most populous areas, i.e., Beijing and Tianjin metropolitans, Pearl River Delta, and Yangzi River Delta.

The apparent N and P costs of food are relatively low in Beijing, because of the large food and feed imports. As a consequence, the N and P losses associated with the production of the food and feed were ‘transferred’ (swapped) to other regions, and thereby led to apparent low N and P food costs for Beijing. Yet, N and P losses to atmosphere, surface waters and groundwater have increased dramatically during the rapid urban expansion and economic growth between 1978 and 2008.

Implementation of a package of integrated nutrient management measures, including balanced fertilization in crop production, precision feeding in animal production, and improved manure management, is the most effective way for increasing the N and P use efficiency in the food chain. When combined with diet change towards less animal-derived protein and with increased imports of animal food and feed, the N and P losses from the whole food chain can decrease by approximately a factor of 3 to 6 (compared with business as usual scenario in 2030).

7.9 Suggestions for future research

Further research is needed to be able to develop the food chain approach and nutrient management at regional level further. Additional research aspects include the analysis of nutrient costs of different food categories, and the exploration of refined strategies for improving NUE and PUE in the food chain at regional level. Also cost (including economical cost) and benefit analyses of these strategies are needed.

The NUFER model needs to be validated using monitoring data. These monitoring data can over time also trace progress in environmental quality, due to the implementation of new nutrient management practices. Also, the monitoring data will aid in developing better models and better forecasts of future problems and possible solutions.

Finally, up-scaling of insights in nutrient efficiencies in the different compartments of the food chain to the global scale and to other countries is needed to be able to understand the effects of globalization on nutrient cycling, and NUE in food production - consumption chains.

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SUMMARY

Introduction

Food production is highly dependent on the use of nitrogen (N) and phosphorus (P) inputs. The use of N and P in food production has strongly increased during the last decades, because of the increase in human population and changes in diets. The losses of N and P to the atmosphere and water have increased at the same time, and these increased losses lead to a range of unwanted environmental problems. However, the relationships between N and P inputs to crop and animal production, the N and P use efficiencies (NUE and PUE), and the N and P losses are complex and difficult to quantify, especially when considering the entire food production and consumption chain at regional and national levels.

China is an interesting case to study N and P flows in the food production and consumption chains, because it is in a rapid economic, social and cultural transition. Its food production is becoming highly intensive, while NUE and PUE are relatively low, and N and P losses to the environment are relatively high. Environmental problems related to N and P losses have increased greatly during the last decades. However, the NUE and PUE of the food production and consumption chain in China at national and regional levels, and the N and P losses are not well quantified, and the factors that affect the NUE and PUE are not well understood.

The main aim of this thesis is to increase the quantitative understanding of the changes and controlling factors of NUE and PUE and N and P losses in the food production – consumption chain at national and regional levels in China in the past 30 years and to develop strategies to increase NUE and PUE. More specifically, the following research questions were addressed:

Q1: What is the current organizational structure of nutrient management and what are the main nutrient management challenges in China?

Q2: What are the N and P use efficiencies, and losses in crop and animal production, food processing, households, and in the whole food chain of China at national and regional scales?

Q3: What are the effects of population growth, changes in human diets and technology developments on N and P use efficiencies in the food chain?

Q4: How did urban expansion affect N and P use efficiencies, and losses in the food chain in Beijing during the past three decades?

Q5: Which options are effective for increasing nutrient use efficiency and decreasing nutrient losses in the food chain of China?

Methods and materials

The main developments in nutrient management at field and farm levels during the last decades were reviewed, and future challenges for nutrient management in the food chain at regional and national levels were identified (To answer Q1).

The simulation model NUFER (Nutrient flows in Food chains, Environment and Resource use) was developed in order to quantify N and P flows in the food chain at national and regional levels. NUFER includes a novel and comprehensive concept of the food pyramid, which allows the unravelling and quantification of N and P flows, balances, losses, and use efficiencies in different compartments of the food chain. The NUFER model distinguishes four main compartments: (i) crop production, with 18 crop types, (ii) animal production, with 11 animal categories, (iii) food processing and retail, and (iv) households, with a distinction between urban and rural citizens. NUFER consists of an input module (with activity data and with transformation and partitioning coefficients), a calculation module, an optimization module and an output module. The model allows assessment of the N and P flows in the food pyramid in two directions, viz. from the food production side and from the consumption side.

Firstly, NUFER was used to simulate historic and current N and P flows, balances, losses and use efficiency in the food chain, using data from statistical sources and farm and household surveys (To answer Q2 and Q3). Secondly, NUFER was used to assess the most effective nutrient management and structural changes in the food production – consumption chain for improving the N and P use efficiencies in the food chain at national and regional scales via scenario analysis (To answer Q3 and Q5). Thirdly, NUFER was used to analyse changes of N and P flows in the food chain of Beijing during its rapid urban expansion between 1978 and 2008 (To answer Q4).

Fertilizer inputs, crop yields and areas, and number of animals in the historic runs were based on statistical data. The composition of the diets of urban and rural citizen was based on household survey reports. Most of the other activity data were derived from information collected during numerous field surveys organized by China Agricultural University and National Agriculture Technique Science Center from 1999 to 2008. Contents of N and P in harvested crop and animal products, N and P excretion values per animal category and the partitioning of animal products in edible and other parts were derived from literature. Model inputs for the future scenarios were based on literature data and assumptions.

Results

An assessment of main development in nutrient management in China during past decades showed that various promising nutrient management concepts and technologies have been developed and tested in crop production already by universities and research institutes. However, adoption of these concepts and technologies in farmers‘ practice is still negligible. More coherent national policies and institutional structures are required for the research-extension-education chain to be able to address the challenges ahead. There is a need for shifting the research focus from nutrient management in crop production at field and farm levels to nutrient management in the entire food production and consumption chain at regional and national levels (Chapter 2).

The ‘food chain’ approach was developed for the purpose of my thesis to study N and P flows in the food production and consumption chain. The food pyramid approach was developed as a hierarchically structured and multilevel analytic framework, with food production at the base and food consumption at the top. The concept helps to visualize and understand the low nutrient use efficiency of the current food production – consumption chain, and the high N and P cost of the current food in China. A set of indicators were developed to assess N and P flows in the food chain.

Total inputs of ‘new’ N and P into the food chain in 2005were 48.8 and 7.8 Tg, respectively. New N (and P) was defined as the total input of N (and P) from outside the food chain, via fertilizers, deposition, biological N fixation, harvested grass from natural grassland, fish from unmanaged water bodies, and imports of feed and food from abroad. Only 4.4 Tg N and 0.6 Tg P reached households as food. The average N and P use efficiencies in the food chain was 9% for N and 7% for P in 2005. Most of the imported N was lost to the environment, i.e., 23 Tg N to atmosphere, and 20 Tg N and 3.0 Tg P to water bodies (Chapter 3).

The N and P cost of food proved to be one of the core indicators, it is defined as the amount of new N and P (in kg) used in the crop and animal production and food processing compartments for the delivery of 1 kg N and P in the food entering households. Between 1980 and 2005, the mean N cost of food in China increased from 6 to 11 kg kg^{-1}. The mean P cost of food increased from 5 to 13 kg kg^{-1} (Chapters 3 and 4).

Between 1980 and 2005, N use efficiency in crop production decreased from 32 to 26%, mainly because of the increased use of N fertilizer which was heavily subsidied by the government. In contrast, NUE increased in animal production from 8 to 16%, because of improved animal breeds and animal feeding. In the whole food chain NUE decreased from 16 to 9%. Similarly, PUE decreased in crop production from 59 to 36%, increased in animal production from 16 to 17%, and decreased in the whole food chain from 19 to 7% (Chapter 4). The main reasons for the decreasing use efficiencies of the food chain for N (NUEf) and P (PUEf) are (i) changes towards a diet with more animal-derived protein, (ii) over fertilization in crop production, and (iii) decoupling of crop and animal production, which has led to less recycling of manure nutrients to crop land (Chapter 3 and 4).

Total N losses to water and atmosphere almost tripled between 1980 (14.3 Tg) and 2005 (42.8 Tg). Estimated P losses to water systems increased from 0.5 Tg in 1980 to 3.0 Tg in 2005. Ammonia (NH_3) emissions and N and P leaching losses (including runoff, erosion and direct manure discharges) were the major loss pathways.

There were significant regional differences in N and P losses in the period 1980-2005. Losses increased greatly in South, East and Central China. Changes over time were relatively small for West and North China. Regions with high N and P losses are in the Beijing and Tianjin metropolitans, Pearl River Delta, and Yangzi River Delta. The food chain analysis approach indicated that the changes in NUE and PUE in crop and animal production are complex. Increases of NUE and PUE over time in animal production may be completely nullified when the necessary recycling of N and P in animal manure is neglected (Chapter 4).

The case study on N and P flows in the food chain of Beijing during a period of rapid urban expansion and economic growth, revealed the importance of structural changes in the food production and consumption chain. The input of ‘new’ N to the food chain of Beijing metropolitan increased from 180 to 281 Gg between 1978-2008, and from 33.5 to 50.4 Gg for P. A total of 66% of the N input and 85% of the P input was wasted in 2008 and diffusively accumulated in soils, landfills and waterways (via crop residues, animal excreta, human excreta and household wastes). Total N losses increased 2.9 folds, and P losses increased even 37 folds (Chapter 5). Recycling wastes and residues and expelling animal production from the peri-urban areas are possible options to increase NUE and PUE and decrease N and P losses in Beijing metropolitan. It is important to link the N and P cycles of urban and rural systems, so as to attain a more sustainable development of metropolitans (Chapter 5).

Possible future changes in the N and P flows in the food chain were also explored. In the business as usual (BAU) scenario towards 2030, consumption of N and P fertilizers in China increased both by 25%, and N and P losses increased by 47 and 71%, respectively, compared to 2005. Scenarios with changes in human diet (less meat, more vegetables, fruits and cereals) and increased imports of animal products indicated that fertilizer consumption and N and P losses decreased relative to BAU. The scenario analyses showed that a combination of balanced fertilization in crop production, precision feeding in animal production and improved manure management are the most effective management options for increasing the N and P use efficiency in the food chain. The scenarios also indicate that imports of N and P in animal feed could be halved, and total N and P losses reduced, if diets would follow the official Chinese food dietary guidelines (including a decrease of the consumption of animal-derived food). If the increasing demand of animal products will be fulfilled by import from other countries, fertilizer N and P consumption in China may decrease by 12%, and nutrient losses by 30% for N and 42% for P relative to the BAU scenario (Chapter 6).

Conclusions

The main conclusions of this thesis are:

- The food chain and food pyramid approach for analysing nutrient flows at regional and national levels is a novel and effective concept for the quantitative assessment of N and P use efficiencies and losses in different compartments of the food chain.
- Between 1980 and 2005, N and P use efficiencies in China decreased in crop production from 32 to 26% for N and from 59 to 36% for P, increased in animal production from 8 to 16% for N and from 16 to 17% for P, and decreased in the whole food chain from 16 to 9% for N and from 19 to 7% for P.
- Total N and P losses from the food production and consumption chain to water and atmosphere increased almost three times for N and six times for P between 1980 and 2005.
- The regional variations in NUE and PUE in the food chain were large; lowest NUE and PUE, and highest N and P losses in the food chain occurred in the most populous areas, i.e., Beijing and Tianjin metropolitans, Pearl River Delta, and Yangzi River Delta.
- The average N and P costs of food are relatively low in Beijing, because of the large food and feed imports. As a consequence, the N and P losses associated with the production of the food and feed were ‘transferred’ (swapped) to other regions, and thereby led to apparent low N and P food costs for Beijing. Yet, N and P losses to atmosphere and surface waters and groundwater have increased

dramatically during the rapid urban expansion and economic growth between 1978 and 2008.

- Implementation of a package of integrated nutrient management measures (including balanced fertilization, precision feeding, and improved manure management), combined with structural changes (including diet change, increased imports of animal food and feed) are the most effective management options for increasing the N and P use efficiency and decreasing N and P losses in the food chain of China. Evidently, increasing imports of food and feed has as consequence that losses elsewhere will increase.
- Application of the food chain approach and the NUFER model can help policy makers in China to plan food production and consumption chains, and thereby manage N and P flows in this chain at regional level.

SAMENVATTING

Inleiding

Voedselproductie is afhankelijk van het gebruik van stikstof (N) en fosfor (P). Het gebruik van N en P in de wereldvoedselproductie is sterk toegenomen door de toename van de wereldbevolking en veranderingen in voedselconsumptiepatronen. Tegelijkertijd zijn de N- en P-verliezen van voedselproductie naar de atmosfeer en naar grondwater en oppervlakte water ook sterk toegenomen, met forse milieukundige gevolgen. Des relaties tussen N- en P-aanvoer naar gewasproductie en dierlijke productie, efficiëntie van N- en P-gebruik (NUE en PUE), en de N- en P-verliezen zijn echter zeer complex en lastig te kwantificeren, met name wanneer de hele voedselproductie - consumptieketen op regionaal en nationaal niveau in ogenschouw wordt genomen.

China is een interessant voorbeeld om N- en P-stromen in de voedselproductie en consumptieketen te bestuderen, omdat het land een snelle economische, sociale en culturele transitie ondergaat. China's voedselproductie is zeer intensief, terwijl NUE en PUE relatief laag zijn, en N- en P-verliezen naar het milieu hoog zijn. De milieuproblemen gerelateerd aan deze N- en P-verliezen zijn sterk toegenomen in de laatste decennia. Echter, de NUE en PUE van de voedselproductie - consumptieketen in China en de N- en P-verliezen zijn niet goed gekwantificeerd op nationaal niveau en regionale niveaus, en de factoren die effect hebben op de NUE en PUE worden niet goed begrepen.

Het algemene doel van het onderzoek, dat in dit proefschrift is beschreven, is om (1) het kwantitatieve begrip van de veranderingen in en de controlerende factoren van NUE en PUE en van N- en P-verliezen in de voedselproductie - consumptieketen op nationaal en regionaal niveau in China in the laatste 30 jaar te verbeteren, en (2) om strategieën voor het verhogen van NUE en PUE te ontwikkelen. Meer specifiek zijn de volgende onderzoeksvragen aan de orde gekomen:

Q1: Wat is de organisatiestructuur van het nutriëntenbeheer in China, en wat zijn de uitdagingen voor de nabije toekomst?

Q2: Wat zijn de N- en P-gebruiksefficiëntie en -verliezen in gewasproductie en dierlijke productie, voedselverwerking, huishoudens en in de gehele voedselketen van China op regionaal en nationaal niveau?

Q3: Wat zijn de effecten van bevolkingsgroei, veranderingen in consumptiepatronen en van technologische ontwikkelingen op de N- en P-gebruiksefficiëntie in de voedselketen?

Q4: Hoe heeft verstedelijking de N- en P-gebruiksefficiëntie en -verliezen in de voedselketen in Beijing in de afgelopen drie decennia beïnvloed.

Q5: Welke opties zijn effectief om de N- en P-gebruiksefficiëntie te verhogen en de N- en P-verliezen te verlagen in de voedselketen van China?

Materialen en methoden

De belangrijkste ontwikkelingen in nutriëntenbeheer op veld- en boerderijschaal in de laatste decennia zijn kritisch beschouwd op basis van literatuuronderzoek. Op basis van deze kritische beschouwing zijn vervolgens de uitdagingen voor nutriëntenbeheer in de voedselketen geformuleerd voor de regionale en nationale schaal, voor de nabije toekomst (om Q1 te beantwoorden).

Het simulatiemodel NUFER (Nutrient flows in Food chains, Environment and Resource use) is ontwikkeld om de N- en P-stromen in de voedselketen te kwantificeren. NUFER bevat een innovatief concept van de voedselpiramide en kan de N- en P-stromen, -balansen, -verliezen en -gebruiksefficiënties in verschillende compartimenten van de voedselketen ontrafelen en kwantificeren. NUFER maakt onderscheid tussen vier hoofdcompartimenten: (1) gewasproductie met 18 gewastypen (2) dierlijke productie met 11 diertypen, (3) voedselverwerking en -handel en (4) huishoudens, met een onderscheid tussen stedelijke en rurale burgers. NUFER heeft vier modules, voor data-invoer, berekeningen, optimalisatie en resultatenuitvoer. Het model maakt het mogelijk om N- en P-stromen in de voedselpiramide in twee richtingen te analyseren, namelijk vanuit de voedselproductie en voedselconsumptie.

NUFER is eerst gebruikt om historische N- en P- stromen, -balansen, -verliezen en -gebruiksefficiëntie te simuleren, gebruikmakend van statistische data en gegeven verzameld via enquêtes onder boeren en burgers in verschillende gebieden (om vragen Q2 en Q3 te beantwoorden). Ten tweede is NUFER gebruikt om via scenarioanalyses opties voor nutriëntenbeheer en structurele veranderingen in de voedselproductie – consumptieketen te analyseren (om Q3 en Q4 te beantwoorden). Ten derde is NUFER gebruikt om de verandering in N- en P-stromen in de voedselketen van Beijing te analyseren gedurende een periode (1978 en 2008) van snelle verstedelijking (om Q4 te beantwoorden).

Meststoffenaanvoer, gewasopbrengsten, gewasarealen en aantallen dieren zijn gebaseerd op statistische data. De samenstelling van het voedsel van de urbane en rurale bevolking is gebaseerd op diverse rapportages van andere studies naar de voedselconsumptie in verschillende gebieden in China. Andere data zijn veelal ontleend aan rapportages van verschillende veldonderzoeken georganiseerd door China Agricultural University en het National Agriculture Technique Science Center tussen 1999 en 2008. De gehalten aan N en P in geoogst gewas en dierlijke producten, N- en P-excretiewaarden per diercategorie en de opdeling van dierlijke producten in eetbare en andere delen zijn gebaseerd op literatuurgegevens. Modelinvoer voor scenario's zijn gebaseerd op literatuur en aannames van deskundigen.

Resultaten

De analyse van de ontwikkelingen in nutriëntenbeheer in China gedurende de laatste decennia laat zien dat verschillende veelbelovende nutriëntenbeheerconcepten en -technologieën reeds zijn ontwikkeld en getest. Echter, het in gebruik nemen van deze concepten en technologieën door boeren in de praktijk is nog steeds minimaal. Dit komt vooral door het grote aantal (circa 200 miljoen) zeer kleine boerenbedrijven (bedrijfsomvang is gemiddeld minder dan 0,5 ha), de geringe scholing en de gemiddeld hoge leeftijd van de boeren. Ook komt het door de hiërarchische organisatiestructuur en ambivalente belangen van de landbouwvoorlichting. Meer coherent nationaal beleid en institutionele structuren zijn nodig om de uitdagingen op te pakken. Er is ook behoefte aan onderzoek naar nutriëntenbeheer in de gehele voedselproductie - consumptieketen op regionaal en nationaal niveau (Hoofdstuk 2).

Voor mijn proefschrift heb ik een innovatief voedselketenconcept ontwikkeld om N- en P-stromen in de voedselproductie - consumptieketen te bestuderen. Een analytisch concept van de 'voedselpiramide' is ontwikkeld, met voedselproductie aan de basis en voedselconsumptie aan de top. Het concept helpt bij het visualiseren en begrijpen van de geringe nutriëntengebruiksefficiëntie van de huidige voedselketen, en de hoge N- en P-kosten van de huidige voedselketen. Een set van indicatoren is ontwikkeld om N- en P-stromen in de voedselketen te analyseren en te waarderen.

De totale aanvoer van 'nieuw' N en P in de voedselketen in 2005 was respectievelijk 48,8 en 7,8 Tg (1 Tg = 10^{12} g, gelijk aan 1 miljard kg). Nieuw N (en P) is gedefinieerd als de totale input van N (en P) van buiten de voedselketen, via meststoffen, atmosferische depositie, biologische N fixatie, gras geoogst van natuurlijke graslanden, vis van natuurlijke, 'onbeheerde' oppervlakte wateren en de invoer van diervoeders en levensmiddelen uit andere regio's. Slechts 4.4 Tg N en 0.6 Tg P bereikte huishoudens in voedsel. De gemiddelde N- en P-gebruiksefficiëntie in de voedselketen was 9 % voor N en 7 % voor P. Het merendeel van de geïmporteerde N ging verloren, 23 Tg N ging naar de atmosfeer en 20 Tg N naar grondwater en oppervlakte water (Hoofdstuk 3).

De N- en P-kosten van voedsel zijn belangrijke indicatoren voor de voedselketen; deze kosten zijn gedefinieerd als de hoeveelheid nieuw N en P (in kg) die gebruikt wordt in gewasproductie, dierlijke productie en voedselverwerking voor de levering van 1 kg N en P in het voedsel op het bord van consumenten. Tussen 1980 en 2005 stegen de gemiddelde N-kosten van voedsel in China van 6 naar 11 kg per kg. De gemiddelde P-kosten van voedsel stegen van 5 naar 13 kg per kg (Hoofdstukken 3 en 4).

Tussen 1980 en 2005 daalde de N-efficiëntie (NUE) in de gewasproductie van 32 naar 26 %, vooral als gevolg van het overmatig gebruik van N-kunstmest die zwaar werd gesubsidieerd door de overheid. In dierlijke productie nam NUE toe van 8 tot 16 % als gevolg van verbeterde dierenrassen en diervoeding. In de gehele voedselketen daalde NUE van 16 tot 9 %. De P-efficiëntie (PUE) daalde in gewasproductie van 59 naar 36 %, steeg in dierlijke productie van 16 tot 17 %, en daalde in de gehele voedselketen van 19 tot 7 % (Hoofdstuk 4). De belangrijkste redenen voor de veranderde gebruikseffici ëntie in de voedselketen van N (NUEf) en P (PUEf) zijn (1) de toename van de consumptie van dierlijke producten, (2) de overbemesting in gewasproductie, en (3) de ontkoppeling van de plantaardige en dierlijke productie, waardoor N en P in dierlijke mest veel minder wordt hergebruikt in gewasproductie (Hoofdstuk 3 en 4).

De totale stikstofverliezen naar water en atmosfeer zijn bijna verdrievoudigd tussen 1980 (14.3 Tg) en 2005 (42.8 Tg). De geschatte P-verliezen naar watersystemen stegen van 0.5 Tg in 1980 naar 3.0 Tg in 2005. Ammoniakvervluchtiging en N- en P-uitspoeling (inclusief afspoeling, erosie en directe mestlozingen) waren de belangrijkste verliesroutes.

Er waren grote regionale verschillen in N- en P-verliezen in de periode 1980-2005. De verliezen zijn sterk toegenomen in zuid-, oost- en centraal-China. De veranderingen in de tijd waren relatief klein voor west- en noord-China. Regio's met hoge N- en P-verliezen zijn de metropolen Beijing en Tianjin en rivierdelta's van de rivieren Pearl (Zhu Jiang) en Yangze (Chang Jiang). De voedselketenanalyses laten zien dat de veranderingen in NUE en PUE in plantaardige en dierlijke productie complex zijn. Een toename van NUE en PUE in dierlijke productie wordt volledig te niet gedaan wanneer de noodzakelijke recycling en hergebruik van N en P in dierlijke mest wordt verwaarloosd (Hoofdstuk 4).

De analyse van N- en P-stromen in de voedselketen van de metropool Beijing tijdens een periode van snelle verstedelijking en economische groei, toont het belang van structurele veranderingen in de voedselproductie - consumptieketen aan. De aanvoer van 'nieuw' N naar de voedselketen van Beijing steeg van 180 naar 281 Gg tussen 1978-2008, en van 33.5 naar 50.4 Gg voor P. In totaal werd in 2008 66 % van de N-aanvoer en 85 % van de P-aanvoer verspild, door storting op stortplaatsen en in waterwegen (via gewasresten, dierlijke uitwerpselen, menselijke uitwerpselen en huishoudelijk afval). Het totale N-verlies steeg 2.9 keer en het P-verlies zelfs 37 keer tussen 1978 en 2008 (Hoofdstuk 5). Het recyclen van N en P in afval en residuen en de verplaatsing van landloze veehouderijbedrijven uit de stad naar het platteland zijn mogelijke opties om NUE en PUE te verhogen en de N- en P-verliezen te verminderen in Beijing. De studie toont aan dat het belangrijk is om de N- en P- cycli van de stedelijke en landelijke systemen te koppelen om tot een duurzamere ontwikkeling van metropolen te komen (Hoofdstuk 5).

Ook de mogelijke toekomstige veranderingen in de N- en P-stromen in de voedselketen zijn onderzocht. Het ‘business as usual’ scenario voor 2030 laat zien dat het gebruik van N- en P-meststoffen in China met 25 % toeneemt en de N- en P-verliezen met respectievelijk 47 en 71 % toenemen, ten opzichte van 2005. Scenario's met veranderingen in consumptiepatronen (gezondere voeding met minder vlees, meer groenten, fruit en granen) en een toename van de invoer van dierlijke producten laten zien dat zowel het gebruik van N- en P-meststoffen als de N- en P-verliezen dalen ten opzichte van het ‘business as usual’ scenario. Een combinatie van evenwichtsbemesting en precisievoeding in dierlijke productie gecombineerd met maximaal hergebruik van de N en P in dierlijke mest in gewasproductie waren de meest effectieve opties om de N- en P-gebruiksefficiëntie in de voedselketen te verhogen. De aanvoer van N en P in diervoeders kunnen gehalveerd worden en daarmee totale N- en P-verliezen drastisch verlaagd worden indien de officiële Chinese voedingsrichtlijnen opgevolgd worden. Als de toenemende vraag naar dierlijke producten door import uit andere landen wordt opgevuld, dan daalt het kunstmestgebruik in China met 12 % en de nutriëntenverliezen dalen met 30 % voor N en 42 % voor P ten opzichte van het ‘business as usual’ scenario (Hoofdstuk 6).

Conclusies

De belangrijkste conclusies van dit proefschrift zijn:

- De voedselketen en voedselpiramide zoals ontworpen en toegepast in deze studie zijn innovatieve en effectieve concepten voor het analyseren van nutriëntenstromen op regionaal en nationaal niveau. Het maakt een kwantitatieve analyse van de N- en P- gebruiksefficiëntie en -verliezen in de verschillende compartimenten van de voedselketen mogelijk.

- De gemiddelde nutriëntengebruiksefficiëntie in China daalde tussen 1980 en 2005 in de gewasproductie van 32 naar 26 % voor N en van 59 naar 36 % voor P. In de gehele voedselketen daalde de gemiddelde nutriëntengebruiks-efficiëntie van 16 naar 9 % voor N en van 19 naar 7 % voor P. De gemiddelde nutriëntengebruiksefficiëntie steeg in dierlijke productie van 8 naar 16 % voor N en van 16 naar 17 % voor P tussen 1980 en 2005.
- De totale N- en P-verliezen uit de voedselproductie - consumptieketen zijn tussen 1980 en 2005 met respectievelijk een factor drie en zes toegenomen.
- De regionale verschillen in NUE en PUE in de voedselketen zijn groot; de laagste NUE en PUE en hoogste N- en P-verliezen in de voedselketen vonden plaats in de dichtstbevolkte gebieden, d.w.z. de metropolen van Beijing en Tianjin en de rivierdelta’s van de rivieren Pearl en Yangzi.
- De gemiddelde N- en P-kosten van voedsel zijn relatief laag in Beijing, vanwege de relatief grote import van voedsel en diervoeders. Door import zijn de N- en P-verliezen, verbonden met de productie van geïmporteerde voedsel en diervoeder, ‘overgeheveld’ (geëxternaliseerd) naar de regio’s waar het voedsel en de diervoeders zijn geproduceerd. Ondanks de afwenteling naar andere gebieden zijn de N- en P-verliezen naar atmosfeer en oppervlaktewater en grondwater dramatisch toegenomen tijdens de snelle verstedelijking en economische groei tussen 1978 en 2008.
- De implementatie van een pakket van geïntegreerde nutriëntenbeheer-maatregelen (evenwichtsbemesting, precisievoeding, en verbeterd mestbeheer) in combinatie met structurele veranderingen in de voedselketen (een gezonder dieet, toename import), zijn de meest effectieve opties voor het verhogen van de N- en P-gebruiksefficiënties en het verlagen van de N- en P-verliezen in de voedselketen van China. Logischerwijs heeft een stijgende import van voedsel en diervoeders tot gevolg dat de verliezen elders toenemen.
- Het concept van de voedselpiramide en het NUFER model geven beleidsmakers in China de mogelijkheden om de voedselproductie - consumptieketens beter te plannen en te sturen, en daarmee de N- en P-stromen in deze keten op regionaal niveau te beheren.

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Lin Ma
Wageningen

PE&RC Training and Education Statement

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

The C.T. De Wit Graduate School PE&RC PRODUCTION ECOLOGY & RESOURCE CONSERVATION

Review of literature (6 ECTS)
- An analysis of developments and challenges in nutrient management in China (2013)

Writing of project proposal (4.5 ECTS)
- Nutrient use efficiency in the food chain of China (2012)

Post-graduate courses (5.2 ECTS)
- Soil ecology: taking global issues underground; PE&RC (2010)
- Complex dynamics in human-environment systems; SENSE (2013)
- Nutrient management tools and nutrient balance at different scales; China Agricultural University (2010)

Invited review of (unpublished) journal manuscript (2 ECTS)
- Environmental Science & technology: China's nitrogen footprint during 1990 and 2009 (2013)
- Science of the Total Environment: impact of human interventions on nutrient biogeochemistry in the Pamba River, Kerala, India (2013)

Competence strengthening / skills courses (2.8 ECTS)
- Scientific publishing; PE&RC (2011)
- Reviewing a scientific paper; PE&RC (2011)
- Techniques for writing and presenting a scientific paper; PE&RC (2013)
- Improving your writing; Language services of WUR (2012)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)
- PE&RC Day (2012)
- PE&RC Weekend (2013)
- PE&RC Symposium: traits as a link between systematics and ecology (2012)

Discussion groups / local seminars / other scientific meetings (4.5 ECTS)
- Discussion group of soil quality group (2010-2013)
- Mathematics, statistics and modelling in Production Ecology and resource Conservation (Maths & Stats (2010)

International symposia, workshops and conferences (9 ECTS)
- 4th International Symposium on Phosphorus Dynamics in the Soil-Plant Continuum (ISPDSPC) (2010)
- 4th International Nutrient Management Symposium: Global Issues in Nutrient Management Science, Technology and Policy (2011)
- Urban Environmental Pollution: Creating Healthy, Liveable Cities (2012)
- 17th International Nitrogen Workshop (2012)
- Workshop of Material Flow Analysis with STAN 2.5 (2013)
- 1st Global TraPs World Conference (2013)
- International Conference on Manure Management and Valorization (2013)