Improving manure management - techniques, impacts and farmer' perceptions

Meixiu Tan

谈美秀

Propositions

1. The diversity in manure management practices can be understood through farm surveys and observations.

(this thesis)

2. Middlemen and financial incentives are vital for recoupling livestock and crop production systems in China.

(this thesis)

3. Improving the predictive performance of a crop growth model without considering key plant physiological processes does not improve the model.

4. The best way to preserve nature is to refrain from managing nature.

5. Accepting farmers' ingenuity is the first step in developing effective agri-environmental policies.

6. Appreciating academic writing is like appreciating spicy food.

Propositions belonging to the thesis entitled:

"Improving manure management – techniques, impacts and farmers' perceptions"

Meixiu Tan

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Improving manure management –

techniques, impacts and farmers' perceptions

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Improving manure management – techniques, impacts and farmers’ perceptions

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Thesis

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Chapter 1 General introduction

1.1 Changing role of manure in agricultural history

Animal manure is a valuable resource of nutrients and organic matter. The application of manure to soil contributes to maintaining or elevating the availability of basically all nutrients in soil, essential for crop growth (Kemppainen, 1989; Sommer et al., 2013). Manure application may also contribute to elevate soil organic matter content (Simonetti et al., 2012), to increase the capacity of the soil to store water (Rayne & Aula, 2020), to improve soil structure (Nyamangara et al., 2001), and to support soil life (Bünemann et al., 2006). In addition, dried manure is also being used as biofuel and construction material in some countries like Ethiopia (Sherman, 2007; Teenstra et al., 2014; Tadesse, 2021). Before 1950s when synthetic fertilizer became widely used, agriculture and societies heavily relied on animal manure for producing adequate amounts of food and feed (Mazoyer & Roudart, 2006). Basically, livestock production and thus manure production were limited by feed availability, and feed availability was limited by the availability of manure. For long, animal manure was regarded as a scarce and valuable resource and was well-utilized (Mazoyer & Roudart, 2006). The amount of manure available largely determined the soil fertility level, the crop yield and the prosperity of families.

With the development of science, technology and globalization, especially from the second half of the 20th century, relatively cheap synthetic fertilizers, high-yielding crop varieties and improved crop husbandry practices became available (e.g., Smil, 2001). These boosted the production of food and feed, and diminished the importance of animal manure. Synthetic fertilizers started to replace in part the role of animal manure in crop production. Livestock farmers in many financially powerful countries got access to marketed feed, improved animal breeds and advanced technology, which facilitated the intensification of livestock production in these countries. The growth of the herd led to a fast increase in animal manure production, which even exceeded the amount of manure needed for fertilization of cropland in some countries and regions (Steinfeld et al., 2013). Forecasts indicate that the global demand for livestock products and the production of manure will increase further during next decades (Alexandratos & Bruinsma, 2012; Godfray et al., 2018).

Nowadays, many farmers prefer to use synthetic fertilizer instead of animal manure for the fertilization of cropland, because manure is bulky and smelly (therefore difficult to process, transport and apply), while synthetic fertilizers are easy to handle and also subsidized in some countries, like China and India. Application of manure costs 10 times more than application of synthetic fertilizer per unit N (Zhang et al., 2016). The preference for synthetic fertilizers is also related to the shortage of labor, as labor is allocated preferably to higher-wages off-farm work (Mazoyer & Roudart, 2006; Chadwick et al., 2015; Jin et al., 2021). Manure utilization as biofuel and construction material has also reduced because of the increased availability of cleaner energy and building material, except in low-income countries. Thus, livestock manure has turned from a resource into a waste or a pollutant to the environment, especially in industrial size farms or regions with high livestock density. This has provoked governments to implement regulations on manure management, notably in the European Union , North America, and China (Sims et al., 2005; Bai et al., 2018).

It is increasingly realized that animal manure is also an essential resource for the circular bio-economy of the near future. Synthetic fertilizers are largely based on mined resources and/or require large amounts of fossil energy for its production, both of which are finite and become scarce. Thus, future societies will need the nutrients and organic matter in animal manure and other organic residues for amending soils and fertilizing crops. This holds for both developed and developing countries (Muscat et al., 2021).

1.2 The need for reducing nutrient losses from manure management

Livestock feed takes up about 60% of the global crop biomass produced. Most of the nutrients and a significant fraction of the organic matter in the feed biomass intake are excreted in livestock manure. During 2010s globally livestock manure excretion were about 130-140 Tg nitrogen (N) and 23-30 Tg phosphorus (P) , which were larger than the total amounts of synthetic N and P fertilizer used in crop production (FAOSTAT, 2017; Potter et al., 2010; Liu et al., 2017).

The global livestock sector was responsible for 80% of the total greenhouse gas (GHG) emissions and for 24-77% of the total ammonia (NH_3) emissions from agriculture (Steinfeld et al., 2006; Sutton et al., 2013). Emissions of GHG to the atmosphere contribute to climate change, and emissions of NH_3 contribute to eutrophication of natural ecosystems and to the formation of atmospheric fine particulate matter with diameter less than 2.5 μm ($PM_{2.5}$), and thus threatens human health (Steinfeld, 2006; Huang et al., 2014). Large fractions of the GHG and NH_3 emissions from the livestock sector originate from enteric fermentation (methane emissions) and animal manure in housing, storages, during manure treatment and following application to cropland. Further, manure discharges, leakages and over-application to cropland contribute to both groundwater and surface water pollution; manure N and P are a main source of surface-water eutrophication (Strokal et al., 2015; Masaka et al., 2013). Evidently, there is a global need to decrease the emissions of GHG and NH_3 from manure to the atmosphere, and to decrease the losses of N and P from manure to groundwater and surface waters.

1.3 Changes in livestock production and manure management in China

Attributed to economic growth, urbanization and dietary shifts during the last few decades, China became the biggest livestock producer and consumer in the world. Livestock density quickly increased in almost all provinces, especially since 1980 when economic reform and opening-up policies started. Between 1980 and 2000, livestock density increased by at least 50% in 13 provinces (out of a total of 31 provinces). Livestock densities in 15 provinces were over 1 livestock unit (LSU)[1] per ha in 2000 (Figure 1.1 a&b). North China Plain and Southwest had higher livestock density than Northwest in 2020 (Figure 1.1 c).

At the same time, livestock production at farm level has been transforming from traditional mixed backyard production systems to specialized industrial systems, often with little or no cropland. Total livestock population reached 441 million livestock units (LSU) in 2010 and 56% of the LSU were raised in landless systems, where basically most feed has to be imported off-farm (Bai et al., 2018). The intensification of livestock production has led to what is now known as “crop-livestock spatial decoupling” and ‘nutrient hot-spots’. This spatial decoupling and the increased nutrient surpluses at livestock farms have increased the burden to the environment (Jin et al., 2021). In 2010, the total amounts of N and P excreted in manure were 22.8 Tg and 4.6 Tg, respectively. About 78% of the excreted N and 50% of the excreted P were lost to environment via gaseous N emissions, leakages and discharge (Bai et al., 2016).

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[1] One livestock unit (LSU) is defined as the grazing equivalent of one adult dairy cow producing 3000 kg of milk annually, without additional concentrated feedstuffs. It is equivalent to about 100 kg N and 15 kg P excreted annually (Oenema et al., 2014)

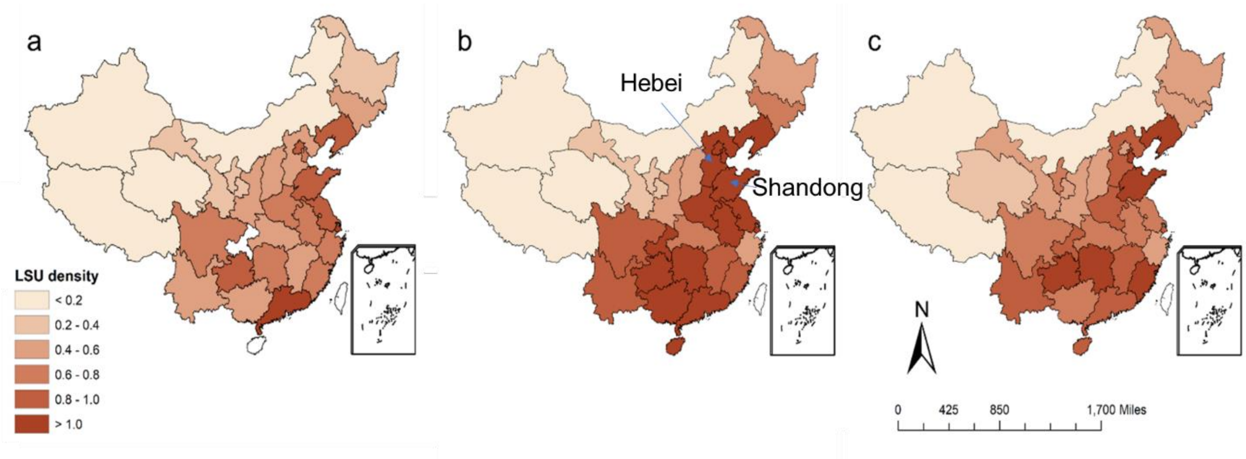

Figure 1.1 Spatial distribution of livestock density in Chinese provinces in 1980 (a), 2000 (b) and 2020 (c). Most provinces intensified livestock production between1980 and 2000. Livestock density seems to have decreased in some provinces between 2000 and 2020, because i) small livestock farms were excluded from the statistical accounting since 2006; ii) strict environmental policies prohibiting livestock production near watersheds; iii) breakout of African swine fever and COVID-19. (Source: Statistic Yearbook, 1981, 2001 and 2021)

Hebei and Shandong are two of the main provinces typically experiencing these changes in China (Figure 1.1). These two provinces took up 3.6% of the total land area of China but produced 15% of total meat, 21% of total milk and 25% of total eggs in 2020 (National Bureau of Statistics, 2021). Livestock production in these two provinces mainly occurs in so-called intensive farms[2]: 64% of the dairy cattle, 21% of the laying hens and 35% of the broilers and pigs were raised in intensive farms in 2010 (Statistical Yearbook, 2011). Meanwhile, Hebei and Shandong are also large producers of cereals, produced in a double cropping system of winter wheat and summer maize, and vegetables and fruit. The large and intensive production of both livestock and crop make these two provinces attractive for research on improving manure management and crop-livestock integration.

In short, large amounts of nutrients and organic matter are excreted in livestock manure. Because of improper storage and management, livestock manure contributes significantly to the emissions of ammonia (NH_3), nitrous oxide (N_2O) and methane (CH_4) into the air, and to

[2] Intensive farms are defined as an operation that has ≥500 pigs (slaughtered), ≥100 dairy cows (stocked), ≥10,000 laying hens (stocked), and ≥50,000 broilers (slaughtered) annually (IAESD and NIES, 2009)

nutrient (notably N and P) and organic matter losses to water bodies, which pollute the environment and threaten human health and biodiversity. It is expected that livestock production increases further to meet the increasing animal-source food demand in China during the next decades. Thus, there is an urgent need to improve manure management, to mitigate nutrient losses and environment pollution, and to increase manure utilization in cropland. Recently, the government has set up a series of policies and action plans to realize agriculture green development, including the "Action Plan Of Zero Fertilizer Growth By 2020", and the "Action Plan For Resource Utilization Of Livestock And Poultry Manure" (MOA, 2015 & 2017). However, there is lack of quantitative information on manure management practices on such diverse livestock farms, and thus estimations of nutrient losses and fates in the production systems are less accurate. The nutrient losses, fertilizer use and soil quality are yet unknown since these polices have been launched for years.

1.4 Need to quantitatively understand manure management in practice

Manure management basically includes a chain of steps, from animal feeding, animal housing, manure collection, storage and/or treatment, to finally manure application to cropland. This manure management chain relates especially to housed (confined) livestock. Grazing animals drop their excrements in the pasture during grazing and partly also in the barn when temporarily confined for milking, calving/lambing and/or supplementary feeding during winter or dry periods. As a result, the manure management chain of grazing animals may greatly differ from that of housed animals (Petersen et al., 2013).

Averaged across all livestock categories in China, about 11% of feed N and 14% of feed P were retained in animal growth, reproduction, and marketed animal products; the remainder was excreted in animal excreta (Bai et al., 2016). The excreta in the housing stage are either collected regularly as slurries (mixture of dung and urine) or as solid and liquid fractions separately. Collected manure from housing systems is often stored in the open yard or lagoons with or without leak-tight floors. In some farms, collected manure from housing is treated, mainly through solid-liquid separation, anaerobic digestion and/or composting. Stored manure and manure treatment products are then applied to cropland, thereby recycling nutrients in manure for crop production. In the whole chain from animal feeding to manure application to cropland, various measures and techniques can be adopted to mitigate nutrient losses and to increase the recycling efficiency of nutrients and organic matter in manure. Figure 1.2 sketches the manure management in a typical intensive dairy farm in China.

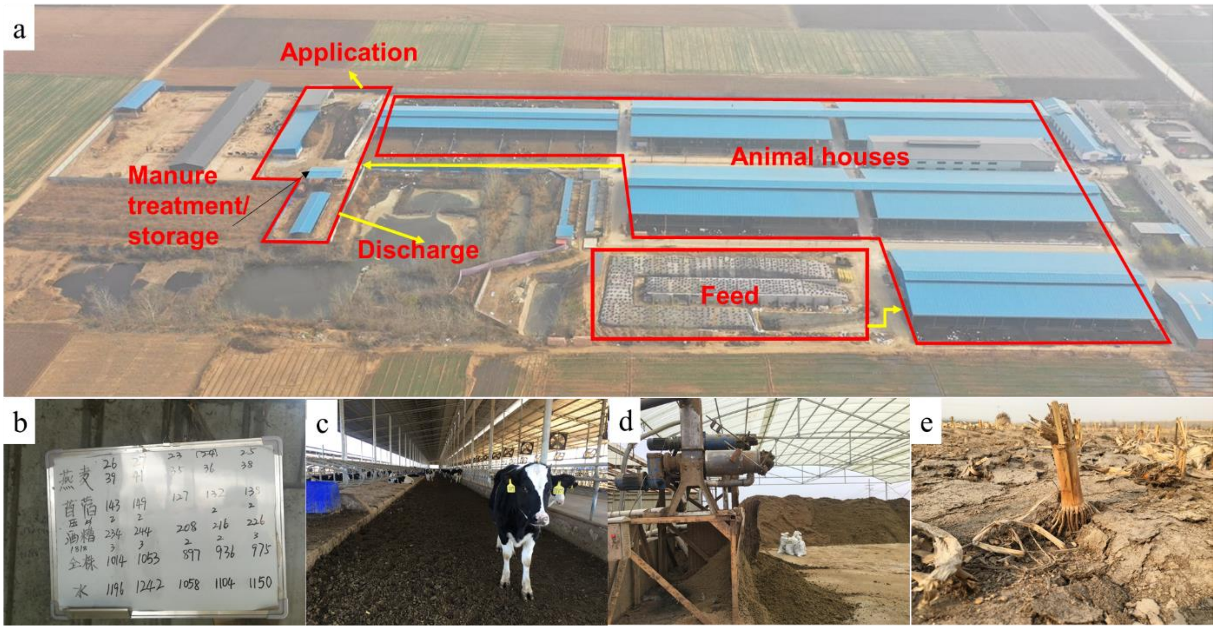

Figure 1.2. Manure management in a typical intensive dairy farm in China. The upper picture (a) shows the farm structure and some nutrient flows (yellow coloured arrows) on the farm. The four pictures below schematically depict a manure management chain; a whiteboard with feed rations of dairy cows (b), animal housing with a concrete floor (c), solid-liquid manure separation with storage of the solid fraction (d), and manure applied to a maize field (e), respectively. (Source: photos were made by the author of this thesis in 2018/2019).

Nutrients are lost from the manure management chain to the environment, either via gaseous emissions or leaching and discharge (Bai et al., 2016). Estimation of the nutrient flows and losses in the manure management chain, and understanding of the influencing factors are required for adoption of improved technologies and manure management planning. Most of the estimated nutrient flows in various livestock systems were based on statistical data, literature from other countries and expert estimations (e.g., Bai et al., 2016; Bellarby et al., 2018). There is lack of empirical data collected on-farm. There is also lack of data and information on farmers' manure management practices and on the drivers and barriers influencing the adoption of advanced manure management techniques in practice. Such data are needed for improving manure management at farm level.

1.4.1 Manure collection, storage and treatment in intensive livestock farms

Manure collection often depends on the housing system and the storage and treatment systems. Animal housing, and manure storage and treatment systems can be main sources of NH_3 and GHG emissions, and various technologies have been developed to reduce these emissions (Sommer et al., 2013; Bittman et al., 2014).

Multiple manure treatment technologies have been developed to increase the utilization of energy and nutrient sources in manure, and to facilitate easy manure transportation (Sommer et al., 2013). Example treatment techniques include anaerobic digestion (to facilitate bioenergy production), solid-liquid separation (to facilitate solid manure transportation), acidification (to mitigate NH_3 emission), composting (to sanitize the manure and to stabilize the organic matter in manure), biological nitrification-denitrification (to decrease the biological oxygen demand and to convert ammonium into mainly nitrogen gas (N_2)), membrane filtration (to purify waste water or to separated solids from liquids, for use in irrigation), drying and pelleting (to compress manure into odor-free and easy-to-handle forms), and combustion/incineration (to obtain recoverable heat, ashes and gasses) (Foged et al., 2011; Hou et al., 2016). Implementation of these techniques in practice is highly variable, because of differences in the characteristics of farms and farmers, culture, available techniques, and governmental policies (Chadwick et al., 2015; Ndambi et al., 2019). Intensive livestock farms with limited cropland have great difficulty to recycle manure to cropland; therefore, these farms often attempt to use treatment techniques to lower the transportation costs and/or to increase the economic value of the organic matter and nutrients in the manure. However, the adoption and functioning of these techniques in different animal systems in China have not yet been well investigated.

1.4.2 Low protein feeding in intensive farms

Low protein feeding is one of the most cost-effective ways to reduce N excretion and thus N emissions from the whole manure management chain while keeping the livestock productivity unchanged (Hou et al., 2015; Reis et al., 2015). Crude protein (CP) content is often used in feed industry as an indicator for protein content, but in general CP includes some 10% non-protein N which may be indigestible for animals. An over-supply of CP in animal diets is excreted in manure (mainly in urine), and thereafter quickly converted to NH_4^+/NH_3. The perspectives for lowering dietary CP depend on the current diet (Bittman et al., 2014). In practice, there is often large variation between farms in the composition of animal feed (Powell et al., 2008; Wang et al., 2014; Oenema and Oenema, 2021). Accurate information on the variations in protein content, composition and digestibility may help to reduce protein surplus cost-effectively. This information may also help to make recommendations to improve animal productivity, and to develop more accurate NH_3 emission inventories at regional and national levels.

Currently, sound empirical data and information about the variation in actual protein content in farm practice in China are missing. As a consequence, studies assessing impacts of livestock production on environmental pollution often use mean values based on controlled condition research trials (e.g., Bai et al. 2013 & 2016; Zhang et al., 2019). The need for accurate farm data increases rapidly, together with the development of livestock production and livestock production systems.

1.4.3 Farmers' perceptions of manure management and treatment

Livestock farmers are the key stakeholders for improving on-farm manure management and treatment. Understanding farmers' notions and perceptions related to improving manure management and treatment is key to identifying the decision-making behaviour of farmers and in targeting those farmers who will most likely adopt improved management practices and techniques in future. Most studies of farmers' perceptions of on-farm manure management techniques have been conducted in Europe. For example, Hoppe and Sanders (2014) found that financial burdens, hardly granted legal permits and limitative environmental policies hinder the development of anaerobic digestion to produce biogas in the Netherlands. Gebrezgabher et al. (2015) highlighted the importance of farmers' education and age and farm size and the unimportance of farmer' knowledge for the adoption of solid-liquid separation in Dutch dairy farms. Viaene et al. (2016) identified the barriers of on-farm composting in Belgium, which included strict regulations, high financial and time investments, lack of supplemental carbon resources and lack of professional experience and knowledge. Hou et al. (2018) found that policy pressure was the most important driver, and financial cost was the most important barrier for manure treatment technologies in livestock-dense European countries. Obviously, farmers' adoption of these technologies differs greatly among countries and regions, probably because of differences in economic conditions, culture, knowledge infrastructure, climate, and policy regulations. Evidently, there is a lack of insights about the main drivers and barriers for improving manure management techniques and there is lack of understanding about farmers' perceptions on improving manure management in China.

In general, farmers' incentive to use a technique is based on the perceived outcomes (good or bad results), the subjective norms (positive or negative attitude from social referents), and on the controlling factors (easy or difficult to apply). These three components constitute the core of the Theory of Planned Behavior (Ajzen, 1991), which is a common theoretical framework applied in various behavioral studies at the interface of agriculture and the environment (e.g. Wauters et al., 2010; Lalani et al., 2016; Wang et al., 2018). This theory has never been applied to study farmers' perceptions of manure management so far.

1.5 Sustaining soil fertility through manure application

Historically improving soil fertility in cropland relied heavily on manure application, because animal manure contains large amount of organic matter, macronutrients (N, P, K, Ca, Mg, etc) and micronutrients (Cu, Zn, etc). Applying manure to cropland has many advantages, for instance 1) replenishing nutrients that have been withdrawn with harvested crop, so as to maintain an adequate soil fertility level and organic carbon content, and improved soil physical condition (Du et al., 2020; Maillard & Angers, 2014); 2) fulfilling circular agriculture and reducing environment impacts (Zhang et al., 2019); and 3) increasing crop yield and food supply (Zhang et al., 2020; Lv et al., 2020). Commonly, regions with high livestock density have a relatively high soil fertility level, and vice versa (Reijneveld, 2013; Tóth et al., 2014).

From the second halve of the 20th century and especially since 1980s, mineral fertilisers started to become widely available also through the governmental subsidies supplied to the whole chain of fertilizer production, storage and transport in China (Chadwick et al., 2015). This made nutrient input not merely dependent on application of animal manure, human excreta, and ashes. The relationship between livestock density and production (manure availability) and soil fertility became less direct, because fertilizer nutrient sources became more important.

Phosphorus (P) is an essential nutrient, fundamental for plant growth and the culprit for water eutrophication at the same time. The P content of manures ranges from 4 to 13 g per kg dry matter; 23-79% of total P is present as solid-phase and in organic form (Chadwick et al., 2015; Barnett 1994). Both the organic and inorganic forms of manure P become less water-soluble and less available to plants after being applied to soil because of a serious of reactions (Abdala et al., 2015). Meanwhile, as manures have a lower N:P ratio than most crops require, over-supply of manure P is unavoidable if crop N requirement is satisfied through manure application (Smith et al., 1998; Kumaragamage & Akinremi, 2018). The over-application may create soil P enrichment, particularly in regions with intensive livestock production systems, where application of manure exceeds often crop requirements for a long time.

Various field or lab experiments have evaluated the influence of manure application on soil P content and P losses through leaching and/or runoff and results are somewhat contradictory. For instance, Ramphisa & Davenport (2020) found that soil Olsen-P content did not differ significantly between fields applied with manure or mineral fertilizer. Sharpley & Smith (1995) found increased total P contents in soil and increased proportions of inorganic P in manure-treated soil. Liu et al (2012) found that manure application results in lower total P contents than fertilizer P application, even though a larger amount of P was applied with manure than with synthetic fertilizer. Such differences are likely related to the differences in the total amounts of P applied, the manure P substitution ratio for synthetic P fertilizer, soil composition and texture, irrigation, manure types used, etc.

It is as yet unknown how livestock density has influenced manure P application to cropland and soil P contents of cropland of livestock farms in comparison to specialized crop farms without livestock. Understanding the relationship among livestock density, manure application, soil fertility and influencing factors will help to guide nutrient management and planning.

1.6 Sustainable Resource Management for Adequate and Safe Food Provision (SURE+)

This PhD thesis is part of the SURE+ project (Sustaining Resource Management For Adequate And Safe Food Provision), which was funded by the Royal Dutch Academy of Sciences (KNAW) and the Ministry of Science and Technology in China (MOST). The SURE+ project is an interdisciplinary research project on the land, water and food nexus in China, aiming at formulating coherent recommendations for adequate and safe food provision based on sustainable resource management. It is a cooperation between social and natural scientists from Wageningen University and six Chinese universities/research institutions. In total six subprojects were carried out under SURE+ and my PhD thesis research constituted part of subproject 3 "*Manure Management For Diminishing Environment Pollution And Improving Soil Quality*". Within this subproject in total 5 PhD students have been working on various specific aspects of the manure management chain and on different manure treatment technologies at different spatial scales. My thesis research focused on the manure management chain at farm level.

1.7 Research Objectives

The general objective of my PhD thesis research was to increase the understanding of the drivers and barriers for improving manure management on intensive livestock farms in China, and to explore options and impacts of improved manure management techniques and practices.

My research focused on intensive farms, because of the rapid development of intensive livestock farms and the disappearance of traditional small farms. Hebei and Shandong provinces were selected as study areas, because of their importance in crop and animal production, and the large need to solving the manure management problem in these provinces.

My main hypothesis was that livestock farms greatly differed in manure management practices and that these variations can be quantified and understood through conducting farm visits, interviews and additional analyses.

The specific objectives of my thesis were as follows:

- to deepen the insight into the manure management practices in intensive livestock farms and to identify the factors influencing the adoption of advanced manure management and treatment technologies (Chapters 2 and 3)
- to assess the variations in nutrient (N and P) flows and losses at farm level, and to identify measures that improve the N and P use efficiencies at farm and farm compartment levels (Chapter 4)
- to examine the relationship between livestock density and soil P contents at farm and regional levels (Chapter 5)

1.8 Outline of this thesis

This thesis contains a general introduction (Chapter 1), four research chapters (Chapters 2-5,) and a general discussion (Chapter 6). Figure 1.3 visualizes the connection of the four research chapters.

Chapter 2 presents the findings related to the adoption of manure treatment techniques and farmers' perceptions of using these techniques, based on an application of the framework of Theory of Planned Behavior.

Chapter 3 reports on crude protein contents of animal diets, and the influencing factors for feed management in modern intensive dairy and poultry farms in Hebei and Shandong provinces in China, based on farm survey and feed sampling analysis.

Chapter 4 presents the variations in N and P flows and use efficiencies of intensive dairy farms at herd, manure and farm level, and explores the effects of advanced management measures on improving nutrient use efficiencies.

Chapter 5 discusses the relationship between livestock density and the P content of the topsoil and subsoil of livestock and crop farms, and explored the influencing factors at farm and county level in Hebei province.

Chapter 6 provides a general discussion of the main findings of the study, and identifies remaining future research needs.

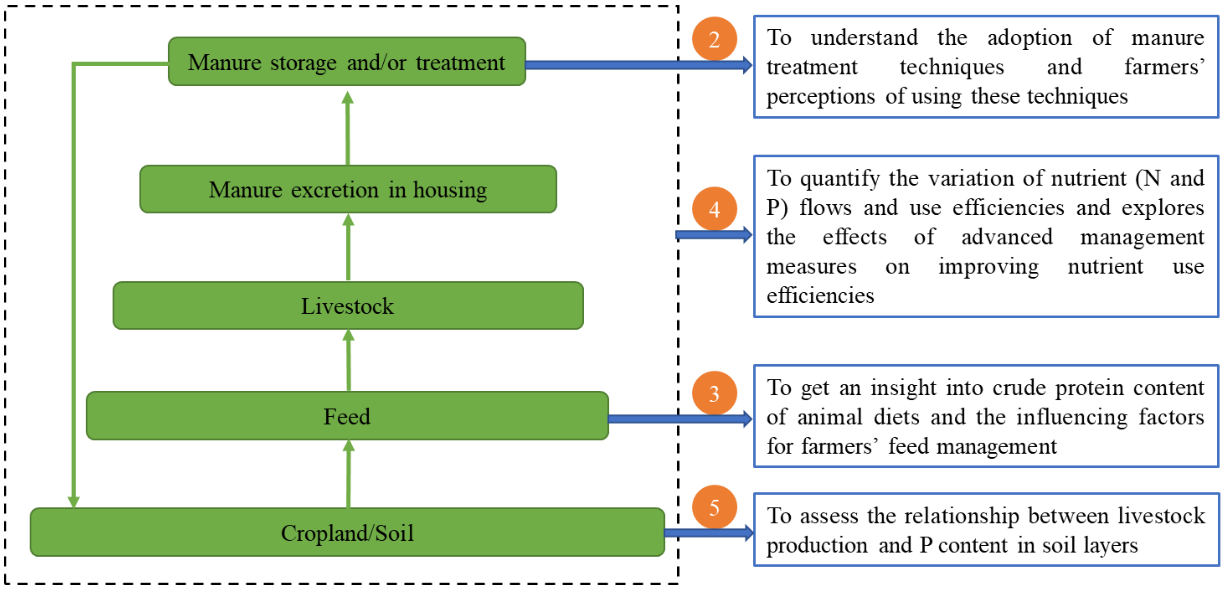

Figure 1.3. Outline of the manure management chain and the chapters of my PhD thesis. The green boxes at the left represent steps in the manure management chain and the green arrows are nutrient flows in the manure management chain. The black dashed line indicates the system boundary of the research. Numbers in the orange pies represent the chapters and the texts in blue boxes show the objectives of these chapters.

Chapter 2 has been published and Chapters 3, 4 and 5 have been submitted to peer-reviewed scientific journals.

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Chapter 2 Operational costs and neglect of end-users are the main barriers to improving manure treatment in intensive livestock farms

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Abstract

Improving manure management is essential to actualize a more circular economy in agro-ecosystems. However, the drivers of and barriers to improving manure management and recycling are not well understood. We report farmers' perceptions of manure management techniques on dairy and poultry farms, with a focus on anaerobic digestion, solid–liquid separation, and composting as common techniques used to facilitate manure management and valorization. We conducted face-to-face interviews with 338 intensive livestock farmers in China. We hypothesized that farmers' behavior is differentially influenced by their perceptions of outcomes, social referents, and controlling factors of the manure management techniques, and by farm and farmers' characteristics. Results indicated that the actual adoption of manure treatment techniques was limited on the surveyed farms (21% dairy farms, 0%–2% poultry farms; other farms were either not equipped with these techniques or the techniques were not used). Most farms had limited cropland and recycled a small but variable percentage of manure (15%–64% for nitrogen and 25%–95% for phosphorus). Farmers' perceptions of the environmental benefits of manure treatment and incentives from government agencies were identified as key drivers for the adoption of manure management techniques. High operation cost, low benefit-cost ratios, technical failures, and lack of a functioning manure market were identified as main barriers. Farm scale, farmers' education and identity also influenced farmers' intention to use manure treatment techniques. Our results indicate that there is need for capacity building in the whole manure management chain, and for monitoring programmes. We argue that greater attention and governmental support should be allocated to (i) the actual operation of treatment techniques (instead of investment subsidies), and (ii) to the end-users of manure treatment products, who need appropriate application machines.

2.1 Introduction

Global livestock production is growing steadily, especially in developing countries, in response to population growth and the trend towards more consumption of animal-source food when income increases (Alexandratos and Bruinsma, 2012). Concomitant with the increases in milk, meat, and egg production, increased amounts of manure are produced, which contains large amounts of organic matter and nutrients, notably, nitrogen (N) and phosphorus (P). The total amounts of manure N are estimated at 139 Tg per year (FAOSTAT, 2017), which is similar to the total annual production of synthetic N fertiliser. Total manure P production is a factor 2 higher than the global annual production of P fertiliser. Most of the manure (>90%) is produced by cattle, pigs, and poultry (Liu et al., 2017) and is not used effectively (Sutton et al., 2013).

Manure management has to be targeted at the effective collection, utilisation, and recycling of the organic matter and nutrients in manure for soil fertility amendment, fertilisation of cropland, protection of the environment, and establishing a more circular agriculture sector and economy (De Boer and Van Ittersum, 2018). Efforts have been made to develop various measures and techniques for recycling organic matter and nutrients from manure and other organic wastes, for example, innovative products such as biochar, struvite, and organo-mineral fertilisers (Maroušek et al., 2020), saving scarce primary nutrient resources (Sommer et al., 2013). However, the implementation of these techniques and measures in practice is highly variable and often low (e.g., Chadwick et al., 2020). Direct recycling of manure recycling in cropland depends on the livestock production system and manure management system. Generally, proper manure recycling is negatively related to livestock density within a region (OECD/FAO, 2015). Large livestock farms with limited cropland have much greater difficulty recycling manure nutrients directly in cropland than mixed crop-livestock systems with sufficient cropland for manure disposal. These large farms without much cropland often attempt to valorise the organic matter and nutrients in the manure by using various treatment techniques.

Manure management principally involves a chain of steps from animal feeding, manure collection in animal housing, manure storage, manure treatment, and manure application to cropland. Because of the risks of nutrient losses, odour nuisance, and pathogen transfer, governmental regulations often require the implementation of low-emission management and sanitation technology, especially in affluent countries with high livestock density (e.g., Bittman et al., 2014). Various manure treatment technologies have been developed and implemented mainly in industrialised farms, such as anaerobic digestion (AD) for biogas production, solid–

liquid separation (SL), oxidation reduction of liquid fractions, and composting or incineration of solid fractions (Meers et al., 2020). Manure treatment may also increase the acceptance of manure by crop farmers (Hou et al., 2018). However, farmers' adoption of these technologies differs greatly among countries and regions, probably because of differences in economic conditions, culture, knowledge infrastructure, climate, and policy regulations (Ndambi et al., 2019). Using agriculture waste to produce biogas for cooking is widely promoted, especially in poor countries (Yasmin and Grundmann, 2019). The payback period of an anaerobic digestor on a dairy farm may range from 4 years, when subsidies are provided, to decades, when no financial support is provided (Lazarus and Rudstrom, 2007). Similar observations have been made for other manure treatment techniques (Larney et al., 2006). Hence, the economic performance of manure treatment techniques is a key factor for their adoption in practice.

Few studies have investigated all drivers and barriers for the actual adoption of manure treatment technologies in practice. Adoption not only depends on the availability but also on the feasibility and acceptability of the technologies according to farmers, and on the incentives from governments, industry, and society. Studies of farmers' perceptions of manure management techniques have been conducted mainly in Europe, for example, a comparison of manure treatment techniques across four countries (Hou et al., 2018), slurry separation in the Netherlands (Gebrezgabher et al., 2015), anaerobic digestion in the Netherlands (Hoppe & Sanders, 2014), composting in Belgium (Viaene et al., 2016), and the use of manure treatment products in Denmark (Case et al., 2017).

China is the biggest livestock producer in the world, with pigs, cattle, and chicken as dominant animal categories (FAOSTAT, 2017). Its livestock production experienced a dramatic transition during the last four decades, accompanied by a gradual disappearance of the traditional mixed backyard and cooperative farming systems, and a rapid appearance of specialised, landless production systems (Bai et al., 2018). During the same period, cheap synthetic fertilisers have become available and have replaced animal manures for the fertilisation of cropland. Consequently, animal manures are often considered waste and are sometimes landfilled or discharged to surface waters (Strokal et al., 2017). After the introduction of the 'zero-increase' fertiliser policy and a ban on manure discharge to surface waters in 2015 (MOA, 2015), and various governmental subsidy programmes, the interests in using animal manures for the fertilisation of cropland and for manure treatment and valorisation are increasing, but the adoption in practice remains low. Suggested barriers for adoption include (i) a lack of information and knowledge, (ii) lack of suitable technology, (iii) no functioning market and distribution system for manure, (iv) no proper regulations and enforcement, and (v) cultural and socioeconomic barriers (Ma et al., 2013). However, these suggestions have not been field tested.

The general objective of our study was to apply the theory of planned behaviour (TPB) to increase the understanding of farmers' perceptions of manure management techniques and the drivers of and barriers to the adoption of improved manure management techniques (Ajzen, 1991). Livestock farmers are the key stakeholders for on-farm manure treatment, and improving the understanding of farmers' notions and perceptions may help increase the speed of the implementation of on-farm manure treatment in practice. Starting in 2017, manure storage and treatment has become obligatory on all large livestock farms in China (MOA, 2017).

We propose three hypotheses: (i) Policy requirements, as a subjective norm, are the most important driver for improving manure management; (ii) economic factors, as behaviour controls, are the most important barriers; and (iii) TPB is applicable to manure management studies and provides useful insights.

To test these hypotheses, we developed questionnaires based on the TPB and selected medium to large-size dairy, pig, and poultry farms from two livestock-dense provinces (Hebei and Shandong) by using a stratified random sampling approach. Face-to-face interviews were conducted with the farmers in 2018 and 2019, and we obtained data from 30 pig farmers. We had planned to interview additional farmers, but because of the outbreak of African swine fever, we stopped our interviews. Therefore, we report the results from only the dairy and poultry farms.

2.2 Materials and methods

2.2.1 Conceptual outline

The TPB has been applied successfully in various behavioural studies at the interface of agriculture (Wauters et al., 2010; Lalani et al., 2016) and the environment (Wang et al., 2018). This theory states that individuals base their behaviour in general on three aspects: (1) their attitude towards the outcomes they expect, (2) their perceived subjective norms from social referents, and (3) their perceived easiness or difficulty as influenced by controlling factors (behaviour control). A meta-analysis summarised the TPB's successes in various behavioural intervention studies (Steinmetz et al., 2016). Notably, the TPB has strong explanatory power, as indicated by the variance of 46%–61% accounted for in the intent to practice an environmental behaviour (Greaves et al., 2013). However, TPB has never been applied to manure management.

We developed two questionnaires based on the TPB. First, a semi-structured questionnaire was used to gain basic insights into manure management practices and to identify relevant outcomes, social referents, and controlling factors related to manure management techniques (Table S1). A total of 16 dairy farms, 22 pig farms and 13 poultry farms were visited in September 2018. The results of the semi-structured survey are shown in Table S2. Financial factors were the most frequently mentioned aspects, including investment and operational costs, economic value of manure treatment products, subsidies, and cost-benefit ratio. These factors can be either drivers or barriers. In addition, technical factors (failures) and social factors (e.g. social referents, functioning of the manure market) were also mentioned. All these factors were used as input for the second questionnaire, to gain deeper and quantitative insights into farmers' perceptions.

The purpose of the second questionnaire was to quantitatively evaluate the outcomes, social referents, and controlling factors. A detailed structured questionnaire was used to quantitate the scores of farmers' perceptions of manure management techniques (Table S3). A total of 141 dairy farms, 98 layer farms and 99 broiler farms were visited in Hebei and Shandong provinces during the period November 2018 to May 2019. A checklist was used to score the manure management practice (Table S4).

The questionnaire was structured in five parts (Table S3):

1) Farm structure, farmer characteristics, and manure management planning.
2) Farmers' intention to use a specific manure management technique within the next 3 years.
3) Farmers' perceptions of the outcomes of specific manure management techniques: (i) what is the extent of the possibility of the outcome (defined as belief strength), and (ii) what is the extent of the bad or good outcome to the farmer (defined as outcome valuation).
4) Farmers' perceptions of referents: (i) to what degree are referents positive or negative towards a specific technique (defined as normative belief), and (ii) to what extent is the farmer willing to comply with a referent's view (motivation to comply).

5) Farmers’ perceptions of controlling factors: (i) to what extent are the factors hindering the use of techniques (defined as control power), and (ii) to what extent are the factors valid for the farm (defined as control strength).

Farmers’ intentions and perceptions of outcomes, referents, and controlling factors were scored on a Likert scale from 1 to 5: 1=not possible or very bad and 5=very possible or very good (Table S3). The synthesised values for outcomes (i), social referents (j), and controlling factors (k) were calculated by using the following set of equations:

$$attitude_i = belief\ strength_i \times (outcome\ valuation_i - 3) \qquad \text{Eq.1.1}$$

$$subjective\ norm_j = motivation\ to\ comply_j \times \left(normative\ belief_j - 3\right) \qquad \text{Eq.1.2}$$

$$behaviour\ control_k = control\ power_k \times (control\ strength_k - 3) \qquad \text{Eq.1.3}$$

Average values were calculated based on the answers of all respondents. The 95% confidence interval was calculated as the average value $\pm 1.96 \times \frac{sd}{\sqrt{N}}$, in which sd is the standard deviation and N is the number of respondents. When this interval did not include 0, the average value was believed to be significantly different from zero. Significant positive values were believed to be drivers and significant negative values were believed to be barriers. An average ‘strength’ score below 3 was defined as a ‘potential driver’ or a ‘potential barrier’ (Hijbeek et al., 2019).

2.2.2 Selection of farms

The study was conducted in the provinces of Hebei and Shandong, China (Figure S1). These two provinces are among the top four livestock-dense provinces and are large wheat, maize, and vegetable producers (Table S5). The climate is typically temperate and monsoonal, with warm and wet summers and cold and dry winters.

We purposefully selected medium to large size ‘intensive farms’ as defined by Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Science (IEDA·CAAS) and Nanjing Institute of Environmental Sciences (NIES) (2009): an operation with at least 100 dairy cows (stocked), 10,000 layer hens (stocked), and 50,000 broilers (slaughtered). These farms will probably remain in business for at least the next 5 to 10 years and are increasingly important to the total animal production. The relative number of farms in these categories was still small (<4%) in 2010, but the relative number of animals ranged from 17% to 76% (Table S6). The number of medium to large farms is rapidly increasing, but unfortunately, the Statistical Yearbook provides no information after 2010. The number of animals per farm was expressed in livestock units (LSU), which enables comparison across livestock categories (Table S7).

Administratively, Hebei is divided into 11 cities and Shandong, 16 cities. Each city has 4 to 24 counties, and each county has up to 1000 villages. We selected counties by the number of dairy and poultry farms on the enterprise database website Qixinbao. We purposefully selected four cities in Hebei and three in Shandong, which have counties with more than 20 dairy farms and/or more than 20 poultry farms. We considered high-density counties to be more advanced and representative than low-density counties. Next, the Animal Husbandry Bureaus of the selected counties were contacted to provide a list of addresses of livestock farms within those counties. We then contacted the farms and asked permission to visit and conduct the survey. One farm per village (the first farm that accepted our request) was selected to obtain geographical spread.

2.2.3 Farm surveys and data analysis

The survey was conducted by PhD and master's students from China Agricultural University. Before the survey, training was provided to the enumerator students to introduce the objectives of the survey, questionnaire, key concepts in manure management, and checklist. A number of dairy and poultry farms were visited as part of the training. Based on the visits, we refined and shortened the questionnaire.

Interviews were conducted by 19 students. Interviews lasted on average 1 hr, farm visits usually took half an hour. Finding the location of the farms was often a cumbersome task, but most farmers accepted our requests for an interview and farm visit.

Data and information from the questionnaires were stored and processed in Windows Excel. For each farm, estimations were made of the N and P flows in the manure management chain on the livestock farms (Figure 2.1). The total N and P excretion by the animals and the fractions of the excreted N and P that entered manure storages, manure treatment installations, and were ultimately applied to cropland were estimated (Supplementary Information C; Tables S8, S9, S10).

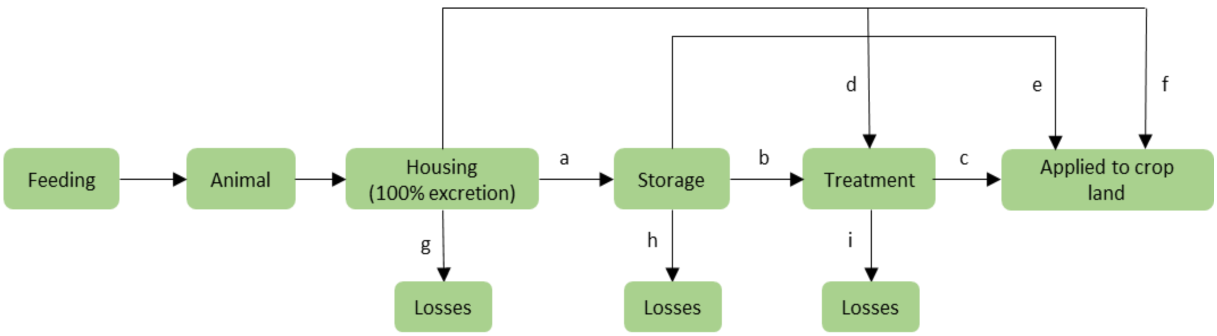

Figure 2.1. Manure management chain of livestock farms. Arrows indicate the flows of nitrogen and phosphorus, from animal feeding to manure application on cropland. Letters indicate the flows estimated in Table 2.2.

Spearman correlation analysis was conducted with the R programming language to explore the correlation between farmers' intentions and the influencing factors (R Core Team, 2015). Differences of farms' and farmers' traits between adopters and non-adopters were analysed in R by using an analysis of variance (ANOVA) combined with a t-test.

2.3 Results and discussion

2.3.1 Main farm and manure management characteristics

Dairy farms had on average 341 dairy cows (lactating and dry cows), 151 heifers (1 to 2 years), and 158 calves (<1 year). There were on average 484 LSU per farm (range 78 to 8358 LSU; Table 2.1), which is close to the mean number of animals on medium to large-scale dairy farms in North China Plain (NCP, Ledgard et al., 2019). Average milk yield was reported at 29.7 kg cow^{-1} day^{-1} (or approximately 9000 kg cow^{-1} yr^{-1}). Average cropland area of the dairy farms was 17.4 ha, and mean livestock density was 59.4 LSU ha^{-1}. Cows were maintained in free-standing cubicle housing the whole year (zero-grazing), but in many cases, the cows had access to a free range playground (Table S11). The average N and P retention in milk and live weight gain were estimated at 21% and 27% of the amounts of feed N and feed P ingested, respectively (Table 2.2). On average, 15% of N and 25% of P excreted by dairy cows were applied to cropland (Table 2.2).

Table 2.1. Mean characteristics of surveyed dairy, layer, and broiler farms; ranges are in brackets.

Characteristics	Dairy farms	Layer farms	Broiler farms
Number of farms surveyed	141	98	99
Mean herd size, in LSU	484 (78–8358)	489 (140–5416)	335 (38–2968)
Number of milking cows	341 (50–5900)		
Number of young stocks	308 (36–4338)		
Average production period	*)	461 days	40 days
Average yield per animal	29.7 kg milk d^{-1} cow^{-1}	21 kg egg hen^{-1}	2.3 kg $broiler^{-1}$
Cropland area per farm (ha)	17.4 (0–600)	1.4 (0–33.3)	0.5 (0–13.3)

*) Milk yield is reported in average milk production per day for the lactating herd. Many interviewees did not know the mean lactation period. We estimate 29.7 × 300 days = 9000 kg cow^{-1} yr^{-1} as a likely upper estimate for the average annual milk production per cow.

Table 2.2. Overview of the calculated nitrogen (N) and phosphorus (P) flows in the manure management chain of surveyed dairy, layer, and broiler farms (see also Figure 2.1).

	Dairy farms		Layer farms		Broiler farms	
	N	P	N	P	N	P
Feed intake (kg/farm)	77200	12487	52027	11790	52052	8133
Retention (% of intake)	21	27	31	30	49	49
Excretion of urine & faeces (kg/farm)	60988	9116	35899	8253	26547	4148
Excretion of urine & faeces (% of intake)	79	73	69	70	51	51
Storage (% of excretion)*	37	54	39	51	24	32
Treatment (% of excretion)**	13	18	8	10	0	0
Recycled (kg/farm)	9148	2279	22975	7840	16990	3941
Lost (kg/farm)	51840	6837	12924	413	9557	207

* percentage of excreted N and P stored for some time (arrow "a" in Figure 2.1).

** percentage of excreted N and P subjected to a form of treatment (anaerobic digestion, solid–liquid separation, composting), indicated by arrows "b" and "d" in Figure 2.1.

Layer farms had on average 489 LSU per farm and 1.9 ha of land. The mean livestock density was 769 LSU ha^{-1}. Layers remain in production on a farm for on average 461 days and produce 21 kg eggs during their lifetime (Table 2.1). All layers were maintained in battery cages in forced-ventilated barns without free range (Table S12). The average N and P retention in eggs produced and body weight was estimated to be 31% and 30% of the amounts of feed N and feed P ingested, respectively. The percentage recovered and applied to cropland was much higher for layer farms than dairy farms (Table 2.2).

Broiler farms had on average 335 LSU per farm. Broilers take on average 40 days to attain a 2.3 kg body weight (Table 2.1); 88% of the broilers were maintained in battery cages in forced-ventilated barns without free range (Table S12), and the remaining broilers were maintained on the littered ground floor. The average N and P retention in poultry meat produced were estimated to be 49% for both N and P. Mean total N and P excretion was 26 and 4 Mg per farm per year, respectively. Estimated recovery fractions of the excreted N and P were similar to those of layer farms (Table 2.2).

Over 90% of the dairy, layer, and broiler farms used leaky open-air manure storages, and less in 10% of the farms used leak-tight and covered basins (Table S13). Dairy farms either store the slurry in the farmyard, in soil pits, or on a concrete floor below a shelter. Similarly, 78% of the layer farms and 61% of the broiler farms store the chicken manure in soil pits or in heaps in the open air for less than 1 month before exporting it to crop farms. We observed that dairy farmers had more difficulty with manure management than the layer and broiler farms did, and as a result, the former had a much lower fraction of the N and P excreted that was used on cropland (Table 2.2). Fresh poultry manure is much drier and has a higher nutrient content than dairy manure, making long-distance transportation easier and acceptance by crop farmers higher (Chadwick et al., 2015). These properties also attract manure distributors to engage in the poultry manure business. By contrast, dairy farms may dispose of some manure at nearby crop farms because the bulky wet nature prohibits long-distance transport (Chadwick et al., 2015).

2.3.2 Implementation of manure treatment technologies

Over 80% of the farmers had heard of one or more manure management techniques, but most of them did not understand the mechanisms and the operation of these techniques. More dairy farmers than poultry farmers had heard of SL and AD. Approximately one-third of the dairy farmers and layer farmers and 18% of the broiler farmers had heard of composting (Table 2.3).

Table 2.3. Overview of the number of farmers who have heard of the indicated techniques, who have equipped their farms with the indicated techniques, who are using them, and who were able to evaluate the manure treatment technologies. Numbers in brackets denote the proportion compared to total surveyed farms. Notably, some farms were equipped with more than one technique.

Questions/aspects	Dairy farms	Layer farms	Broiler farms
Heard of any of the treatments	123 (87%)	86 (88%)	81 (82%)
Heard of SL separation	121 (86%)	73 (74%)	57 (58%)
Heard of composting	46 (33%)	35 (36%)	18 (18%)
Heard of AD digestion	115 (82%)	81 (84%)	75 (76%)
Equipped with any of the treatments	64 (45%)	6 (6%)	0
Equipped with SL separation	55 (39%)	2	0
Equipped with composting	8 (6%)	2	0
Equipped with AD digestion	19 (13%)	3	0
Used any of the treatments	29 (21%)	2	0
Used SL separation	24 (17%)	0	0
Used composting	7 (5%)	1	0
Used AD digestion	2 (1%)	1	0
Total response to the treatments	120 (85%)	79 (81%)	75 (76%)
Response to SL separation	71 (50%)	33 (34%)	26 (26%)
Response to composting	23 (16%)	20 (20%)	8 (8%)
Response to AD digestion	36 (26%)	31 (32%)	44 (44%)

Nearly half (45%) of the dairy farms were equipped with one or more manure treatment techniques: the most common was SL (39%). A composting installation was available on 6% of the dairy farms and AD on 13% of the dairy farms. However, less than half of the SL was actually used, and two out of the 19 AD were still used. Additionally, 6% of the layer farms and no broiler farms were equipped with manure treatment techniques (Table 2.3). The response rate for the evaluation of manure treatment techniques was more than 75% for all three groups of farms and the highest for dairy farmers. However, the response to specific techniques was much lower mainly because the farmers did not know of these techniques.

These results concur to some extent with those of Zhao et al. (2017), who surveyed demonstration farms in the NCP from 2012 to 2015. They reported that a large fraction of the dairy and poultry farms used AD and composting, probably because these farms had easy access to governmental support, especially the farms in the Beijing municipality. Zhao et al. (2017) did not report on SL probably because the encouragement of the government to use this technique on dairy farms started only recently.

2.3.3 Farmers' perceptions of manure treatment technologies

2.3.3.1 Solid–liquid separation

Figure 2.2 presents the results of farmers' evaluation of SL. Six outcomes were identified as drivers and four outcomes were identified as barriers. The drivers were mainly related to the expected environmental benefits: farmers believed that using SL contributes to improving on-farm and public environments and reduces the odour nuisance. Moreover, compared to raw slurries, separated solid and liquid manure fractions are easier to manage in next-step processing and/or transport, and solid fractions have a higher acceptance by crop farmers. The easier management and higher acceptance of the solid fraction is mainly because of the much lower water content compared to that of raw slurry (Zhang et al., 2019). Some of the dairy farms followed the instructions from the government to use solid fractions as cheap bedding material in cubicles (MOA, 2017). This practice may have led to the use of this technique being more frequent on dairy farms than on poultry farms (Table 2.3).

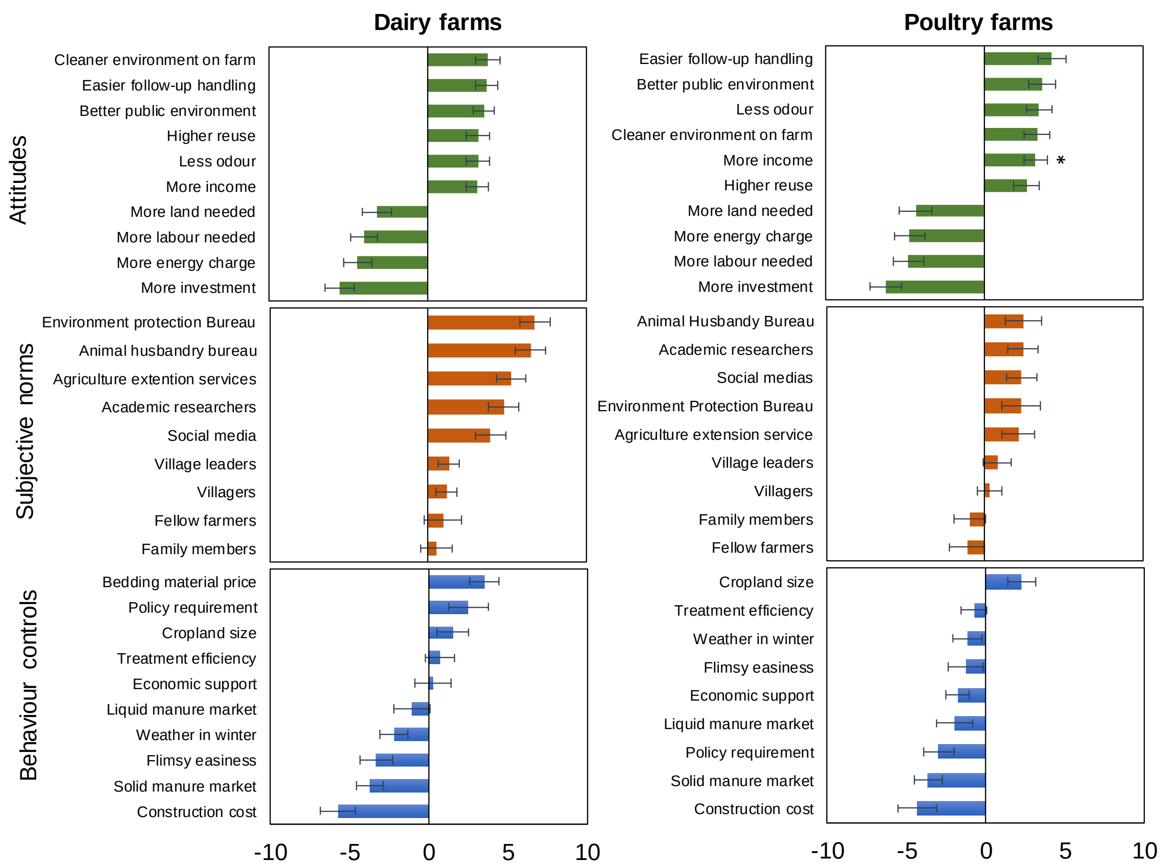

Figure 2.2. Drivers of and barriers to using solid–liquid separation. Solid bars indicate average scores; the error bars (lines) indicate the 95% confidence interval. * indicates an underlying control power<3, which means not an important controlling factor.

Notably, the evaluation of the outcomes did not differ much between dairy and poultry farmers (Figure 2.2). An increase in income was evaluated more positively by dairy farmers than poultry farmers; the latter thought that the possibility of this outcome was low (<3 on the Likert scale). Dairy farmers felt much more pressure from social referents to invest in SL than poultry farmers did (Figure 2.2). Most of the pressure was from governmental agencies (Environment Protection Bureau, Animal Husbandry Bureau, and agriculture extension services). The academic researchers and social media reports also pressured dairy farmers to use SL, mainly through the news, reports, or seminars on the internet. Fellow farmers and family members appeared to be a barrier to investments in SL on poultry farms.

Behaviour controls may involve financial, technical, and policy-related requirements and factors. Controls differed for dairy farmers and poultry farmers (Figure 2.2): there were more barriers for poultry farms than on dairy farms. The major barriers to investing in SL were construction costs, lack of a functioning manure market, and inferior techniques, and poor operation performance, especially in winter. Lack of cropland on the farm was observed to be a driver on both dairy farmers and poultry farms.

2.3.3.2 Anaerobic digestion

Five outcomes were identified as significant drivers for using AD (Figure 2.3): an improved environment on the farm, fewer insects, better human health, less energy use, and better manure quality. Four outcomes were identified as strong barriers: resulting digestates are difficult to process, increased labour need, less income, and safety risks. Again, the differences between dairy and poultry farms were relatively small in the outcome evaluation.

Farmers' perceived subjective norms for using AD are similar to those of SL: (1) social pressure to use AD was mainly from governmental agencies, academic researchers, and social media; (2) dairy farmers felt more pressure than poultry farmers felt; (3) villagers and village leaders pressured dairy farmers but not poultry farmers; (4) family members and fellow farmers did not support AD, and this phenomenon became a barrier for poultry farmers (Figure 2.3). Construction subsidies were perceived by dairy farmers as drivers to purchase AD. Construction cost was the biggest barrier, but the lack of subsidies for the operation of the digestors, low prices for biogas, and policy requirements were also reported as major barriers (Figure 2.3).

Farmers’ perceptions of the economic performance of AD were opposite to the positive results presented by Sefeedpari et al (2019). This difference may be related to differences between our and their research: the research methods (interviews vs. life-cycle analysis calculations), climate (Iran vs. NCP), and farm scale (a single large-scale farm with 9000 cows versus medium to large farms [50 to 5900 cows in our study]). The dairy farm of Sefeedpari et al (2019) was assumed to produce a large, steady quantity of biogas and electricity year-round, and the AD in NCP showed poor performance during the cold winter. However, the scale of operation is critical; centralised AD with the collection of animal manure from medium-size and near-distance farms may be economically more attractive than the on-farm AD at medium-size farms.

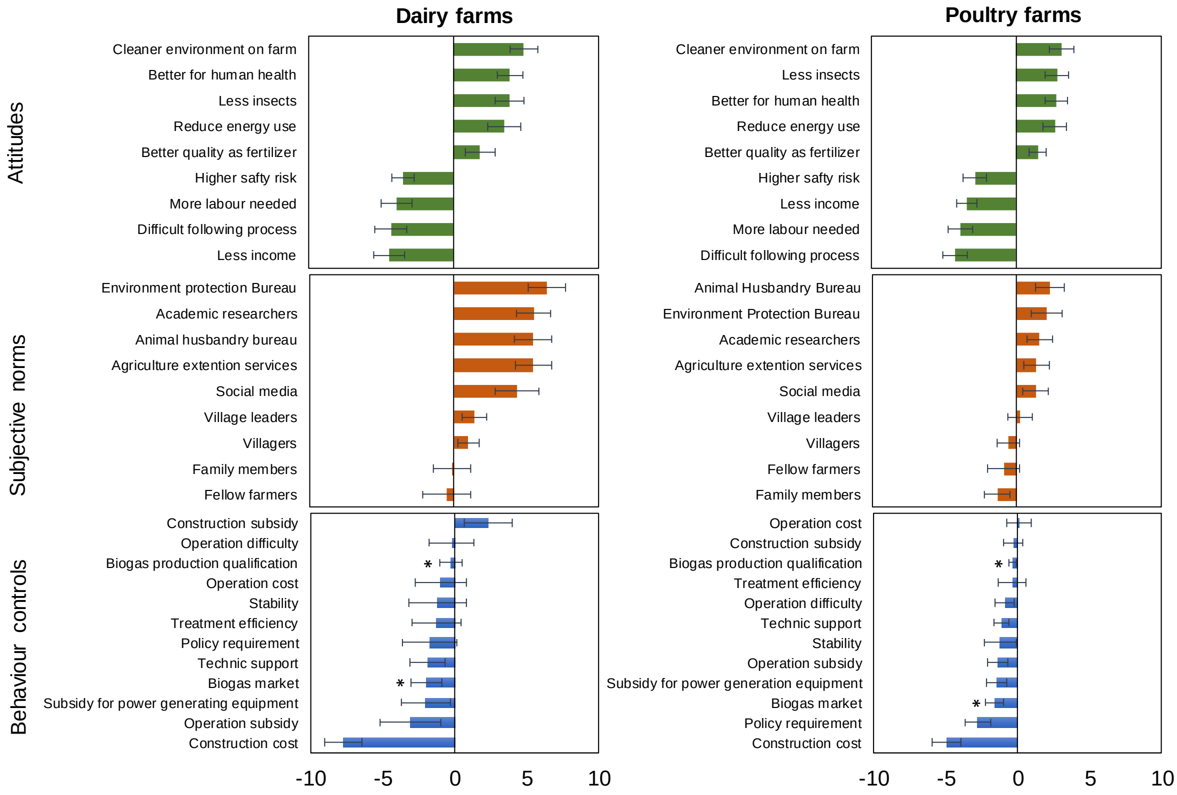

Figure 2.3. Drivers of and barriers to using anaerobic digestion. Solid bars are the average scores; error bars (lines) indicate 95% confidence intervals. * indicates an underlying control power<3, which means not an important controlling factor.

2.3.3.3 Composting

Six outcomes of composting served as drivers, and two outcomes were identified as barriers, for both dairy and poultry farms (Figure 2.4). An increased income was the most important driver, but less odour nuisance and a cleaner farm environment also acted as drivers. Better human health was a potential driver. The main barriers to composting were the required labour cost and the land area necessary (row composting was the most common and requires a relatively large surface area).

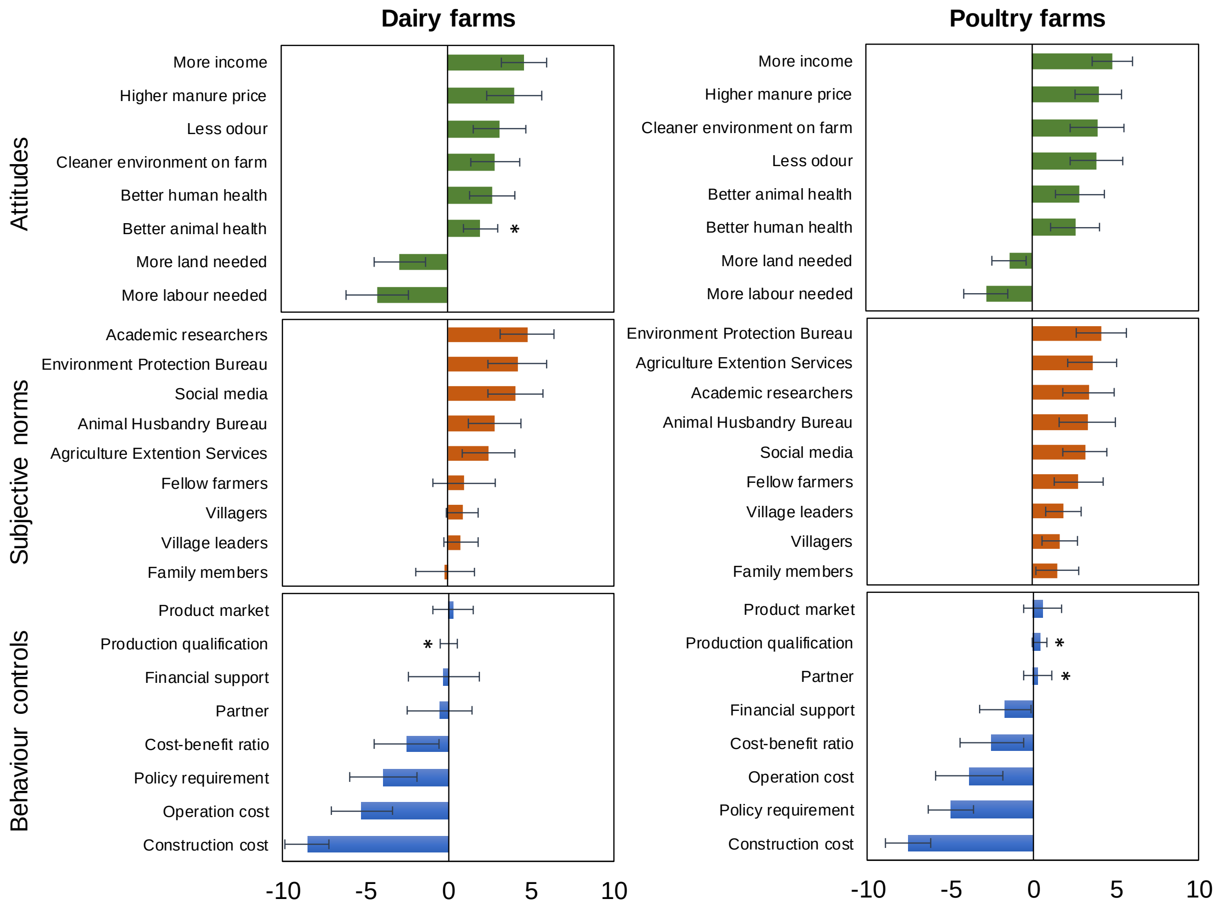

Figure 2.4. Drivers of and barriers to using composting. Solid bars are the average scores; error bars (lines) indicate 95% confidence intervals. * indicates an underlying control power<3, which means not an important controlling factor.

Dairy farmers and poultry farmers felt positive pressure from especially academic researchers, social media, and governmental agencies to use composting installations. Poultry farmers felt also pressure from fellow farmers, family members, and villagers. Regarding behaviour controls, farmers reported only significant barriers (Figure 2.4). High construction and operation costs were the main barriers. Notably, (the lack of) policy requirements were also reported as a barrier because the policy does not require composting; thus, farmers cannot obtain financial support. The (lack of a functioning) market for composted manure was also reported as a significant barrier; as a result, the benefit-cost ratio of composting manure was low.

2.3.4 Relations between perceptions and behavior

Behavior is determined by both intention and controlling factors, according to the TPB. We analyzed the effects of both the intention and controlling factors in the adoption of SL in dairy farms. Adopters had significantly higher intention than non-adopters (Table 2.4). Five controlling factors belonging to three aspects were significantly different between adopters and non-adopters. The first aspect is a financial point, including the construction cost and economic support. Both adopters and non-adopters evaluated them to be important, but values from non-adopters were negative (-6.2 and -0.4 for non-adopters, and -2.6 and 4.2 for adopters). The policy requirement is also evaluated differently; the adopters reported higher scores (on average 6.9) than non-adopters did (on average 1.7), which means that adopters perceived higher pressure from the policy requirement than non-adopters did. Technical aspects including the treatment efficiency and applicability in winter is a third factor that differed significantly; adopters scored 4.5 (high efficiency) and reported low inapplicability in winter (-0.1) and non-adopters scored -0.1 (low efficiency) and reported strong inapplicability in winter. Unfortunately, we were not able to examine relations between intention, controlling factors, and actual behavior for other treatment techniques and for poultry farms because too few farmers had adopted these techniques to conduct the analyses.

Table 2.4. Evaluation scores for intention and controlling factors of adopters and non-adopters of solid–liquid separation in dairy farms, and the statistical significance (*P* value) of the differences between the two groups by using the t-test in R.

Intention/ controlling factors	Total valid sample n=70	Non-adopters n=59	Adopters n=11	*P* value
Intention	3.8	4.7	3.3	0.005
Construction cost	-5.7	-6.2	-2.6	0.016
Flimsy easiness	-3.3	-3.6	-0.9	0.076
Weather in winter	-2.2	-2.5	-0.1	0.035
Policy requirement	2.5	1.7	6.9	0.002
Bedding material price	3.5	3.3	5.0	0.177
Economic support	0.3	-0.4	4.2	0.002
Treatment efficiency	0.7	-0.1	5.3	0.001

Liquid manure market	-0.9	-1.3	1.3	0.110
Cropland size	1.6	1.5	2.4	0.489
Solid manure market	-3.6	-3.7	-3.1	0.582

The statistical correlation between farmers' perceptions of social referents and farmers' intention to use SL was high, indicating that social referents were major factor influencing farmers' intention to use SL (Figure S2). By contrast, the correlation coefficients were relatively low between farmers' attitude, social norms, and controlling factors and their intention to use AD. The number of barriers was also larger for AD than for SL. Further, correlations coefficients were relatively high for the relationship between farmers' perceptions of social referents and farmers' intention to use composting. Correlation coefficients tended to be higher for dairy farms than for poultry farms (Figure S2).

2.3.5 Influences of farm and farmers' characteristics

The TPB considers that (internal) outcomes, (external) social referents, and controlling factors are important in decision-making. The theory derives a one-point in time record of the intention and behaviour but does not help predict future behaviour (McEachan et al., 2011). The theory can be used for identifying drivers and barriers in practice (Hughes et al., 2009), but personnel traits and socioeconomic and environmental conditions should also be considered (Gifford and Nilsson, 2014; Wang et al., 2018). In our questionnaires, we therefore explicitly included questions related to personnel traits, farm structure, and performance characteristics. We further analysed the traits of adopters and non-adopters of SL in dairy farms (Table S14). There were no significant differences ($P>0.05$) between adopters and non-adopters in personal traits (Table S14). This finding suggests that farmer traits were not strongly influencing factors for real adoption of SL.

Dairy farmers' intention to use SL was positively and significantly ($P<0.01$) related to farm scale, as reflected by farm area, number of dairy cows, milk yield per cow, and number of workers (Table S15). Similar observations were made in the United States for dairy farms (Aguirre-Villegas & Larson, 2017). We found that higher educated farmers had a greater intention to use SL; by contrast, a negative relation between farmers' intention to use SL and farmers' education was reported for The Netherlands (Gebrezgabher et al., 2015). Dairy farmers' intentions to use AD and/or composting were negatively related to farm scale; thus, larger farms were less likely to use these techniques than smaller farms, which contrasts with the findings of Aguirre-Villegas & Larson (2017). Dairy farmers with more experience had a relatively strong intention to use composing than less experienced farmers did (Table S15).

Correlations between farm and farmers' characteristics and intentions to use manure treatment techniques were weaker for poultry farmers than for dairy farmers. Farmers with or without successors did not have significant differences in intention to invest in manure treatment techniques. Owner-managers had significantly ($P<0.05$) lower intention to use SL than managers did, for both dairy farms and poultry farms, suggesting that the investment burden is a major factor (Table S15).

2.3.6 Drivers and barriers for manure management techniques

The manure management chain has multiple steps (Figure 2.1). The ultimate goal is to collect excreted N and P and to recycle these on cropland effectively, with minimal losses (Chadwick et al., 2005; Bittman et al., 2014). Our results indicate that poultry farms were more successful than dairy farms in using manure nutrients on cropland, despite poultry farms having less land (Table 2.2). Manure treatment techniques are meant to facilitate the manure nutrient utilisation and/or to add value (biogas, compost) to the manure management chain. Our study indicated that farmers partially understood the sequence of steps of the manure management chain and the mechanisms of manure treatment (section 2.3.2 and Table 2.3). This finding has many policy implications.

Farmers' valuations indicated that there are various driving factors for using manure treatment techniques (Figures 2.2, 2.3, 2.4). This finding was supported by the Spearman correlation analysis between the factors and intention (Figure S2). Common drivers for all techniques include the perceived good outcomes and the subjective norms from governmental agencies. Construction subsidies, the high price for conventional bedding materials in dairy cubicles, and policy requirements were perceived as drivers for using SL on dairy farms. Construction subsidies were also a driver for using AD. However, the adoption of those techniques in practice was still low (Table 2.3), suggesting that either the drivers were too weak or the barriers too strong. Notably, adopters of SL on dairy farms evaluated investment costs, policy requirements, and treatment efficiency significantly different from non-adopters (Table 2.4), suggesting that these factors had a strong impact on adoption.

SL is one of the four key technologies promoted and financially supported by the government (MOA, 2017): 'large scale dairy farms should use solid-liquid separation, and separated solids should be used as bedding material for dairy cattle after rapid fermentation or sterilization at high temperature'. The other three key technologies are (i) collection and application of manure to the field after storage in an oxidation pond by specialised companies; (ii) large-scale use of AD, and the resulting biogas should be used for electricity generation and the digestate for producing organic fertilisers; (iii) application of slurries and liquid manure from large-scale farms to cropland after treatment in oxidation ponds. Our results reflect that the current policies have influenced dairy farmers' decisions on manure treatment practices to some extent, but that there are serious barriers to the full adoption of the proposed treatment techniques. The acquisition of the technologies is promoted and supported, but its actual use is not. One dairy farmer said, 'no requirement, no use'. This farmer's opinion reflects that the perceived outcomes (Figures 2.2, 2.3, and 2.4) were not strong drivers. This result also applies to poultry farms. Surprisingly, the government provides no incentives for transporting manure to crop farms and for using manure on crop farms.

The major barriers to using manure treatment techniques were the financial burdens (Figures 2.2, 2.3, 2.4), as observed in other regions (Hoppe & Sanders, 2014; Viaene et al., 2016). This finding was also in line with our hypotheses. The modest technical readiness levels also hindered using the equipment. Both the high operation cost and technical failures may explain why only 44% of the solid–liquid separators and only 11% of the biogas plants were operating (Table 2.3). Technical readiness level (TRL) is defined as the readiness (maturity) of a technology for its implementation; it ranges from TRL1 (scientific research is beginning) to TRL9 (a technology has been "flight proven") (NASA, 1974). Commonly, TRL gradually decreases as the technology is being applied outside its original context. Our results suggest that the solid–liquid separators and the anaerobic digesters on dairy farms were not TRL9, at least not on the surveyed farms. This phenomenon may also be caused by poor maintenance. Farmers reported that the separators were easily damaged by the sand used as bedding material, suggesting that the combination of techniques was inappropriate. This problem increased the maintenance cost (Hjorth et al., 2010).

Our results indicated that the current focus on subsidising the purchase and construction of manure treatment techniques is an ineffective policy strategy because of the high operation costs and technical failures. As long as cheap, subsidised synthetic fertilisers are available, crop farmers will be reluctant to accept bulky raw slurries or costly manure treatment products. Additionally, as long as the government does not implement strict regulations for manure management and a functioning manure market, livestock farmers will be reluctant to invest in improved manure management. We argue that subsidies for synthetic fertilisers should be phased out and the use of marketed manure products should be supported. In the short term, subsidies for investments in manure treatment techniques should be reverted to subsidies for manure treatment products. Additionally, capacity building is necessary to develop and implement a systems approach and to establish monitoring ad verification programmes. Evidently, the government’s policy of supporting the implementation of manure treatment techniques without considering the impact on the whole chain, and without clear performance targets, has been ineffective (De Vries et al., 2015; Hou et al., 2017).

2.4 Conclusions

Manure management technologies for the valorisation of manure-derived products and for facilitating manure recycling on cropland are essential to ensure a more circular economy in agricultural systems. Our study reveals the existence of a diversity of drivers and barriers for implementing key manure treatment technologies in practice. Current manure management practices on medium and large-scale livestock farms in China are relatively poor. The interviewed farmers were aware of the environmental benefits of using manure treatment and were supported by government agencies to invest in anaerobic digestion, solid–liquid separation, and composting, but the actual use of the techniques was limited (<21% on dairy farms, <2% on poultry farms). Major barriers were the financial burden because of the high operational costs and low manure price, which were infrequently subsidised. Technical failures also made continual use of these techniques difficult. These barriers were observed to be larger than the incentives from the perceived good outcomes and subjective norms from social referents, and thus partly support our hypotheses. The incentives differed among farms types: dairy farmers perceived greater pressure to invest in manure management techniques than poultry farmers did, and the latter cooperated closely with manure distributors to transport the poultry manure to vegetable and fruit growers. The factors influencing farmers’ intentions may differ between countries, depending on the farm and farmers’ background, suggesting that country-specific observations are necessary. The extended TPB framework proved applicable and useful in identifying drivers and barriers and may also be used in other regions and countries experiencing serious challenges related to the sustainable intensification of agricultural production. However, the framework cannot be used to predict farmers’ future behaviour.

We conclude that in China, a systems approach is necessary for which all the steps of the manure management chain are considered in an integrated manner. Capacity building, extension, and monitoring and verification programmes are also necessary. Additionally, the government should consider reverting (i) subsidies on investments in manure treatment techniques to subsidies on the actual operation of the techniques and (ii) subsidies on the delivery of synthetic fertilisers to subsidies on the actual use of manure on cropland. Further research should evaluate the impact of the suggested changes for livestock farmers and the actual use of manure treatment techniques.

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Supplementary information

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Chapter 3 Decision making environment of low-protein animal feeding in dairy and poultry farms in China

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This chapter is submitted under revision

Abstract

Low protein feeding is a strategy to decrease nitrogen excretion and ammonia (NH_3) emissions from animal manures, but too low protein contents decrease animal productivity. The optimal protein content depends on many factors, including animal category, age and production level, and on the availability, composition and digestibility of feed ingredients. The variation in protein contents of rations and the decision making environment are not well-known in developing countries, which hinders making accurate NH_3 emission inventories and strategies to reduce NH_3 emissions. We investigated farmers' knowledge and perceptions about low protein feeding and the actual protein content in 141 dairy farms, 98 layer hen farms and 99 broiler farms in China. We did face-to-face interviews, based on Theory of Planned Behaviour, and collected and analysed feed samples and examined diet formulas from feed companies. The mean protein contents of the silage maize based diets of heifers (119±25 g/kg DM) and milking cows (159±20 g/kg DM) were relatively low, but with relatively large variations between farms. The mean protein contents of the maize and soybean based diets of broilers decreased from 245 g/kg DM in the first week to 219 g/kg DM in the 6th week and complied with recommendations for low-protein diets. The mean protein contents of the maize and soybean based diets of layers ranged from 176±37 g/kg DM for hens in the pre-laying phase to 184±22 g/kg DM for productive hens. The interviews revealed that farmers had little knowledge and concerns about the feed protein content. Most farmers simply followed the instructions of feed delivering companies or contracting companies. The mean protein level in the diets was close to the recommended levels for low-protein animal feeding, but there was large variation between farms, suggesting scope for improvements on many farms. Animal production contributes largely to the NH_3 emission in China, and our research indicates that there is scope for lowering emissions through low-protein animal feeding on some dairy farms and on some layer farms. We suggest training and education programs for farmers and advisors to increase the knowledge about the crucial role of protein in animal productivity and NH_3 emission mitigation, and to develop precision animal feeding strategies. Our research findings may support organizations to accurately assess NH_3 emissions from animal production and to efficiently target animal farms where low protein feeding will be most effective to decrease NH_3 emissions.

3.1 Introduction

Livestock is a main consumer of global plant biomass and nutrients, but most of the ingested organic matter and nutrients are excreted again in animal manure (Herrero et al., 2013). These manures are important for the fertilization of cropland and for the maintenance of soil fertility, and are used in some countries also as biofuel or building material. The total amounts of nitrogen (N) and other nutrients in animal manure are as large as or larger than the total amounts of N and other nutrients in synthetic fertilizers used in the world (FAOSTAT, 2017). However, animal manure is also a main source of anthropogenic ammonia (NH_3) and nitrous oxide (N_2O) emissions to the atmosphere (Steinfeld et al., 2006), and a main contributor to pollution of watercourses in some countries (Bouwman et al., 2013). Forecasts suggest that the demand for animal-source food will further increase at a rate of 1.3% p.a. during the next decades, especially in developing countries (Alexandratos and Bruinsma, 2012). As a result, the environment pressure from animal production and animal manure will also increase, unless effective measures are taken to improve livestock productivity and manure utilization, and to reduce emissions.

There is great interest worldwide in techniques and management approaches that reduce N losses, without negative influence on animal productivity and farm profitability (e.g. Bittman et al., 2014). Adjusting the protein intake by the animals is one of the most cost-effective ways to improve livestock productivity and reduce N excretion and N emissions from manure management systems (Hou et al., 2015; Reis et al., 2015). Protein consist of amino acids which are essential building blocks of animal tissues and organs, and vital to the maintenance, growth, and reproduction of all animals. For precise animal feeding, information is needed about the contents and digestibility of the amino acids in the feed, to be able to match with the animal requirements for the specific amino acids, as function of animal category, age, sex, productivity and environmental conditions (McDonald et al., 2010). In practice though, most farmers manage the total protein content of the animal feed, often based on information about the content of crude protein (CP), which is a common measure of the protein content, but in general also include some 10% non-protein N. Supply of CP to animals in excess of their demands is excreted in urine and feces (henceforth manure); total N excretion and the associated NH_3 emissions from manure during storage tend to increase more than proportionally with the CP content of the diet (Portejoie et al., 2004).

Animal feeds with good quality protein, i.e., with all essential amino acids in the proper ratios are often scarce in developing countries, and often limit livestock production (Abegaz, 2005; FAO, 2003). In contrast, the protein contents of animal feeds in developed countries are often relatively high, as farmers often follow a “high input-high output” strategy, to avoid the risk of a decreased animal productivity (FAO, 2003; Kim et al., 2019). Intensively managed dairy farms tend to over-supply CP to dairy cows in their attempts to boost milk yield (VandeHaar and St-Pierre, 2006), although it is well-known that animal productivity does not increase further beyond a certain CP level (Colmenero & Broderick, 2006; Kerr & Kidd, 1999), and even may decrease milk yield because of the extra energy needed to get rid of the excess urea N via urine. Hence, oversupply of CP in animal feed results in a reduced N use efficiency, increased feed cost and thus a reduced marginal profit. Low-protein feeding (with or without supplementing specific amino acids) has therefore been promoted to increase farm profit and to reduce total N excretion and the associated NH_3 emissions from manure during storage and following application to land (Canh et al., 1998; Frank et al., 2002; Bittman et al., 2014).

Though detailed guidelines for animal feeding are available, there is often a relatively large variation between farms in mean protein content of the animal feed (Powell et al., 2008; Wang et al., 2014; Oenema and Oenema, 2021). Surpluses of protein in the animal feed may be reduced cost-effectively, provided there is accurate information available on the variations in protein content, composition and digestibility (Reis et al., 2015). However, in developing countries there is often little empirical data and information about the variation in actual protein content in farm practice. This holds also for China, which is the largest livestock producer and consumer in the world, mainly due to its large human population. This lack of accurate information hampers making accurate assessments of the role of livestock production in for example N pollution of the environment. Modelling studies often assume a mean value based on controlled condition research trials (e.g., Bai et al. 2013 & 2016; Zhang et al., 2019). Snap-shot farm surveys indicate however that there is a huge variation in CP content in practice, which is not well-understood (Powell et al., 2008; Wang et al., 2014; Qu et al., 2017). The need for accurate farm data is rapidly increasing because of the rapid increase in livestock production and the associated increase in manure N production and NH_3 emission burden (Bai et al., 2018). Accurate information is also fundamental for making recommendations to improve animal productivity, and for developing NH_3 emission inventories and NH_3 emission mitigation strategies at regional and national scales.

Livestock farmers are the key stakeholder in animal feeding management, and their knowledge about protein in animal diets and the factors influencing protein use is crucially important for effectively implementing low-protein feeding. Farmers' decision making is influenced by various factors, including their education (knowledge) and perception of the outcomes, especially to the financial outcomes (van Valkengoed & Steg, 2019). Apart from their social referents, policy requirements and availability of technical support may also influence the adoption of manure management techniques in general and low-protein feeding in particular. The attitude to perceived outcomes, subjective norms from social referents, and perceived controls from controlling factors, together, constitute the main structure of Theory of Planned Behaviour (TPB, Ajzen et al., 1991), which is a widely used framework to study farmers' agro-environment behaviour (e.g., Wang et al., 2018; Hijbeek et al., 2019). To our knowledge, no study has been conducted to explore farmers' perceptions on feeding strategies, such as low-protein feeding. In particular, there is as yet limited understanding about drivers and barriers for promoting such strategies in practice.

The aim of our study is to increase the understanding of the factors controlling the variations in feed use and CP content of the feed in livestock farms in China, and to understand farmers' perceptions about low protein feeding. We hypothesis that: i) CP content of animal diets greatly differs among livestock farms, especially in dairy farms; and ii) farmers' willingness to accept low protein feeding is mainly influenced by their social referents. We did farm visits to collect information on diet formulas and sample feedstuff in medium to large size dairy, pig and poultry farms. During the visits, farmers were interviewed face to face about their knowledge about crude protein and their perceptions of low protein feeding, using the framework of TPB. The farm visits were conducted in 2018 and 2019, but because of the outbreak of the African Swine Fever, interviews with pig farmers had to stop after visiting some 30 pig farmers. Therefore, only the results of dairy and poultry farms are reported here.

3.2 Materials and Methods

3.2.1 Conceptual model and farm survey

In the framework of the Theory of Planned Behaviour (TPB), human behaviour is believed to depend on three aspects: (1) their attitude toward the outcomes they expect to occur; (2) their perceived subjective norms from social referents; and (3) their perceived easiness or difficulty as influenced by controlling factors (behaviour control). Based on this framework, a two-step farm survey was conducted: first a qualitative step and second a quantitative step. The qualitative survey was conducted in September 2018 with a semi-structured questionnaire, to gain a basic insight into the feed and farm management practices and to identify relevant factors involved in low protein feeding. With a stratified random sampling approach, we visited 16 dairy farms, 22 pig farms and 13 poultry farms in Hebei province. The relevant factors identified are presented in Table S3.1, and these results were used as input for the second step.

For the second survey, we selected medium to large size ‘intensive farms’ as defined by IAESD and NIES (2009): operations with at least 100 dairy cows (stocked), 10,000 layer hens (stocked) and 50,000 broilers (slaughtered), because a rapidly increasing proportion of animals is housed in these farms (Bai et al., 2018). We selected four cities in Hebei and three in Shandong, with counties with more than 20 dairy farms and/or more than 20 poultry farms. One or two counties with the highest livestock density were selected within a city. The Animal Husbandry Bureaus of selected counties were then contacted to provide a list of addresses of livestock farms within those counties. We then contacted the farms and asked permission for conducting the survey and visit. Only one farm per village was selected (the first farm that accepted our request) to have geographical spread.

The second survey was conducted from December 2018 to May 2019, with the purpose to quantitatively evaluate the outcomes, social referents, and controlling factors, and to collect feed samples and information about feed use. A total of 141 dairy farms, 98 layer farms and 99 broiler farms were visited; main farm characteristics are given in Table S3.2. A structured questionnaire was used. Farmers were firstly asked about their background (age, education, etc), the farm, animal feeding practice, and manure management. Then, questions about the feed formulae, feed protein and their concerns related to protein were asked, followed by a quantitative valuation of factors. For the detailed questionnaire used, please see Table S3.3&S3.4. A comparable survey on the same farms was conducted to examine farmers' perceptions on manure management and treatment techniques (Tan et al., 2021)

3.2.2 Feed sample collection and analysis

For comparison, feed samples were collected from the replenished feed trough; samples were taken from several spots and depths, and then bulked (about half a kilogram fresh weight). Labels from bags of purchased feed compounds were also collected. Samples were dried at 65 °C for 48 hours until constant weight and packed in plastic bags in a laboratory in China. Samples were then shipped to and analysed at Eurofins Agro Laboratories in Wageningen (https://www.eurofins-agro.com/; Reijneveld et al., 2014) using standard and certified procedures.

3.2.3 Data analysis

Average values of all TPB factors examined in the survey were calculated based on the answers of the respondents. The 95% confidence interval was calculated as the average value $\pm 1.96 \times \frac{sd}{\sqrt{N}}$, in which sd is the standard deviation and N is the number of respondents. When this interval did not include 0, the average value was believed to be significantly different from zero. Significant positive values were believed to be drivers and significant negative values were believed to be barriers. An average ‘strength’ score below 3 was defined as a ‘potential driver’ or a ‘potential barrier’ (Hijbeek et al., 2019). To analyse the influence of farms’ and farmers’ characteristics on factors in the TPB, we used R programming language (R Core Team, 2015) with Spearman Rank correlation analysis (for that x and/or y is ranking type value), Pearson correlation analysis (for that x and y are both continuous type values), or one-way ANOVA analysis (for that x is factor type value).

3.3 Results and discussion

3.3.1 Farmers’ knowledge and concerns about protein in rations

The vast majority (74%) of dairy farmers based the ration of dairy cattle on advice from feed companies (Figure 3.1A), which is a common practice in intensively managed dairy farms relying on significant feed import (e.g. Dou et al., 2001). Even though also 74% of the dairy farmers stated that they were concerned about the crude protein (and energy) contents of the feed (Figure 3.1C), 76% of farmers did not know the CP level of the total mixed ration on their farm (Figure 3.1B). Decisions about feed protein content were also based on the perceived feed conversion ratio and the feed price (Figure 3.1D). Feed companies influenced medium-size farms most, also because the large farms (18% of dairy farms) had their own animal nutritionist; these nutritionists defined the concentrate/supplementary feeding and protein content (Figure 3.1A).

Also, 72% of the layer farmers based the ration of the layers on recommendations from feed companies which delivered the compound feed (Figure 3.1A). Layer farmers valued the brand of the feed and the feed conversion ratio most (Figure 3.1D). About one quarter of the layer farms mixed corn, soybean and a premix of vitamins, minerals and additives on the farm by themselves, based on their own experience (Figure 3.1A). About 50% of the layer farmers were concerned about the CP content of the ration (Figure 3.1C).

All broiler farms used contract farming, which means that the contracting companies managed the feeding of the animals in "remote control". Hence, contracting companies defined the composition of the rations, medicine to use, and the final weight of the broilers. Most of broiler farmers were concerned about the feed conversion ratio (53% of total response), as this defined their success, but they did not care much about the feed CP content (Figure 3.1C&D).

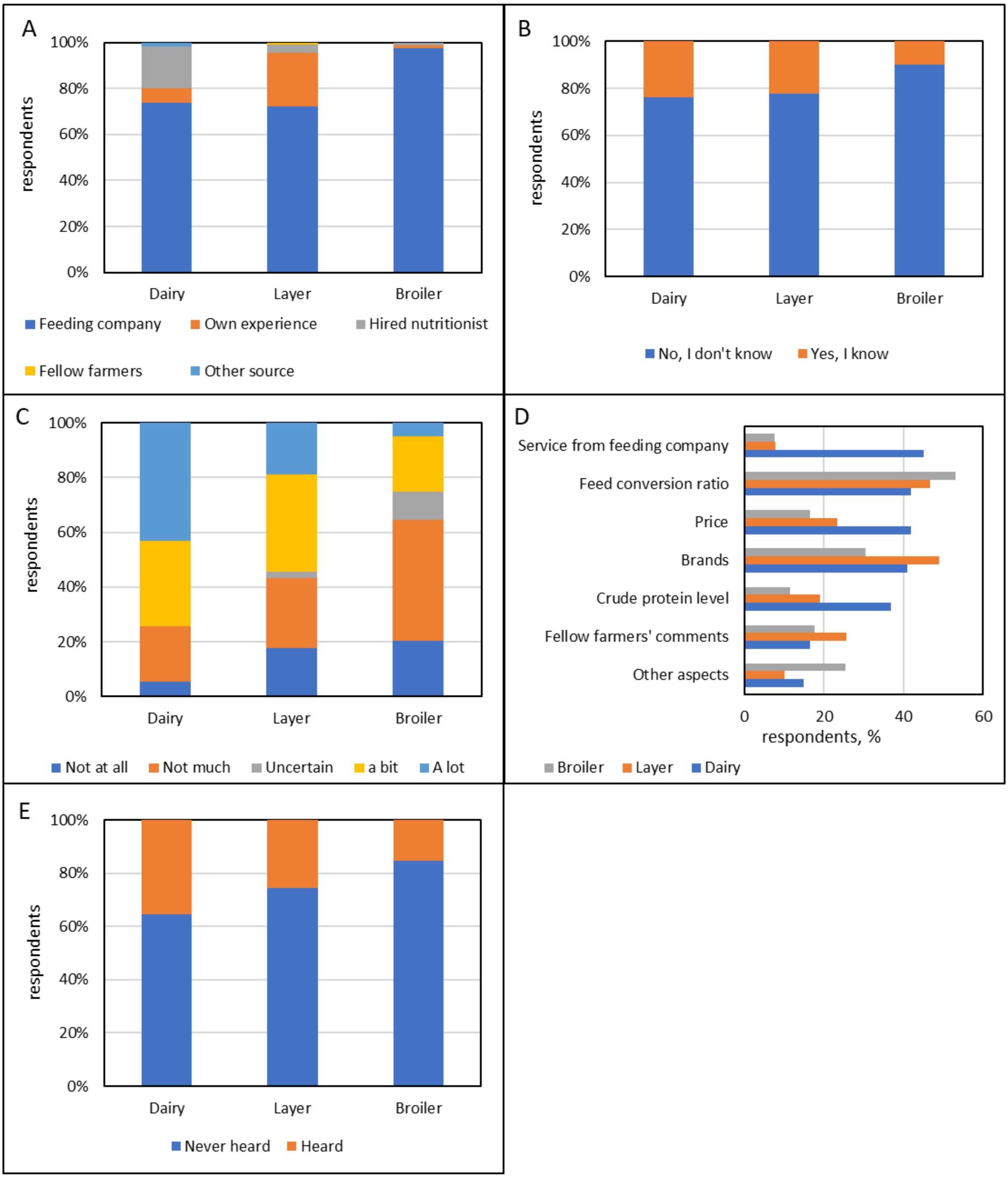

Figure 3.1. Farmers responses to the questions: A “Who is formulating the diet of your animals? ”; B “Do you know the crude protein level of the diet of your animals”; C “Are you concerned with the crude protein level of the diet of your animals”; D “What aspects do you pay special attention to when formulating the diet”; E “Have you ever heard about low protein feeding”.

Evidently, the majority of dairy and layer farmers relied on advice from feed companies, as regards the composition and CP content of the rations. In addition, feed companies usually provided additional services as part of Precision Livestock Farming, in particular to dairy farmers, including recommendations for the composition of the rations as a function of lactation and season, and observations on animal health. Different feed companies may provide different services, which strongly influenced farmers’ decisions on the feed company and the rations (Banhazi et al., 2012). The high degree of reliance on feed companies was found to be related to farmers’ low education (Jia et al., 2012; Figure S3.1) and to the high proportion of imported/purchased feed as a result of the limited area of arable farm land (Tan et al., 2021). Most farmers did not know much about the value of CP and about the optimal CP content of rations, as a function of animal productivity. Their knowledge and skill related to feed and feed management were mainly derived from training programmes organized by feeding companies or by the local animal husbandry bureau (data not shown). Farmers more open to attending these training programmes often have better management skills and better animal performance (Oenema et al., 2011; Castle et al., 1972). A small proportion of farmers (the very large farms) were financially powerful to employ professional managers with a university degree in animal nutrition and/or in veterinary sciences (Figure 3.1A).

3.3.2 Protein contents of rations of dairy cattle, layers and broilers

Laboratory analyses of 356 feed samples from dairy farms indicated that the mean CP content of the ration of milking cows was 159±20 g/kg DM (Figure 3.2). The average value is close to the target for low protein feeding suggested by Li et al., (2009). These authors indicated that this CP level did not negatively influence milk yield and milk CP content but significantly decreased N excretion compared to a ration with a CP content of 178 g/kg . With a CP content of 159 g/kg in the ration, 67% of the N intake was excreted in urine and faeces, and about 2.9 g N cow^{-1} d^{-1} was lost via NH_3 emission from the barn, i.e., about 10 kg N per cow per year (Li et al., 2009). The average CP level corresponded to a medium to high ambition level for low-protein animal feeding according to Bittman et al., (2014). Dietary CP content for calves, heifers and dry cows were 131±41, 119±25, 122±33 g/kg DM, respectively (Figure 3.2). The

CP contents of the rations of these three animal categories were even lower than the high ambition level to reduce NH_3 emission, according to Bittman et al., (2014).

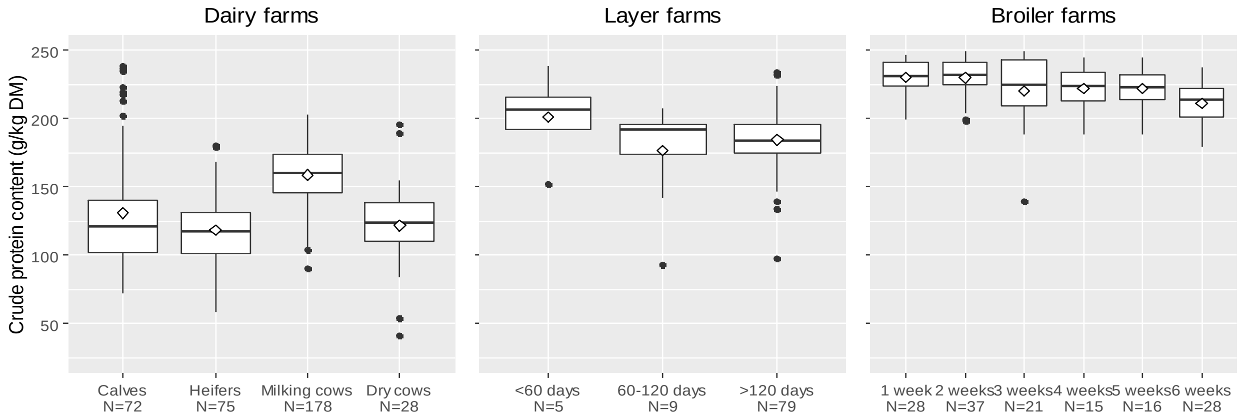

Figure 3.2. Box plots of crude protein content of feed diets of (a) dairy farms, (b) layer farms, and (c) broiler farms, in g per kg dry weight (DM). Boxes indicate the 25 percentile (lower border) and 75 percentile values (upper border), while the line in the box represents the median and the diamond the average crude protein content. Vertical lines indicate the 5 and 95 percentile values. The number of observations are indicated in the x-axis.

For chicks (younger than 60 days), pre-layers (60-120 days) and productive layers (older than 120 days), the CP contents of the diets were 211±39, 176±37, 184±22 g/kg DM (Figure 3.2). The information on the labels from purchased compounded feeds indicated that the feed CP contents were minimal 205, 155, and 161 g/kg FW (~13% water content, Figure S3.2) for these three categories, respectively. The CP content of the feed for young chicks was at the upper end of recommended ranges (NRC, 1994; Bittman et al., 2014). For hens in the pre-laying phase and for productive layers, the mean CP contents were in the middle of the recommended ranges (NRC, 1994; Bittman et al., 2014). Recommendations from Chinese national standards (SAMR & SA, 2018) for optimal CP contents tend to be somewhat higher than those from NRC (1994) and Bittman et al (2014). Results of 79 analysed feed samples for laying hens indicate that the CP content in 11 samples was below and in another 11 samples above the recommended levels according to the Chinese national standards (SAMR & SA, 2018).

All 99 broiler farms used compounded feed (from 38 different companies). Broiler farms decreased the feed CP content with broiler age, from 245±21 g/kg DM in the first week to 219±26 g/kg DM in the last week, from the analyses of 145 feed samples (Figure 3.2). The laboratory analyses of feed samples gave higher CP contents (4 to 26 g/kg DM) than indicated on the labels of purchased feed (Table S3.5). Hence, the information on the labels only provided a rough value (guaranteed content). The actual CP contents were at the lower end of the recommended ranges (NRC, 1994), i.e., 256 g/kg DM for 0-3 weeks and 222 g/kg DM for 3-6 weeks, but at the medium level according to Bittman et al (2014). Results of the analyses of 145 broiler feed samples indicated that 22 samples were below and 33 samples were above the Chinese national standard (SAMR & SA, 2018).

Bai et al., (2013 & 2016) and Xu et al., (2017) used relatively low dietary CP contents in their national-scale calculations of total N excretion and NH_3 emissions, for all animal categories, when compared to our estimations (Table S3.6). This suggests that their estimated N excretion and NH_3 emissions are possibly underestimated. In the scenario studies conducted by Zhang et al (2019), the CP content of the ration of dairy cattle was decreased from 170 g/kg DM to 150 g/kg DM, so as to reduce NH_3 emissions by 24%. Evidently, the baseline CP content (170 g/kg DM) used by Zhang et al., (2019) and Gao et al., (2013) was much higher than our mean estimates (159 g/kg DM), which suggests overestimation of the NH_3 emission abatement potential through low-protein animal feeding. Our estimates provide up-to-date estimates of the CP content in rations, and therefore provides a basis for more accurate assessments of the NH_3 emission abatement potential of low-protein animal feeding, and of the N footprint of livestock products.

Even though the rations were determined by feed companies, there were large differences among similar farm types in the CP content of rations. This may be attributed to a lack of national standards and a lack of data and information exchange between companies and between farmers (Wang et al., 2010). Feed companies provide recommendations based on their own knowledge and marketing concepts. Currently, there are thousands of feed companies in China, and the competition is often fierce. Smaller companies often do not have the resources to examine and test the recommended rations; they may adjust the ration also according to farmers' purchasing power, their perceptions about risks and risk avoidance, and the accessibility to specific feed ingredients (Enting et al., 2010).

3.3.3 Relationships between feed CP content and animal productivity

Relationships between the CP content of the ration of dairy cows and milk yield per cow are shown in Figure 3.3. The relationships were weak as reflected by the low regression coefficients (<0.12) and the low correlation coefficients (R^2 <0.019), independent of the expressions of CP content and milk yield. This result contrasts with the results of several experimental studies which suggest that milk yield increases with the CP content of the ration until the CP content reaches a level of about 16.5% (e.g., Frank& Swensson, 2002; Colmenero& Broderick, 2006). This contrast may be attributed to the multiple noise interferences in our study. In experimental studies, almost all factors (e.g., energy level of the feed, age and lactation stage) have to be similar except the CP content of the ration. However, other controlling factors than the CP content of the ration may have differed in our study. For example, milk yield is measured in experimental studies, while milk yield in our study was derived from farmers' information. Further, only average milk yield data of the farm were available, and used in Figure 3, but visual observations of the herds suggested that there was a relatively large variation in milk production per cow within herds. Our snap-shot feed sampling approach likely provided accurate assessments of the mean CP content of the ration during the survey period, because essentially all farms used whole-mixed rations, suggesting that daily to weekly variations in the composition of rations were small. Most farms differentiated the feed composition according to low-productive and high-productive cows, and without protein supplementation to highly productive cows (no precision nutrition). Hence, our dataset was not well suitable to derive a relationship between CP content of the ration and milk yield per cow. It may not be excluded that highly productive cows on some farms underperformed during early stages of the lactation with an adequate mean CP content of the ration (159 g/kg), while low productive cows were oversupplied with protein at that level.

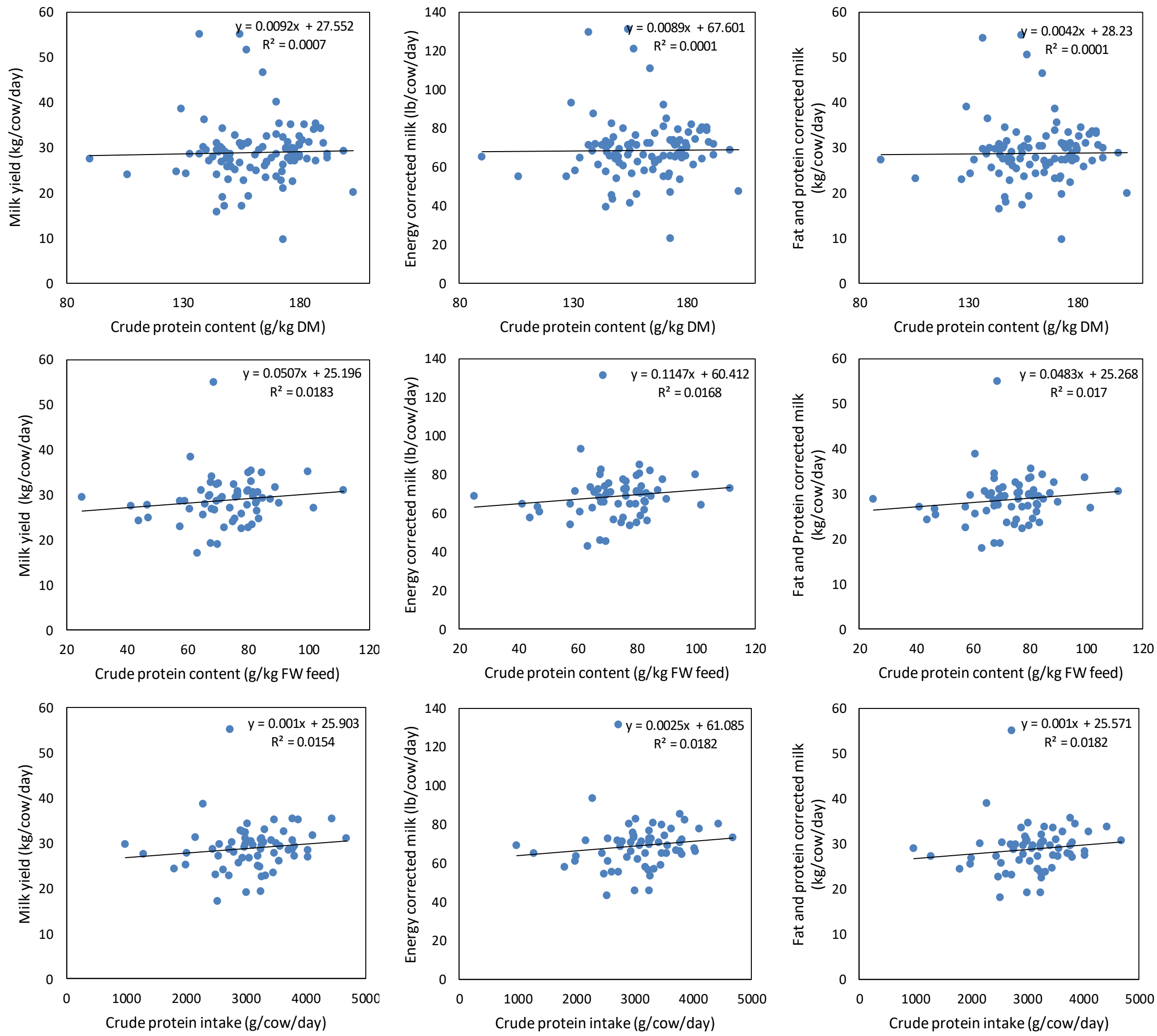

Figure 3.3. Relationships between crude protein content and intake on milk yield, energy corrected milk and fat and protein corrected milk. Linear correlation coefficients were <2% (not shown).

Figure 3.4 shows the relationship between CP content of the ration and egg yield. Again, no clear and significant relationship was found between CP content of the ration and egg yield at farm level, despite the wide variation in CP contents. Previous experimental studies revealed significant positive relationships between feed protein contents (from 143 g/kg to 181 g/kg) and egg yield (McDonald, 1979). The lack of a significant relationship in our study is likely related to the multiple factors that affect this relationship, including hen breed and productive stage, feed management, inhouse climate and conditions, and animal health (Rizzi & Chiericato, 2005; Cunningham et al., 1960; Fouad et al., 2016). These factors were different at different farms.

Moreover, egg yields were based on farmers' estimates for the whole laying period, based on an average number of eggs per hen and average egg weight.

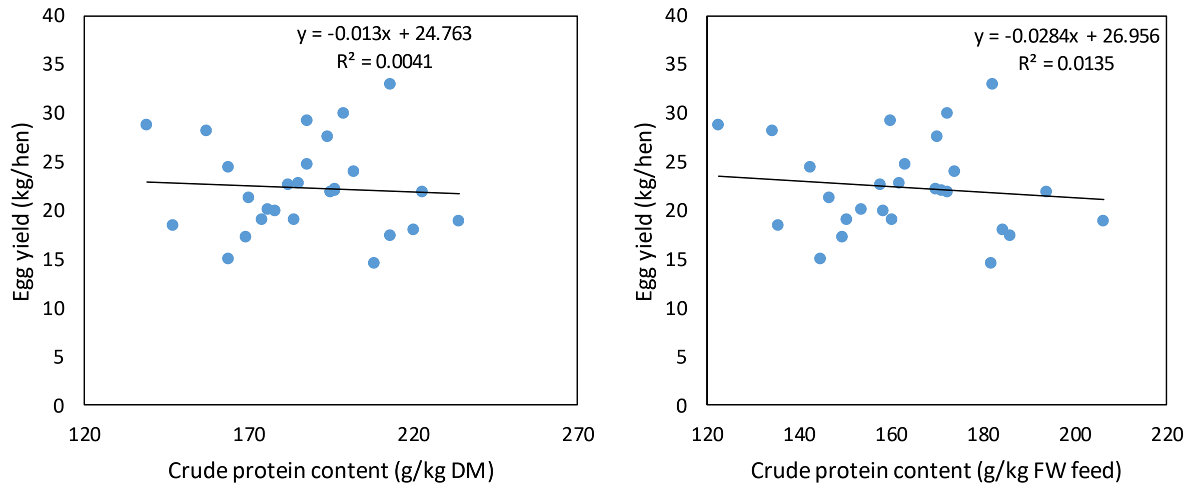

Figure 3.4. Relationships between crude protein content and intake and egg yield. Linear correlation coefficients were <2% (not shown).

Relationship between CP content of the ration and productivity of broilers cannot be assessed accurately due to lack of accurate productivity data and the narrow range of CP contents.

3.3.4 Farmers' perceptions of low protein feeding

Most dairy farmers (65%) had never heard about low-protein animal feeding (Figure 3.1E). After given explanation, 87% of the farmers responded to the other questions related to low-protein feeding, while 13% denied to answer the questions. Dairy farmers believed that low-protein rations may improve animal health, save feed cost and reduce emissions from manure (Figure 3.5A), but were also worried about the effects of low-protein rations on farm performance and farm profit.

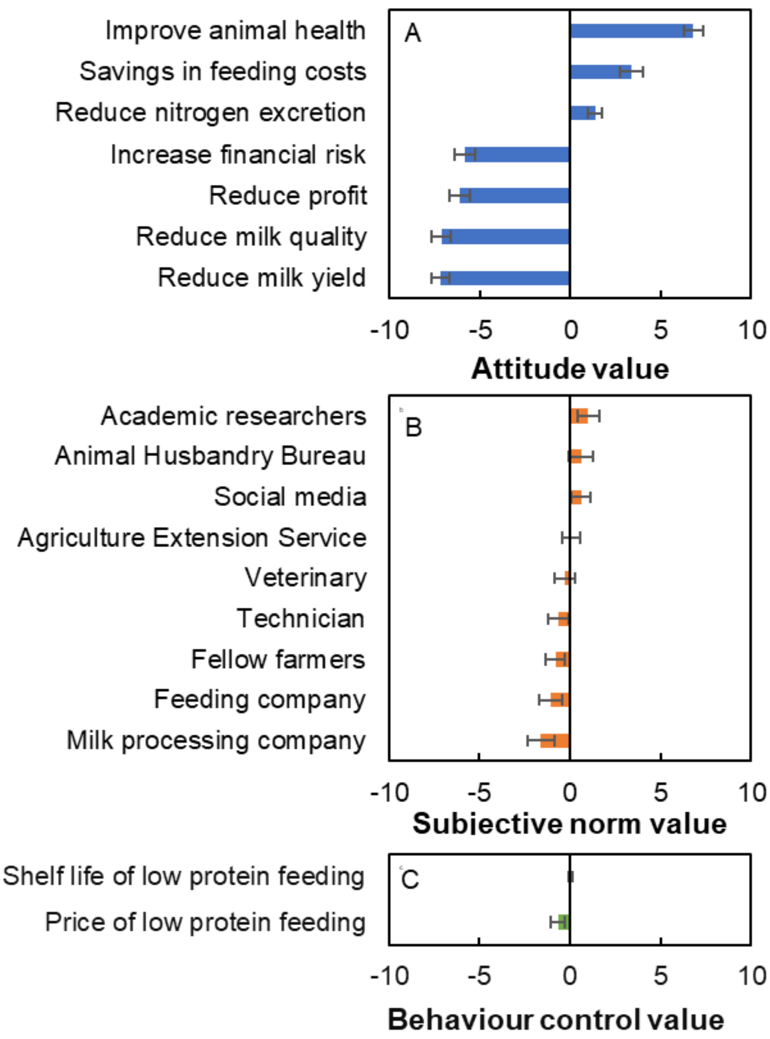

Figure 3.5. Dairy farmers' mean valuation to low crude protein feeding: A attitude to outcomes; B subjective norms; C perceived controlling factors. Lines indicate 95% confidence interval (N=122).

Dairy farmers believed that milk processing companies held the most negative attitude to low-protein rations, because milk processing companies prefer milk with high milk protein content (Figure 3.5B). Further, farmers believed that feeding companies, fellow farmers and workers were also not in favour of low-protein feeding. These perceptions of social referents appear stronger than reported before about the influences of milk processing companies (Fuller et al., 2005) and feed companies (Dou et al., 2001) on dairy farm management in the USA. Oenema et al., (2011) reported about the importance of academic researchers and fellow farmers for decisions related to feed composition and protein intake of dairy cows on pilot farms in The Netherlands. Our results indicate that the influence of social referents on farmers' views related to animal feeding decreased in the order milk processing company > feeding company > academic researchers > fellow farmers > other referents (Figure 3.5B). The availability and price of low-protein feed were seen as barriers for low protein feeding; farmers believed that low-protein feed was not available from feed companies (Figure 3.5C).

Most layer farmers (~75%) also had never heard about low-protein feeding (Figure 3.1E). Yet, 90% of the farmers responded to the other questions related to low-protein feeding after we explained the basic idea of low protein feeding. Farmers were worried that animal health and egg production would be influenced by low protein feeding. They also believed that low protein rations would reduce feed cost (Figure 3.6A). The worries were stronger for hot summers when animals tend to eat less and low protein rations may induce amino acid deficiencies (Furlan et al., 2004). Three referents were identified as supportive to low protein feeding and 4 referents were identified as against low protein feeding (Figure 3.6B). Social referents against low protein rations included fellow farmers, egg purchasers, and feeding companies; these referents have closer relationships and more interactions with layer farmers than referents who support low protein feeding. Further, farmers identified no significant controlling factors, either as driver or barrier (Figure 3.6C).

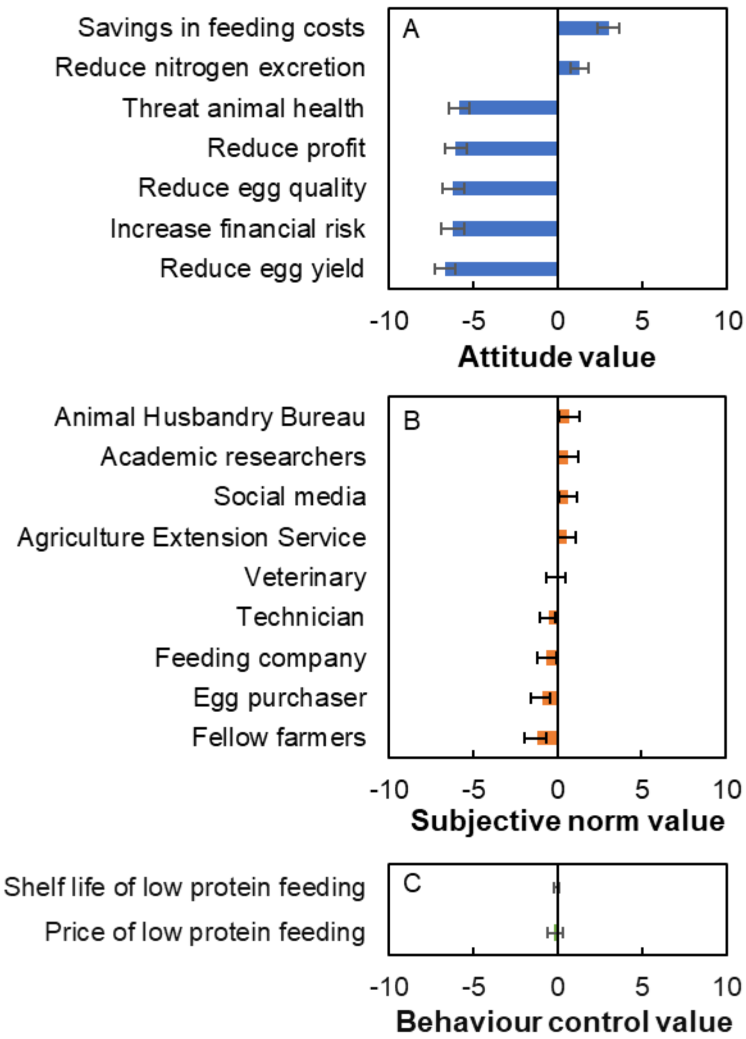

Figure 3.6. Layer farmers' mean valuation to low crude protein feeding: A attitude to outcomes; B subjective norms; C perceived controlling factors. Lines indicate 95% confidence interval. (N=90).

As much as 85% of broiler farmers had never heard about low protein feeding (Figure 3.1E). Broiler farmers used feed prescribed by the contracting companies. They did not know much about protein. They believed that low protein feeding may save feed cost, but has negative effects on animal health, and in the end on farm profit (Figure 3.7A). They believed that the contracting company and fellow farmers were not supportive to low protein feeding (Figure 3.7B). Farmers did not identify any controlling factor as significant driver or barrier for low protein feeding (Figure 3.7C).

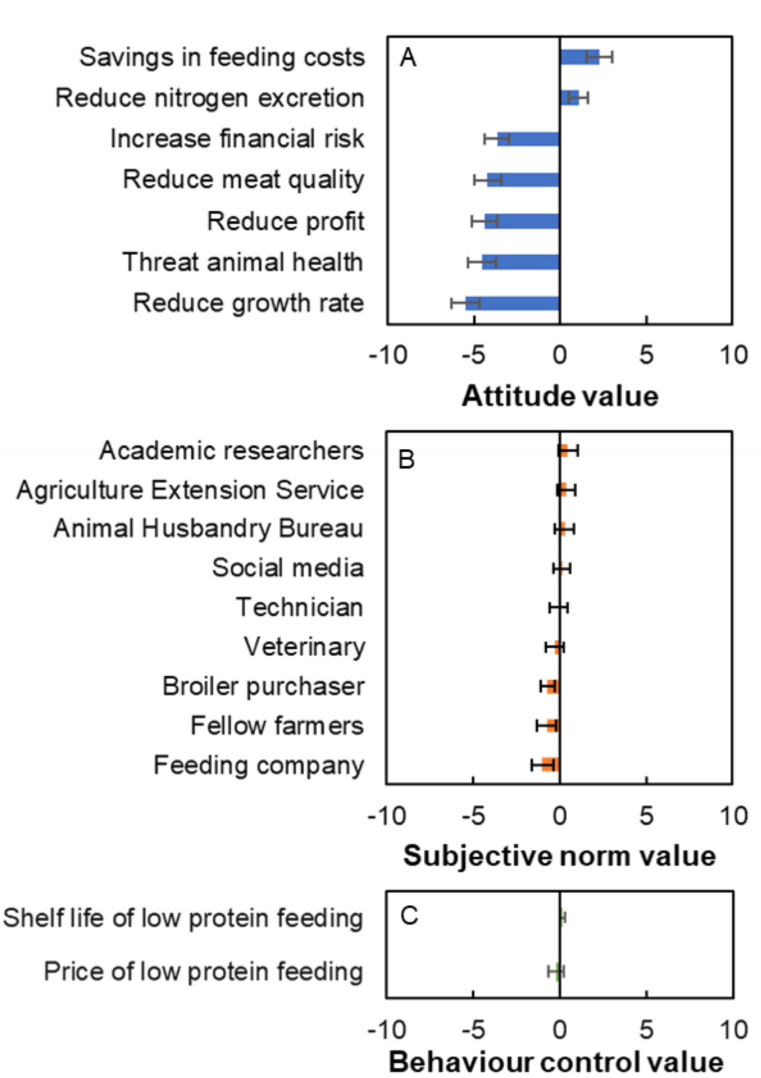

Figure 3.7. Broiler farmers' mean valuation to low crude protein feeding: A attitude to outcomes; B subjective norms; C perceived controlling factors. Lines indicate 95% confidence interval. (N=79)

Summarizing, social referents had a strong influence on farmers' perceptions of low protein feeding, while controlling factors were not important. Most farmers (dairy, layer and broiler farmers) had little knowledge about protein and the protein content of the rations, although they indicated that the protein in the ration was a concern. Feed companies and/or contracting (processing) companies often decided about the composition and protein content of the ration. Many of these companies also had a role in monitoring animal health and productivity. This indicates that feed and contracting companies have an important role to play whenever low protein feeding is introduced as a measure to lower the N excretion by livestock and/or the NH_3 emissions from livestock manures.

3.3.5 Relationships between farmers' characteristics and farmers' intention to use low-protein rations

Relationships between farms' and farmers' characteristics and farmers' intention to use low protein rations are presented in Tables S3.7-S3.9. Farmers from large dairy farms had greater intention to use low protein rations than farmers from small dairy farms. In addition, farmers using rations with a low CP content (<155 g/kg DM) had significantly higher intention to use low protein rations than farmers using rations with a relatively high CP content (>165 g/kg DM). Furthermore, farmers' intention to use low protein rations was significantly correlated with their evaluations of outcomes and perceptions on social referents (Tables S3.7-S3.9). Large farmers gave higher scores to the outcome 'saving feed cost' than small farmers, but lower scores to the outcome 'reducing N excretion'. Even though well-educated farmers have been found to be more concerned about new techniques (Zhao et al., 2009), the influence of dairy farmers' characteristics (including education) on the intention to use low protein rations was not statistically significant in our study.

The intention of layer farmers to use low protein feeding was not related to farmers' characteristics (Table S3.8). The intention was positively correlated to the outcome "saving feed cost", the social referents "veterinarians", and the controlling factor "price of low protein feed"; hence, a relatively low price of low protein feed and a positive attitude of veterinarians would stimulate the adoption of low protein feeding. Egg yield and farmers' experience were correlated to their valuation of social referents and controlling factors (Table S3.8). Interestingly, relatively old farmers used lower protein in rations than young farmers.

The intention of broiler farmers to use low-protein feeding was also not related to farmers' characteristics (Table S3.9), because the intention to do so was low, as the rations were defined by contracting companies. Well-educated and experienced farmers and farmers of large farms held a relatively negative attitude towards social referents. Evidently, broiler farmers behaved as contracting farmers; there was much less diversity among broiler farmers than among layer farmers (Table S3.2 and Figure 3.1). Contracting makes animal husbandry and feeding practices more similar (Sheppard et al., 2009).

3.3.6 Composition of the rations and effects on N excretion

Most farmers had little knowledge about optimal protein levels in animal feed and relied on the advice of companies (Figure 3.1a). Nonetheless, the dietary CP content of dairy and layer rations varied greatly among farms. This is mainly because there are thousands of feed companies in China and no strict and harmonized guidelines; many feed companies have their own diet formulations (Enting et al., 2010). There is also a large heterogeneity among farms in farm and animal management and risk avoidance strategies (Komarek et al., 2015). In addition, farmers' accessibility to different feeding materials also differ. The 93 dairy farms used in total 27 kinds of feeding materials. Maize silage was the dominant dry matter provider, contributing on average 34% to the total amount of dry matter in the rations of calves, heifers and milking cows, and 29% to the total amount of dry matter in the rations of dry cows. Commercial bag feeding (including concentrates, mineral supplements, vitamins) provided another 25% to the total amount of dry matter in the rations (Table S3.10).

Less than 20% of the layer farms used full compounded feed, more than 80% of the farms put the feed ingredient together and mixed these by themselves (Table S3.11). Maize and soybean meal were the main constituents (maize > 60%; soybean meal >24%). On average, the CP content in dairy and broiler diets were close to level of low protein feeding, suggested by NRC (1994), NRC (2001) and Bittman et al. (2014). The fairly good CP contents may be related to farmers' high concern to the feed conversion ratio: feed companies providing unbalanced feed may result in farmers switching to other feed companies.

Based on the statistical data of the farms and the mean CP content of the ration, we estimated the total N excretion on each farm, using the equation $N_{excretion} = N_{intake} - N_{retention}$. The mean annual N excretion was estimated at 61.0 Mg N per dairy farm, 35.9 Mg N per layer farm and 26.5 Mg N per broiler farms (Figure S3.3). The excretion corresponded to 79, 69, and 51% of the total N intake, which was 77, 52 and 52 Mg N per farm per year, for dairy, layer and broiler farms, respectively. The other 21%, 31% and 49% of the total N intake were retained for maintenance or growth or animal product (i.e., milk and egg). The excretion rates of layers and broilers were much lower than results from Gao et al., 2013 (i.e., 76.8% excretion rate of both layers and broilers), because comparably lower feed CP contents were found and used in our study. Based on additional analysis of experimental data from 39 studies involving 156 treatments showed that with 1% increase in dietary CP, N excretion increases on average by 31 g/cow/day (data shown in Figure S3.4a), mainly driven by the urinary N excretion (Figure S3.4b&c), which is the major source of NH_3 emission. Follow up NH_3 emissions in the manure management chain accounts for about 15%, 28% and 18% of the total N excretion, for dairy, layer and broiler farms, respectively (Velthof et al., 2012).

3.4 Conclusions

The protein content of the ration of livestock affects livestock productivity, N excretion, and the NH_3 emissions and other emissions from livestock manures. There is a narrow optimal range, which depends on livestock category, age and productivity, but also on feed ingredients and feed availability. We interviewed 338 dairy and poultry farmers in the North China Plain, where the livestock sector is booming and where livestock manures create large environmental problems. We found that these farmers had little or no knowledge about protein in feed and about the environmental impacts of protein overfeeding. Most of them had not heard about low-protein feeding as a management technique to lower N excretion and the NH_3 emission potential. Farmers simply followed the recommendations of the feed or contracting companies, although large livestock farms tend to have their own university-trained animal nutritionist. There are many different feed and contracting companies, which often have their own feed formulae, and as a result there is a relatively wide variation among farms in the crude protein content of the ration. The mean crude protein content of the ration of dairy cows was 159±20 g/kg DM. The mean CP content of the ration of productive layers was 184±22 g/kg DM, and that of broilers ranged from 245 g/kg in the beginning phase to 219 g/kg DM in the later stages. These data can be used as base for accurate regional inventories of N emissions from livestock production.

Our study implies that any attempt to introduce low-protein animal feeding in livestock production in China requires the active involvement of feed and contracting companies. There is a huge diversity among dairy and layer farms, and there is also a huge diversity among feed and contracting companies, with little uniformity in feed recommendations and formulations. Our study also indicates that some recent studies about NH_3 emissions from livestock farming in China may not have used correct feed protein contents in baseline scenarios. Apart from the ongoing governmental support to livestock farmers for improving manure management techniques, there is a great need for supporting farmers to increase the awareness and knowledge level related to animal feeding and the impacts of animal feeding on manure composition and associated environmental impacts.

Acknowledgement

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Supplementary information Chapter 3

Table S3.1 Summary of the results of the first, semi-structured survey, related to farmers' perceptions of possible outcomes, social referents, and controlling factors related to the use of low protein animal feeding.

Factors	Times mentioned*	Aspects involved
Outcomes		
• Improve animal health	16	Financial
• Save feeding cost	3	Financial
• Reduce nitrogen excretion	2	Environmental
• Increase financial risk	3	Financial
• Reduce profit	4	Financial
• Reduce product quality	7	Financial
• Reduce product yield	15	Financial
Social referents		
• Academic researchers	3	Social
• Animal Husbandry Bureau	0	Social
• Social media	2	Social
• Agriculture Extension Service	0	Social
• Veterinary	3	Social
• Technician	4	Social
• Fellow farmers	13	Social
• Feeding company	14	Social
• Product purchaser	5	Social
Controlling factors		
• Price of low protein feeding	2	Financial
• Shelf life of low protein feeding	1	Financial

Table S3.2. Overview of the surveyed livestock farms

Dairy farms (N=141)		Unit
Breeds		
• Holstein	140	farms
• Jersey	4	farms
• Fleckvieh	4	farms
Total mix ration percent		
• Milking cow	100	%
• Non-milking cow	97	%
Mean herd size	484±742	LSU/farm
Number of milking cows	341±539	Heads/farm
Number of young stocks	308±406	Heads/farm
Milk yield	29.7±9.2	kg/cow/day
Layer farms (N=98)		
Breeds		
• Lohmann	13	farms
• Hyline	62	farms
• ISA	4	farms
• Chinese local breeds	26	farms
Housing		
• Cage housing	100	%
• Free range	0	%
Feed		
• Self-mixing	82	%
• Full compound	18	%
Ad libitum access to feed	100	%
Mean herd size	35±64	thousand birds/farm
Egg yield	21±5	kg egg/hen
Broiler farms (N=99)		
Breeds		
Fast and small breed	15	farms
Fast and big breed	74	farms
Slow grow breed	13	farms
Feed		
• Self-mixing	0	%
• Full compound	100	%
Ad libitum access to feed	100	%
Housing		
• Cage housing	88	%
• Free range with litter floor	12	%

Table S3.3. Questions used to understand farmers' knowledge of feed compositions and animal feed protein contents.

1. What is the source of your animal diet formula? (single option)
A. From the premix feeding company B. From my own experience C. From our hired nutritionist D. By referring to fellow-farmers E. Other source.
2. Do you know the crude protein content of the diet of your animals? (single option) A. Yes, I know B. No, I don't know
3. Are you concerned with the crude protein level of the diet of your animals? (single option) 1-Not at all 2-Not much 3-Uncertain/Not sure 4-A bit 5-A lot
4. What aspects do you pay special attention when you decide the feed to use? (multiple option) A. Service from feeding company B. Feed conversion ration C. Price D. Brands E. Crude protein level F. Judgement from fellow farmers G. Other aspects
5. Have you ever heard about low protein feeding? (single option) A. Yes, I have heard. B. No, I have never heard.

Table S3.4. Questions in the second, structured questionnaire used to quantify farmers' valuation for outcomes, social referents, and controlling factors of low protein animal feeding.

What is your intention to (continue) use low protein feeding in following three years?	1=no intention; 5=high intention	
A. Outcomes		
1. If 1=not possible and 5= very well possible, to which extent do you think by low protein feeding, the following outcomes will occur (belief strength)		
2. If 1=very bad and 5=very good, to which extent do you evaluate the goodness of the following outcomes (outcome valuation)		
	Belief strength	Outcome valuation
Save feeding cost		
Reduce egg yield		
Reduce egg quality		
Reduce profit		
Increase financial risk		
Improve animal health		
Reduce nitrogen excretion		
B. Social referents		
1. If 1=very against and 5=very supportive, to which degree do you think the following referents is toward using low protein feeding? (normative belief)		
2. If 1=not willing at all and 5=very willing, to which extent are you willing to comply with the referent's view? (motivation to comply)		
	Normative belief	Motivation to comply
Feeding company		
Egg purchaser		
Technician		
Fellow farmers		
Veterinary		
Agriculture Extension Service		
Animal Husbandry Bureau		
Academic researchers		
Social media		
C. Controlling factors		
1. How to you evaluate the following factors here? (control strength)		
2. To what extent the factor is important to influence your adoption of low protein feeding? (control power)		
	Control strength	Control power
Price of low protein feeding	1=very high, 5=very low	1=not important; 5=very important
Shelf life of low protein feeding	1=very short, 5=very long	1=not important; 5=very important

Table S3.5. Dry matter content and CP content of broiler feeds over a six weeks. Information derived from feed labels, from feed companies.

	1 week	2 weeks	3 weeks	4 weeks	5 weeks	6 weeks
Dry matter content (g/kg feed)	860±2	860±2	861±2	860±2	860±1	860±1
CP content (g/kg feed)	207±9	207±8	202±7	187±9	181±17	166±18
Observations (number)	42	46	33	36	34	14

Table S3.6. Crude protein (CP) content used in simulation studies and comparison with our sample analysis (unit: g/kg DM)

	Gao et al. (2007)	Bai et al. (2013)	Bai et al. (2016)	Xu et al. (2017)	Zhang et al. (2019)	Our results
Dairies						
• Calves		105	110			131±41
• Heifers		132	130			119±25
• Cows	170	140	145	105	170	159±20
Layers						
• Pre-laying hens			180			176±37
• Productive hens			170	123		184±22
Broilers						
• Starter			200			245±21
• Grower			170			
• Finisher			150			219±26

Table S3.7. Influence of dairy farms' and farmers' characteristics on farmers' intention to use low-protein feeding and on their evaluation about the outcomes, social referents and controlling factors. Orange colour indicates Spearman correlation analysis; green colour indicates ANOVA analysis; blue colour indicates Pearson correlation analysis. Dark colour indicates P<0.05 and light colour indicates P>0.05.

		Farm scale			Milk yield and quality				Farmers' characteristics				CP behaviour	
	Intention	Animal heads	LSU	Milking cows	Milk yield	Milk fat	Milk protein	FPCM	Identity	Experience	Age	Education	CP content	CP content as factor
Intention	1	0.36	0.34	0.26	0.01	0.11	0.08	0.01	P=0.735	0.03	-0.04	P=0.376	-0.05	P=0.009
CP of DM	-0.05	0.06	0.05	0.02	0.03	0	-0.13	0.05	P=0.874	0	-0.06	P=0.281	1	
CP of DM-as factor	P=0.009	0.05	0.04	0.02	0.1	0.09	-0.34	0.12	P=0.956	-0.08	-0.01	P=0.112		1
Outcomes														
• Save feeding cost	0.42	0.32	0.34	0.26	-0.12	0.23	0.1	0	P=0.618	0	-0.02	P=0.604	0.04	P=0.955
• Reduce milk yield	0.34	0.05	0.05	-0.06	0.07	0.1	0.05	0.10	P=0.718	0.13	0.09	P=0.537	0.08	P=0.987
• Reduce milk quality	0.32	0.13	0.12	0.04	0.07	0.09	0.03	0.04	P=0.525	0.12	-0.08	P=0.341	0.04	P=0.845
• Reduce profit	0.15	-0.1	-0.12	-0.09	-0.13	-0.09	0.05	-0.12	P=0.385	-0.04	-0.03	P=0.715	-0.12	P=0.412
• Increase financial risk	0.05	-0.14	-0.15	-0.1	-0.1	0.07	0.18	-0.06	P=0.881	-0.11	-0.05	P=0.738	-0.12	P=0.278
• Improve animal health	-0.22	0.02	0.02	0.1	-0.05	0.03	0.11	-0.05	P=0.212	-0.04	-0.17	P=0.533	-0.12	P=0.297
• Reduce nitrogen excretion	-0.13	-0.31	-0.3	-0.18	-0.02	-0.15	0	0.04	P=0.516	0.058	-0.02	P=0.530	-0.08	P=0.508
Social referents														
• Feeding company	0.2	-0.02	-0.02	-0.01	-0.04	-0.16	-0.05	0.09	P=0.315	0.075	-0.07	P=0.323	0.09	P=0.015
• Milk processing company	0.31	0.05	0.06	0.12	-0.18	0.01	0.06	-0.07	P=0.191	0.02	-0.08	P=0.076	-0.05	P=0.154
• Technician	0.39	-0.1	-0.11	-0.06	-0.14	-0.04	0.09	-0.01	P=0.11	0.16	0.03	P=0.981	0.05	P=0.25
• Fellow farmers	0.27	-0.01	-0.01	0.02	-0.15	0.01	0.08	-0.05	P=0.076	0.17	0	P=0.635	0.06	P=0.247
• Veterinary	0.24	0	-0.01	0.01	-0.08	0.06	0.16	0.05	P=0.067	0.14	0.02	P=0.913	0.05	P=0.687
• Agriculture Extension Service	0.26	-0.1	-0.11	-0.07	-0.03	0	0.13	0.10	P=0.574	0.14	0.1	P=0.701	-0.02	P=0.212
• Animal Husbandry Bureau	0.17	-0.15	-0.17	-0.18	-0.01	-0.11	-0.03	0.09	P=0.974	0.01	0.11	P=0.825	0.07	P=0.974
• Academic researchers	0.17	-0.12	-0.12	-0.08	-0.04	0	0.16	0.15	P=0.872	0.01	0.12	P=0.897	0.05	P=0.317
• Social media	0.23	-0.08	-0.09	-0.05	0.12	-0.02	0.15	0.22	P=0.621	0.04	0.05	P=0.899	0.01	P=0.701
Controlling factors														
• Price of low protein feeding	0.16	0.13	0.14	0.15	-0.12	-0.04	-0.01	-0.09	P=0.013	0.19	-0.02	P=0.729	-0.02	P=0.496
• Shelf life of low protein feeding	-0.04	-0.02	-0.03	0.03	-0.1	0.03	0.1	-0.07	P=0.751	0.04	-0.01	P=0.322	-0.17	P=0.424

Table S3.8. Influence of layer farms' and farmers' characteristics on farmers' intention to use low-protein feeding and on their evaluation about the outcomes, social referents and controlling factors. Orange colour indicates Spearman correlation analysis; green colour indicates ANOVA analysis; blue colour indicates Pearson correlation analysis. Dark colour indicates P<0.05 and light colour indicates P>0.05.

		Farm characteristics		Farmers' characteristics				CP behavior	
	Intention	Stocked chicken	Egg yield	Identity	Experience	Age	Education	CP content (regarding DM)	CP content (regarding FW)
Intention	1	0.01	-0.07	p=0.75	0.21	0.04	p=0.852	-0.02	0.01
CP content (regarding DM)	-0.02	-0.04	-0.05	p=0.523	-0.24	-0.37	p=0.348	1	
CP content (regarding FW)	0.01	-0.03	-0.08	p=0.59	-0.25	-0.37	p=0.373		1
Outcomes									
• Save feeding cost	0.36	0	0.09	p=0.602	0.04	-0.03	p=0.21	0.01	-0.04
• Reduce egg yield	-0.02	0.13	0	p=0.97	-0.07	-0.18	p=0.321	-0.06	-0.03
• Reduce egg quality	0	0	0	p=1	0	0	p=1	0	0
• Reduce profit	0	0	0	p=1	0	0	p=1	0	0
• Increase financial risk	0	0	0	p=1	0	0	p=1	0	0
• Improve animal health	0	0	0	p=1	0	0	p=1	0	0
• Reduce nitrogen excretion	0.09	0	-0.12	p=0.213	-0.05	-0.01	p=0.562	-0.07	-0.04
Social referents									
• Feeding company	0.14	0.01	-0.35	p=0.62	0.16	0.04	p=0.792	0.01	0
• Milk processing company	0.12	-0.11	-0.08	p=0.701	0.13	-0.03	p=0.596	0.18	0.18
• Technician	0.1	-0.05	-0.18	p=0.883	0.14	0.11	p=0.943	-0.02	-0.04
• Fellow farmers	0.1	-0.15	-0.11	p<0.01	0.04	-0.07	p=0.187	0.14	0.12
• Veterinary	0.21	-0.1	-0.18	p=0.205	0.09	0.01	p=0.547	0.1	0.1
• Agriculture Extension Service	0.1	-0.01	-0.04	p=0.938	0.22	0.13	p=0.551	0.2	0.16
• Animal Husbandry Bureau	0.13	0	-0.03	p=0.383	0.12	0.07	p=0.767	0.15	0.13
• Academic researchers	0.11	0.01	-0.1	p=0.905	0.21	0.15	p=0.75	0.2	0.16
• Social media	0.16	-0.01	-0.05	p=0.914	0.2	0.02	p=0.676	0.3	0.27
Controlling factors									
• Price of low protein feeding	0.22	-0.09	0.05	p=0.763	-0.07	-0.14	p=0.117	0.13	0.13
• Shelf life of low protein feeding	-0.01	0.12	0.32	p=0.962	-0.26	-0.17	p=0.406	0.09	0.11

Table S3.9. Influence of broiler farms' and farmers' characteristics on farmers' intention to use low-protein feeding and on their evaluation about the outcomes, social referents and controlling factors. Orange colour indicates Spearman correlation analysis; green colour indicates ANOVA analysis; blue colour indicates Pearson correlation analysis. Dark colour indicates P<0.05 and light colour indicates P>0.05.

	Intention	Farm characteristics		Farmers' characteristics			
		Stocked chicken	Meat yield	Identity	Experience	Age	Education
Intention	1	-0.04	-0.21	p=0.623	-0.19	-0.15	p=0.938
Outcomes							
• Save feeding cost	0.09	-0.07	-0.15	p=0.018	-0.21	-0.08	p=0.659
• reduce chicken weight	0.21	-0.3	-0.01	p=0.066	-0.12	0	p=0.121
• reduce meat quality	0.03	-0.12	0.18	p=0.136	0.02	0.03	p=0.711
• reduce profit	0.17	-0.12	0.07	p<0.01	-0.06	0.09	p=0.112
• Increase financial risk	0.2	0	0.22	p<0.01	0	0.16	p=0.23
• Improve animal health	-0.12	-0.22	0.07	p=0.199	-0.08	-0.04	p=0.96
• reduce nitrogen excretion	-0.13	-0.04	0.29	p=0.285	0.12	0.16	p=0.492
Social referents							
• Feeding company	0.2	-0.2	-0.09	p=0.027	-0.24	0.19	p=0.066
• Broiler processing company	0.12	-0.2	-0.09	p=0.457	-0.25	0.04	p=0.117
• Technician	0.06	-0.37	0.09	p=0.119	-0.04	0.15	p=0.166
• Fellow farmers	0.21	-0.28	-0.07	p=0.377	-0.2	0.07	p=0.094
• Veterinary	-0.11	-0.29	0.13	p=0.467	-0.1	-0.02	p=0.015
• Agriculture Extension Service	-0.01	-0.3	0.15	p=0.242	0	0.1	p=0.011
• Animal Husbandry Bureau	0.03	-0.31	0.16	p=0.222	0.01	0.07	p=0.009
• Academic researches	0.01	-0.28	0.14	p=0.456	-0.05	0.04	p=0.090
• Social media	0	-0.28	0.14	p=0.381	-0.01	0.05	p=0.017
Controlling factors							
• Price of low protein feeding	0.12	0.02	-0.12	p=0.347	0.01	0.07	p=0.796
• Shelf life of low protein feeding	-0.16	0.02	0.09	p=0.369	0.22	0.07	p=0.474

Table S3.10. Mean use of feed ingredients in diets of calves, heifers, lactating and dry dairy cows (unit: kg DM/head/day). The number brackets following animal categories shows the number of diet formulas collected, and the number between brackets following the feed ingredients indicates the percentage of farmers using the specific ingredients.

	Calves (N=33)	Heifers (N=75)	Lactating cows (N=169)	Dry cows (N=57)
Roughage				
• Maize silage (100%)	2.95	3.32	7.55	3.75
• Alfalfa (96%)	0.14	0.13	2.24	0.05
• Maize straw (23%)	0.47	0.51	0.06	0.31
• Oat straw (75%)	0.40	0.28	0.87	2.89
• Chinese wild rye (56%)	0.83	1.40	0.42	1.40
• Hay (20%)	0.36	0.36	0.15	0.50
• Peanut straw (19%)	0.42	0.33	0.15	0.11
• Alfalfa silage (8%)		0.14	0.11	
• Rice straw (14%)	0.29	0.37	0.05	0.20
• Maize hay silages (4%)	0.42	0.23		0.18
• Sweet potato straw (1%)			0.01	
• Barley straw (1%)	0.05	0.02		
• Sorghum (2%)	0.11	0.02		
Concentrates				
• Cotton seed (67%)			0.67	
• Steam-flaked corn (70%)	0.04	0.02	1.94	0.09
• Sugar beet (26%)	0.02	0.01	0.19	0.07
• Distilled grain (26%)			0.73	0.04
• Soybean meal (44%)	0.06	0.04	0.36	0.05
• Commercial feeding* (100%)	2.43	2.48	5.62	3.34
• Corn meal (13%)			0.23	0.02
• Soybean hulls (4%)			0.03	
• Wheat bran (2%)	0.06	0.04		
• Soybean cake (5%)			0.03	0.01
• Fat powder (6%)			0.01	
• Cottonseed meal (1%)			0.01	
• DDGS (2%)			0.02	
• Rapeseed meal (1%)			0.02	
Total	9.04	9.69	21.46	13.02

Table S3.11. Diet formulas used in layer farms

	Pre-laying hens (N=62)	Productive hens (N=82)
Full compounds		
• Percentage of farmers using full compounds	18	12
• Average Crude Protein (% DM)	178	185
Self-mixture		
• Pre-mix feeding (%)	5.1	4.8
• Soybean meal (%)	24.3	24.7
• Maize corn (%)	63.3	61.2
• Wheat bran (%)	6.0	0.7
• Other (%)	1.4	8.6

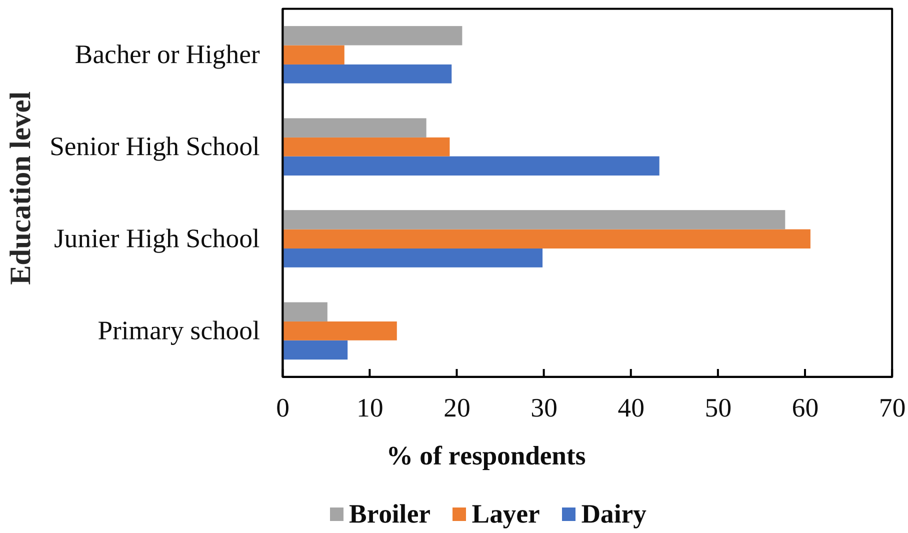

Figure S3.1. Education level of the interviewed farmers.

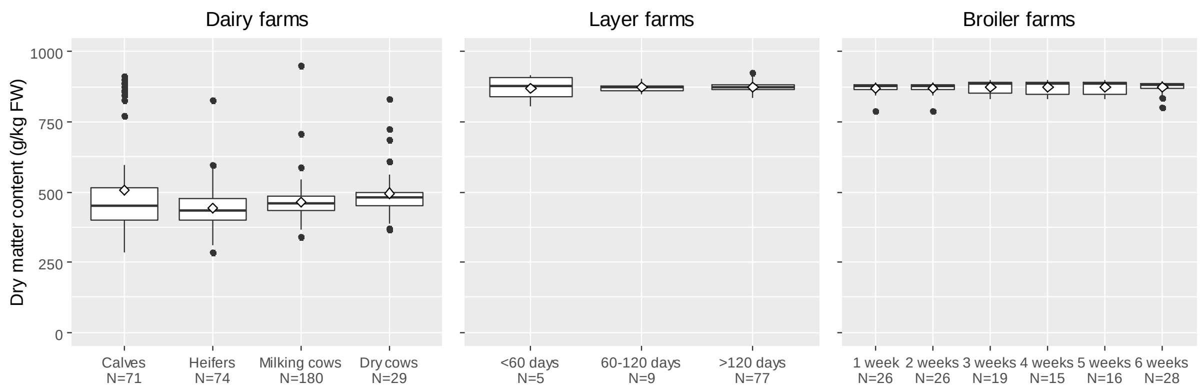

Figure S3.2. Dry matter content of feed diets regarding to fresh weight (FW). Boxes indicate the 25 percentile (lower border) and 75 percentile values (upper border), while the line in the box represents the median and the diamond the average crude protein content. Vertical lines indicate the 5 and 95 percentile values. The number of observations are indicated in the x-axis.

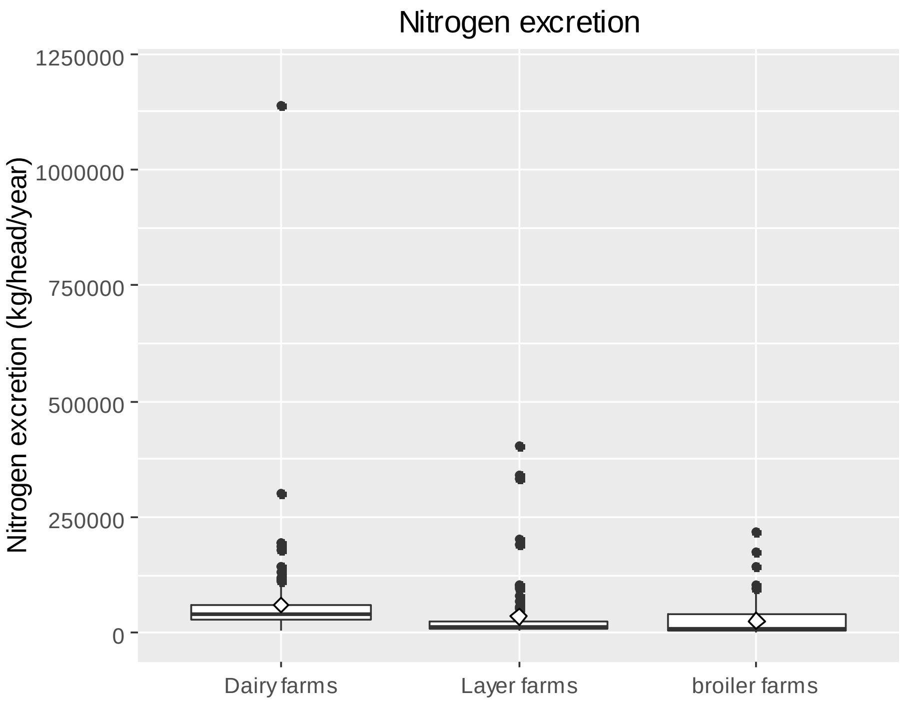

Figure S3.3. Nitrogen excretion at farm level. Boxes indicate the 25 percentile (lower border) and 75 percentile values (upper border), while the line in the box represents the median and the diamond the average feed intake. Vertical lines indicate the 5 and 95 percentile values.

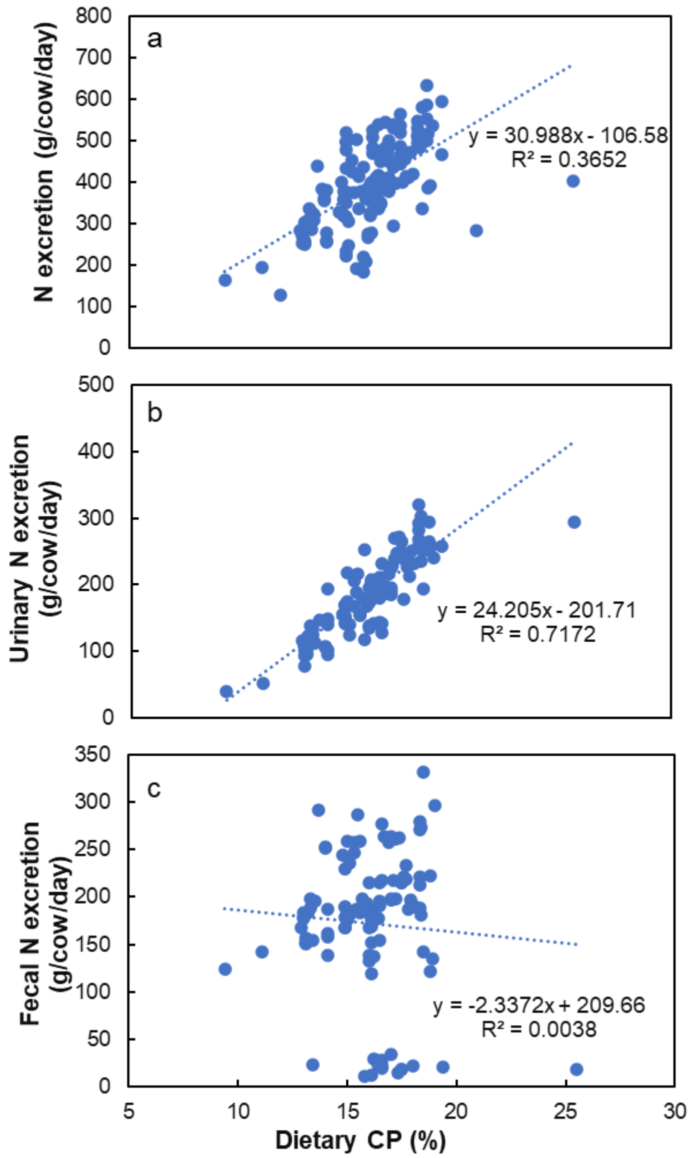

Figure S3.4. Relationship of N excretion (a: total N excretion; b: urinary N excretion; c: fecal N excretion) and dietary CP content of dairy cows, data sourced from: Zhai et al., 2007; Wang et al., 2014; Powell et al., 2008; Guo et al., 2019; Gao et al., 2013; Broderick, 2003; Castillo et al., 2001; Davidson et al., 2003; Frank and Swensson, 2002; Groff and Wu, 2005; Wattiaux and Karg, 2004; Hristov et al., 2004; Lee et al., 2012; Petit et al., 2005; Agle et al., 2010; Mutsvangwa et al., 2016; Chibisa and Mutsvangwa, 2013; Colmenero and Broderick, 2006; Eriksson et al., 2004; Whelan et al., 2011; Kauffman and St-Pierre, 2001; Recktenwaldd et al., 2014; Hynes et al., 2016; Broderick and Reynal, 2009; Brito and Broderick, 2007; Reynal and Broderick, 2005; Lee et al., 2015;Aguerre et al., 2016; Focant et al., 2019; Staerfl et al., 2012; Petit 2003; Mutsvangwa et al., 2016; Leonardi et al., 2003; Śliwiński et al., 2004; Ruiz et al., 2002; Ipharraguerre and Clark, 2005; Noftsger and St-Pierre, 2003; Knowlton et al., 2001; Haig et al., 2002.

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Chapter 4 Nutrient use efficiency of intensive dairy farms in China – current situation and an analyses of options for improvement

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This chapter is submitted under revision

Abstract

Global dairy production has a relatively large share in the total emissions of nitrogen (N) and phosphorus (P) to air and water bodies, which are a concern. However, there are large differences among dairy farming systems in performances, and these are not well understood. This relates especially to emerging market economies such as China, where dairy production is increasing, and new dairy farms are relatively large and intensive, with little farmland. This study estimated of N and P flows and use efficiencies (NUE and PUE) of 141 dairy farms at farm, herd, and manure management levels. Emission mitigation technologies were also explored for the effects of improving farm nutrient use efficiencies on each farm via scenario analyses. We collected data from farm survey and feed sample analyses. Based on the empirical management data, a nutrient flow model was developed and used for the quantification of nutrient flows.

We found a substantial variation among the farms in NUE (53±20%) and PUE (84±22%) at farm level, but not at herd level. Our estimates of NUE and PUE are much higher, and N and P losses much lower, than previous estimates. Effects of management technologies varied greatly among farms; increases in farm-level NUE ranged from 0-53% and for PUE from 0-79%. Improving manure storage and treatment technologies and increasing manure export had relatively large effects on farm-level NUE and PUE and nutrient losses, while effects of low-protein feeding were limited.

Our findings highlight the need of farm-specific technologies, targeted to specific aspects of the whole manure management chain, to improve NUE and PUE of the industrial dairy production sector in China. Further, manure application limits are needed to prevent excessive manure applications and nutrient losses from cropland.

4.1 Introduction

More than 80% of the world's population regularly consumes dairy products (FAO and GDP, 2018). Forecast suggests that global consumption of dairy products will increase by about 2% per year during next decades (OECD-FAO, 2018). However, dairy production exerts also significant pressures on the environment and natural ecosystems, and thereby compromises its sustainability (Steinfeld & Gerber, 2010; Uwizeye et al., 2020). Global dairy production contributed about 30% to the total greenhouse gas (GHG) emissions from livestock production in 2017 (FAOSTAT,2021) and about 49% to the total NH_3 emissions from livestock production in 2010 (Uwizeye et al., 2020). Diffusion of manure nitrogen (N) and phosphorus (P) from dairy farms to water bodies also contributes significantly to eutrophication of surface waters (Xue & Landis, 2010; Biagini & Lazzaroni, 2018). A burgeoning dairy production also results in a burgeoning manure production, as only a fraction of the carbon (C) and nutrients in the feed of dairy cattle is retained in milk and liveweight gain; the remainder is excreted via faeces and urine. The large amounts of organic matter, N, P, and other (micro) nutrients in dairy cattle manure make it a good fertilizer to improve soil quality and to nourish crops (Parsons et al., 2007). However, the mixture of faeces and urine has a low dry matter content and is bulky, making collection, storage and transport often difficult and expensive (Chadwick et al., 2015).

Burgeoning dairy production is occurring especially in China and other rapidly developing countries (Gerber et al., 2013). Driven by population growth and dietary change, domestic dairy consumption will increase further by 28-331% in China towards 2050 (Li et al., 2017; Bai et al., 2018a) even though a significant fraction of the domestic demand may be covered by import (Bai et al., 2018b; Du et al., 2018).

The rapid increase in dairy production has been accompanied by fundamental changes in production systems (Bai et al., 2016 & 2018a). New dairy farms have become specialized, have little or no cropland, and deliver all milk to processing industries, which increasingly set constraints on milk quality and thereby indirectly on the cleanliness of production technology and on the health of the herd. Such changes may have also impacts on manure production and management, either directly or indirectly. Analysing such changes requires a chain approach, from animal feeding and animal housing, to manure collection, storage and possible treatment, followed by manure application to cropland (Chadwick et al., 2015 & 2020). Nutrient flows and losses in this chain can be modified through various measures and technologies, whereby measures in the first part of the chain affect the nutrient flows and losses in the later parts of the chain. Evidently, insight into the nutrient flows within the chain is essential also for developing effective on-farm emission mitigation strategies (Bai et al., 2013; Sefeedpari et al., 2019).

Currently, there are few empirical data and limited quantitative understanding about the variations in nutrient losses at various stages of the manure management chain of relatively new and intensive dairy farms in China. There is also limited empirical information about the causes of this variation. Previous studies either considered an “average” farm of a region (Bai et al., 2013 & 2016; Zhang et al., 2017; Zhao et al., 2017), or based their analysis on just a few demonstration farms (Li et al., 2017; Ma et al., 2021).

In this study we aimed at (1) increasing the understanding of the relationships between farm characteristics, management practices, N and P losses, and N and P use efficiencies (NUE and PUE) by examining a large number of newly-established intensive dairy farms in practice, and (2) to explore and assess options to improve NUE and PUE of these dairy farms. Currently, about half of market-oriented dairy farms are ‘intensive’ and they manage 61% of the national dairy cattle stock (China Dairy Industry Statistical Yearbook, 2019). Considering the flourishing of intensive farms, we focused on dairy farms with >100 dairy cows per farm. We made detailed farm surveys and visits, and build a model to estimate N and P losses and NUE and PUE of these farms.

4.2 Materials and Methods

4.2.1 System description

The dairy farm system studied here includes a chain of processes: on-farm feed production, animal feeding, dairy production, manure excretion, manure collection, storage and treatment, as well as manure application on cropland of the farm and export of manure from the farm (Figure 4.1). Losses of N and P from the main part of the chain, i.e., cattle housing, manure storage and treatment stages were quantified, using farm survey data, on-farm observations and analyses of feed samples, literature data and a model for calculating N and P losses.

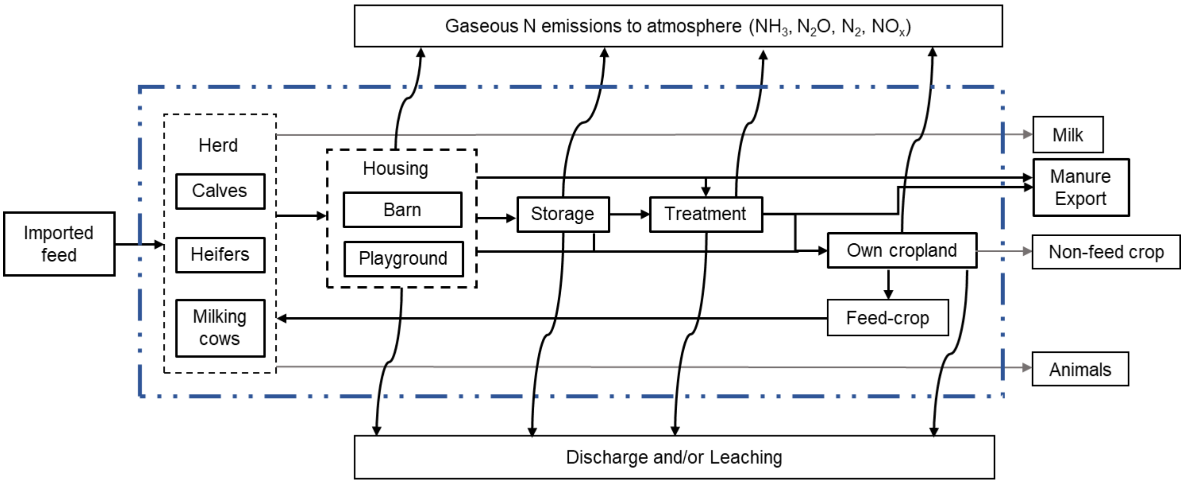

Figure 4.1. Conceptual scheme of nutrient flows and losses in the manure management chain of the studied dairy farms. Boxes with solid line indicate specific components of the manure management chain (the two boxes with black broken line indicate the herd and the animal housing, respectively). Arrows indicate the flows of N and P. The box with the blue broken line indicates the farm boundary.

4.2.2 Quantifying nutrient flows

We used a mass balance approach to estimate the N and P flows and losses from the manure management chain. The amounts of N and P excreted by the cattle were estimated from the N and P intake minus the N and P retained in milk and live weight gain, i.e., $NU_{excretion} = NU_{intake} - NU_{retention}$, where NU represents N or P.

4.2.2.1 Feed intake and nutrient retention by livestock

Total feed intake by the cattle on a farm was calculated from the number of livestock per category and the feed requirements per livestock category (calves, heifers and milking cows, Figure 4.1). Feed intake per head was estimated on the basis of the energy requirements for maintenance, growth (live weight gain) and production (IPCC, 2006; Bai et al., 2016), see Supplementary Information (SI). Nutrient intake was calculated from the feed intake per head and the nutrient contents of the feed. Feed-specific N and P contents were analysed from feed samples collected from the surveyed farms (see below).

Nutrients are retained in the animal body through live weight gain (including reproduction) and in the milk produced. Milk yield, protein content of milk and live weight gain of calves and heifers were derived from interviews and farm records. The N and P contents of the animals' body and the P content of milk were derived from literature (SI Eq.S4.6 and Table S4.1).

4.2.2.2 Nutrient excretion and losses in housing systems

Total nitrogen (TN) excretion was further divided into ammoniacal nitrogen (TAN) and faecal-N excretion, based on the protein digestibility of the feed ration which was obtained from the analyses of feed samples (SI Eqs.S4.7 & S4.8).

The housing system commonly consisted of a sheltered free-stall feeding barn and an unsheltered playground (open lot). Floor type and manure removal technique and removal frequency were largely different between open lot and sheltered barn. Manure excretion in the barn and on playground were allocated according to the estimated fractions of time spent in each part. Manure removal technique and manure removal frequency (cleaning frequency) were recorded during the farm visits and talks with the farmers.

Nutrient losses from barn and playground were calculated separately and were based on the floor type and cleaning frequency. For each floor type and cleaning frequency we estimated emission factors (EFs) and emission reduction factors (ERF, Table S4.1), based on the GAINS modelling approach (Amann et al., 2011) and literature data. Ammonia (NH_3) emissions were estimated as a proportion of the amount of TAN, while emissions of N_2O, N_2 and NO_x were estimated as a proportion of total N in manure. We estimated leaching factors (LF), as function of floor type and TAN (Table S4.1). These emission and leaching factors are uncertain, because of the lack of measurements on dairy farms in China. Therefore, we conducted additional uncertainty analyses (see Section 4.2.7).

Manure collection occurred either as slurry (i.e. urine and feces mixed together) or separately as liquids (which run directly to lagoons over a sloping floor) and solids (which were scraped and then heaped outside on the farm yard. When liquids and solids were collected separately, it was assumed that 70% of the TAN, 10% of the fecal-N and 10% of P were in the liquid fraction. The proportions of collected manure being stored, treated, exported, applied or discharged were derived from the farm survey (see below).

4.2.2.3 Nutrient losses from manure storage and treatment

Nutrient losses during manure storage were estimated as function of the type of storage (open yard, open lagoon or closed basin storage), duration of storage and the floor type of the storage system, using specific EFs and ERFs (SI Eq. S4.21&4.22).

Manure may be treated directly after collection from the housing systems or after a short storage in the open yard or open lagoons. We observed three types of manure treatment techniques:

solid-liquid separation (SL), anaerobic digestion (AD), and composting of the solid manure fraction (CM). The screw press was used in SL, in all cases; we assumed that 90% of total N, 100% of TAN and 15% of total P were in the liquid fraction (Hou et al., 2017). Nutrient losses during AD and CM were estimated simply by assigning emission factors to these processing steps (SI Eq. S4.28-4.32).

4.2.3 Collection of farm data

Farm structure and management data were collected through farm visits and surveys, using a structured questionnaire. The questionnaire included specific sections about feed use, herd characteristics, and manure management practices in animal housing, manure storage, manure treatment technology, manure application on own farmland and manure export (Table S4.2-S4.9). From November 2018 to May 2019, a total of 141 dairy farms were visited in Hebei and Shandong provinces, which are among the top dairy production provinces in China. In 2016, 3.1 million dairy cattle (22% of national total) were housed within these two provinces, contributing 13% to the national milk production (China Dairy Industry Statistical Yearbook, 2019). We selected dairy farms randomly from randomly selected counties within the two provinces, using lists of dairy farms obtained from agricultural bureaus. Only dairy farms with more than 100 dairy cows were included in the survey; small farms were disregarded, because they are disappearing quickly (China Statistic Yearbook, 2012;Jin et al., 2021). Small farms also have limited opportunity to invest in improving milk quality and manure management. During the survey, whole mixed feed samples (in total 354 samples) were collected from each farm (1 to 3 samples per farm; each sample consisted of three subsamples and was in total about 1 kg fresh weight) for analysis of the metabolizable energy, digestibility, and N and P contents of the ration.

Parameters used to calculate N and P retention, the emission and emission reduction factors (EFs and ERFs) for NH_3, N_2O, NO_x and N_2 emissions, and the N and P leaching factors for each stage of the manure management chain were derived from international literature but were adjusted to local conditions where needed using experts' knowledge (Table S4.1).

For dairy farms with cropland, crop cultivation and management were derived from the survey data. Estimates of N and P uptake per unit area were derived from literature (Ma et al., 2010). Cereal crops (including their grain and straw) were assumed to be used as feed, while the on-farm produced vegetables and fruits were assumed to be marketed.

4.2.4 Estimation of nutrient use efficiencies

The N and P use efficiencies were calculated at the herd, manure management system and farm levels, as follows:

$$NuUE_{herd,i} = \frac{NU_{retention,i}}{NU_{intake,i}} \times 100\%$$ Eq. 4.1

$$NuUE_{manure,i} = \frac{NU_{apply,i} + NU_{export,i}}{NU_{excretion,i}} \times 100\%$$ Eq. 4.2

$$NuUE_{farm,i} = \frac{NU_{retention,i} + NU_{export,i} + NU_{non-feed\ crop,i}}{NU_{feed\ imported,i}} \times 100\%$$ Eq. 4.3

Where $NuUE_{herd,i}$, $NuUE_{manure,i}$, $NuUE_{farm,i}$ represent N or P use efficiencies at herd, manure, and farm levels of farm i, respectively (kg/kg). $NU_{apply,i}$ is the amount of manure N or P applied on own cropland at farm i (kg/farm/year). $NU_{export,i}$ is the amount of manure N or P exported to other farms (kg/farm/year). $NU_{feed\ imported}$ is the amount of purchased feed imported to the farm. The farms did not import and use synthetic fertilizers.

4.2.5 Possible measures to improve manure management

Five possible measures were examined to reduce N and P losses and to improve NUE and PUE at each dairy farm (Table S4.10). The measures included, low-protein animal feeding (O1), improved manure storage (O2), a ban on manure discharge combined with enlarged manure storage capacity (O3), a ban on manure discharge combined with enlarged manure treatment capacity (O4), and combinations of these measures (O5, Table S4.10). For each farm, the current management practice was used as the reference. Changes of the NUE and PUE by applying those measures were quantified, so as to compare their effectiveness, thus:

$$\Delta NuUE_{i,k} = NuUE_{i,k} - NuUE_{i,0}$$ Eq. 4.4

Where $\Delta NuUE_{i,k}$ is the change of NUE or PUE by applying measure k at farm i; $NuUE_{i,k}$ is the NUE or PUE by applying measure k at farm i; $NuUE_{i,0}$ is the NUE or PUE at farm i with current management practice.

4.2.6 Data analysis

All calculations were performed in R programming language (R Core Team, 2021). Average and standard deviations of nutrient flows and nutrient use efficiencies of the 141 farms were weighted for the number of LSU per farm, using R package *Hmisc* (Harrell & Harrell, 2019). The correlations between farms' and farmers' characteristics, nutrient flows and nutrient use efficiencies were analysed using Pearson correlation analysis in R. Visualizations were performed with R packages *ggplot2* (Wickham, 2016).

4.2.7 Uncertainty and sensitivity analysis

Uncertainties in our estimates may result from uncertainties in (i) sampling, (ii) measurements, (iii) parameters and coefficients, and (iv) farmers' responses (Oenema et al., 2003). We sampled and analysed 141 farms out of thousands of farms (1108 intensive dairy farms in Hebei in 2018 and an unknow but likely similar number in Shandong), and visited them once.

We conducted a global sensitivity analysis (Hoops et al., 2016; Uwizeye et al., 2017) to estimate the uncertainty of nutrient flows and nutrient use efficiencies of the whole intensive dairy production sector, instead of only for the sampled farms, to compensate for possible sampling biases. We performed Monte Carlo simulations using @RISK software (Palisade Corporation) by varying parameters and inputs in the model used to estimate NUE and PUE. Uncertainties in the inputs and parameters were described with probability density functions (PDFs) obtained from survey results and literature (Table S4.11). Statistical dependency and logistic relationship were considered carefully in the setting of the inputs and parameters. For example, the impact of farm scale on the adoption of manure treatment techniques was analysed and found to be insignificant, therefore the numbers of dairy cows and fraction of manure treated were independent to each other. Further, cropland area was normalized with LSU, and the PDF of the normalized cropland area is used in the sampling setting. We ran 5000 iterations to find the probability distributions of the nutrient use efficiencies, using the software's built-in functionality. Results are presented with the uncertainty range covering 95% of the statistical outcomes. In addition, we analysed the sensitivity of nutrient use efficiencies to possible variation (uncertainties) in inputs and parameters using @RISK software, to examine the contributions of inputs and parameters to the total uncertainties (see SI).

4.3 Results

4.3.1 Characteristics of surveyed farms

A total of 141 dairy farms with on average 331 dairy cows (median 250; range 50 to 5900) participated in this study. Most farms (94%) were family farms with on average 18 dairy cows per laborer (range 5-40 dairy cows per laborer). There were on average 9.2 young stock (calves and heifers) per 10 cows (range 3.7 to 30.0). Productivity was on average 8910 kg milk per cow per year (7946 kg FPCM per cow per year). Farms had on average 17.4 ha cropland (median

1.9 ha; range 0.3 to 600 ha). All cows were kept in free-stall barns with concrete floor (there were no farms with a slatted floor and slurry storage underneath). None of the farms applied grazing. Excreted manure in the barn was collected on 77% of the farms at least twice a day and then stored for days to months before being treated and/or applied to field and/or exported. On the other 23% of farms, slurries were collected less frequently (1 to 7 times per week). Manure (slurries) was stored either on the ground of the farm yard or in open lagoons often with concrete floor and walls; there were no covered basins. Storage capacity was limited, and thus storage time was also limited, in general. Manure treatment was found on 21% of the surveyed farms; solid-liquid separation was the dominant treatment technique (on 17% of the farms). As most farms had little or no cropland, only a small portion of the manure was used within the farm; instead a significant fraction was exported to nearby crop farms.

4.3.2 Nutrient flows and variations at farm level

Figure 4.2 presents the average N and P flows per dairy cow at farm level. Mean annual feed intake was 248 kg N and 40 kg P per cow per year (including accessory young stock). Over 95% of the feed N and P were purchased. Cows retained on average 21% N and 28% P in milk and LWG, and the remainder (79% N and 72% P) was excreted in urine and faeces, i.e., 197 kg N and 30 kg P per cow per year (including young stock). Total gaseous N losses via emissions of ammonia (NH_3), nitrous oxide (N_2O), di-nitrogen (N_2) and/or nitrogen oxides (NO_x) to air were estimated at 45% of the total N excretion. Discharge and leaching losses together were estimated at on average 12% of excreted N and at 23% of excreted P. A total of 51% of the excreted N and 89% of the excreted P were applied on-farm or exported to nearby crop farms. Manure application on own farmland of the 85 farms with cropland was on average 1364 kg N and 281 kg P per ha per year, which is far above mean annual N and P demands of the crops grown.

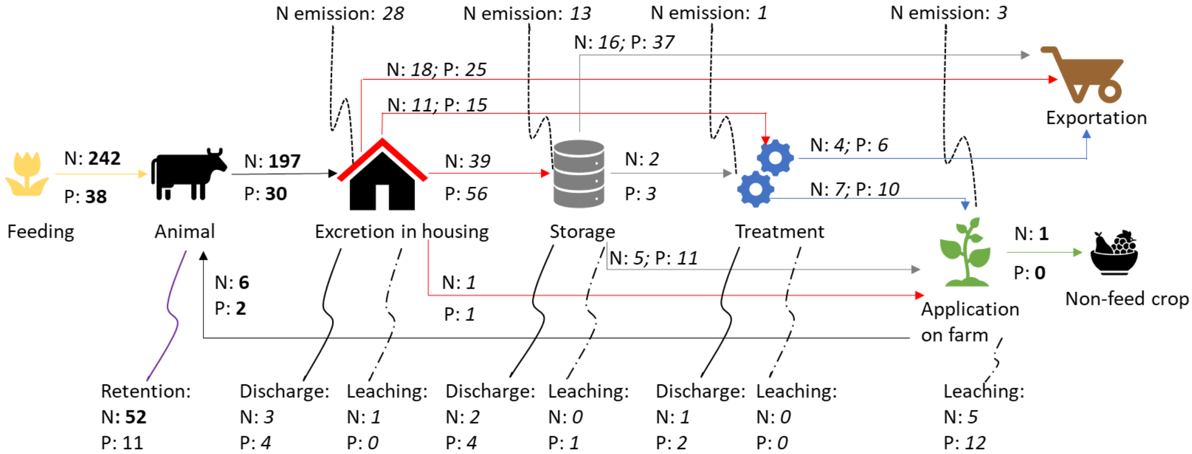

Figure 4.2. Mean N and P flows on the 141 surveyed dairy farms. The central part shows the flows of N and P in feed and manure, the upper part shows the gaseous N losses to the air, the lower part shows the N and P losses via leaching and discharge/disposal (units: bold numbers: kg per cow (including accessory young stock); numbers in italics: % of total excretion).

Variations among farms in NUE and PUE at herd, manure and farm levels, and in the excretion and losses of N and P per 1000 kg FPCM produced are shown in Figure 4.3. NUE_{herd} ranged from 14% to 35% with an LSU-weighted average of 21%. PUE_{herd} ranged from 19% to 49% (LSU-weighted average 27%) (Figure 4.3A). Distributions of NUE and PUE at manure and farm levels were skewed to the right, particularly for PUE: roughly half of the farms had almost all P excreted in manure efficiently utilized (Figure S4.1). However, the other half of the farms managed the manures differently, as reflected by the large variation of PUE_{manure} (Figure 4.3A). Nitrogen losses were relatively large and differed greatly among farms. On average 23.4 kg N and 3.5 kg P were excreted in manure per 1000 kg FPCM produced (Figure 4.3B), with 15.3 kg N and 0.9 kg P lost per 1000 kg FPCM produced, via discharge, leaching and/or gaseous emissions (Figure 4.3B).

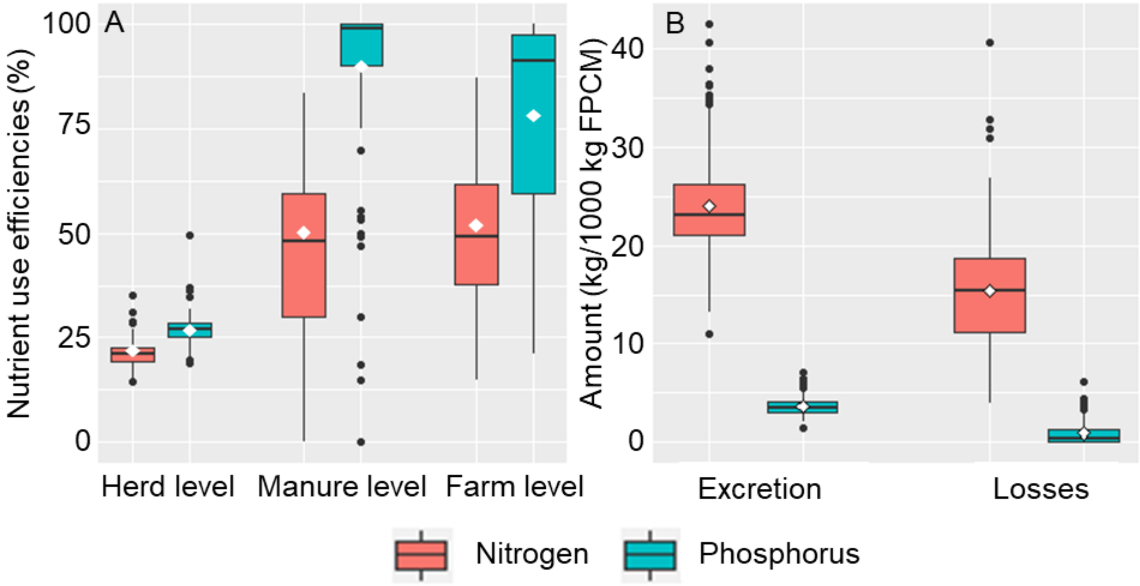

Figure 4.3. Variations among farms in N and P use efficiencies at herd level, manure management chain level and farm level (a), and variations among farms in N and P excretion and N and P losses at farm level expressed in kg per 1000 kg FPCM (b). Boxes indicate the 25 percentile (lower border) and 75 percentile values (upper border), while the line in the box represents the median and the diamond represents the LSU-weighted average. Vertical lines indicate the 5 and 95 percentile values, and dots extreme values.

4.3.3 Linking nutrient use efficiency to farm and farmers' characteristics

Pearson correlation analysis revealed that the cropland area managed by the farms was a main factor influencing manure N and P flows (P<0.01, Figure 4.4B&C and Figure S4.2). With an increase of the cropland area, a greater proportion of manure was applied to the field and less manure was exported. However, the NUE and PUE of the farm, herd, and manure management systems were not significantly influenced by the cropland area (P>0.05, Figure 4.4A).

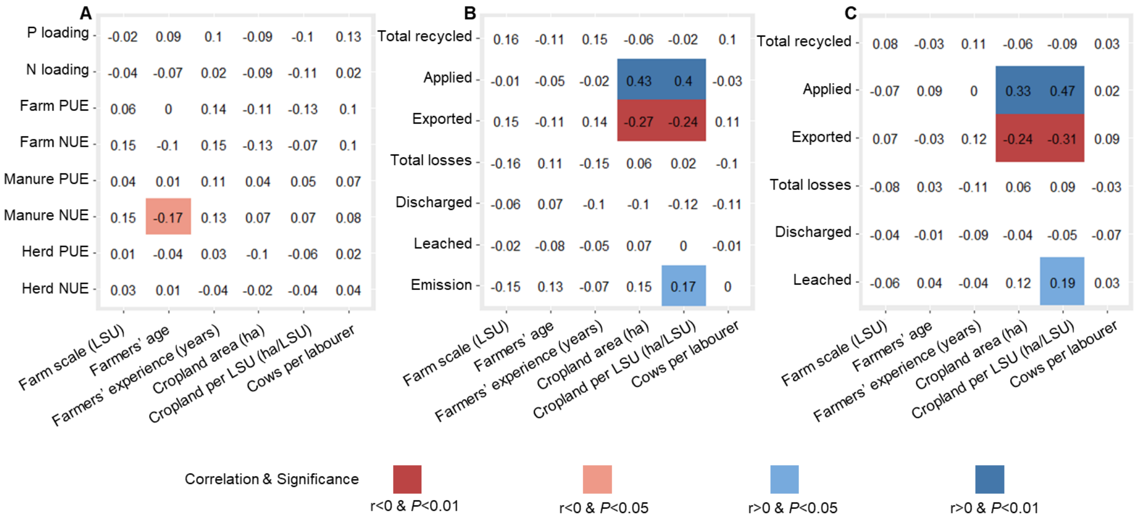

Figure 4.4. Correlation matrix of farm and farmers' characteristic (x-axis) and (A) manure N and P application rates on own cropland and NUE and PUE at farm, herd and manure management system levels; (B) N flows in % of N excretion; (C) P flows in % of P excretion. Red colours indicate negative and blue colours indicate positive correlation coefficients

4.3.4 Effects of emission mitigation measures

Effects of mitigation measures on mean NUE and PUE were relatively small, but there were remarkably large differences among farms and among measures (Figure 4.5). With current feed and manure management practices, NUE_{herd} was 21±3%, NUE_{manure} 50±22%, and NUE_{farm} 53±20%. Similarly, PUE_{herd} was 27±3%, PUE_{manure} was 89±22%, and PUE_{farm} was 84±22%. Among the 141 farms, 39 farms can improve farm NUE by 10-32% (absolutely) through covered and leak-tight manure storage (O2). Combinations of covered and leak-tight manure storages with solid-liquid separation (O5-2) may increase farm NUE by 10-49% on 65 out of the 141 farms. On average, a single change from current manure storage practices to covered and leak-tight manure storage (O2) increased NUE_{manure} by 10±11% (LSU weighted) and PUE_{farm} by 6±8% (LSU weighted). NUE_{farm} can be increased by 12±13% through a combination of improved manure storage and manure treatment (O5-2).

Improving manure storage did not change mean farm PUE much, because P losses through leaching were relatively small. Loss of P mainly occurred through discharge of manure to surface waters; a ban on discharge increased mean PUE_{manure} to ~100% and mean farm PUE by 5-69% on 17 out of the 141 farms (O5-2). On some farms, we observed that manure solids were accumulating in evaporation lagoons and farm yards, because farmers were unable to export the manure to other farms in a timely manner. We assumed that manure P was conserved in these lagoons and yards, but that manure N was largely lost.

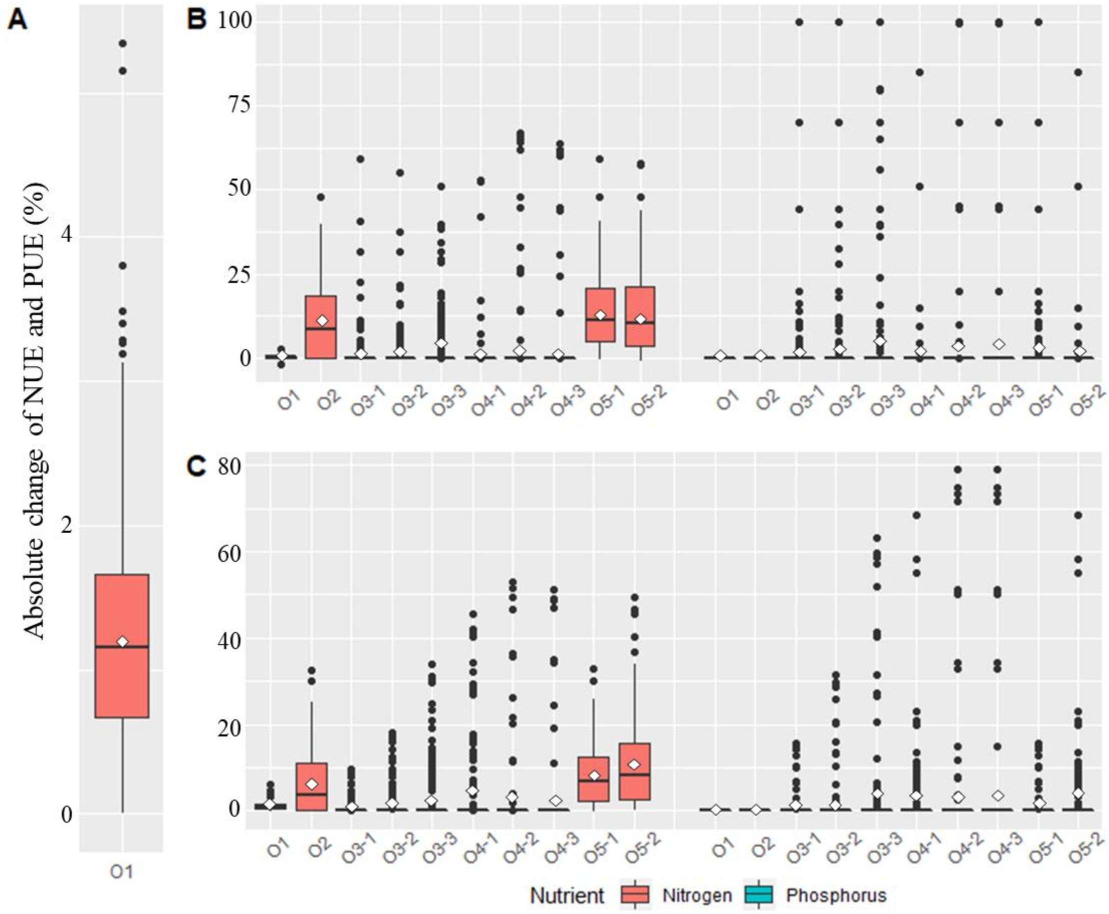

Figure 4.5. Boxplots of changes of NUE (red boxes) and PUE (green boxes, at the right hand of panel B and C, but the 25% and 75% PUE are too close therefore the green colours are not visible) at (A) herd level; (B) manure management system level and (C) farm level by applying different measures (O1: low protein feeding; O2: improving manure storage type; O3: enlarged manure storage; O4: enlarged manure treatment; O5: combination measures (Table S10). Boxes indicate the 25 percentile (lower border) and 75 percentile values (upper border), while the line in the box represents the median and the diamond represents the LSU weighted average. Vertical lines indicate the 5 and 95 percentile values. Dots indicate extreme values.

4.3.5 Uncertainty and sensitivity analyses

Table S4.12 and Figure S4.3 present the results of the uncertainty and sensitivity analyses. Uncertainties (coefficient of variations) in mean NUE were 20% at herd level, 34% at manure system level, and 24% at farm level. Uncertainties in mean PUE were 18% at herd level, 28% at manure system level, and 25% at farm level. Hence, uncertainties were larger in mean NUE than in mean PUE. Also, uncertainties in NUE and PUE were larger for the manure system than for the whole farm and herd. Herd level NUE and PUE were most sensitive to the number of heifers and dairy cows, and the N and P contents of the feed, respectively. Farms with greater number of cows had higher NUE_{herd} and PUE_{herd} than farms with a small number of cows. The larger number of young stock, the lower NUE_{herd} and PUE_{herd}, because dairy cows use feed N and P more efficiently than heifers. Changes in the milk yield per cow and the maintenance coefficient had a relatively large impact on NUE_{herd} and PUE_{herd}. The results emphasized the importance of herd health and management for improving herd level NUE and PUE.

Both NUE_{manure} and PUE_{manure} were sensitive to the fraction of slurry discharged, which contributed 60% to the total uncertainties. Next, uncertainties in losses from slurries in stables were more sensitive than those from the slurries in playground and storages. In general, uncertainties in the ‘slurry system’ contributed more to the uncertainties in NUE_{manure} and PUE_{manure} than the uncertainties in the “Ganqingfen” system (i.e., solid manure, Fang et al., 2020).

Farm level NUE and PUE were most sensitive to the fractions of manure exported and discharged, in the form of either slurries or solids, indicating that manure exportation and discharge are most influential factors for NUE and PUE at farm level (see SI).

4.4. Discussion

4.4.1 Dairy production in China

Traditionally, dairy production in China was dominated by small-scale family farms with 1 to 5 cows and cooperative farms with 5 to 20 cows. In cooperative farms, several families shared one milking parlour and one milk tank, while herd and cropland were owned and managed by individual farmers. Following the melamine scandal in 2008, small-scale dairy production was quickly replaced by large “industrial-like” farms, to better guarantee milk quality (Wang et al., 2021). In total 48% of the number of market-oriented dairy farms were ‘intensive’ in 2018, and these farms managed 61% of the national dairy cattle stock (China Dairy Industry Statistical Yearbook, 2019). Mean milk yield per cow was higher in the surveyed farms (8910 kg/year) than the national average (7800 kg/year, Report of Dairy Herd Genetic Improvement in China, 2020). We do not exclude the possibility that some of our farmers reported milk yields of the better performing period of the year.

Concomitant with the increasing dairy production, cattle manure production has also increased rapidly during the last decades, and these manures are often not well collected, stored, recycled and utilized (Bai et al., 2016; Zhang et al., 2017). The poor utilization of animal manure has been related to the spatial decoupling of livestock production systems from crop production systems, the high cost associated with the collection, transport and application of these manures to cropland, and to the availability of subsidized fertilizers (Jin et al., 2021; Ma et al., 2021). Chinese government has recently announced a range of environmental policies and support programs to facilitate cleaner production, including precision livestock feeding and promoting proper manure storage and manure treatment (MOA, 2017 & 2019). However, the uptake of manure treatment technologies in practice is still limited, because of several barriers (Tan et al., 2021).

4.4.2 NUE and PUE at herd, manure system and whole farm levels

We used NUE and PUE at herd, manure and farm levels as indicators to evaluate the nutrient management performance of the dairy farms. Herd level NUE (21±3%) and PUE (27±3%) were much higher than previous estimations of NUE_{herd} (11%) and PUE_{herd} (12%) by Bai et al., (2013). This difference is partly related to a difference in data origin (farm survey vs modelling), to the progress in dairy production performance during the last 10 years, and to the fact that we examined 141 large 'intensive' farms, while Bai et al. (2013) modelled an 'average typical' dairy farm. Yet, herd level NUE and PUE were lower in our farms than in those of the Netherlands (23-26% for NUE_{herd} and 30-34% for PUE_{herd} in 2015, Oenema & Oenema, 2021) and the USA (18-33% for NUE_{herd} and 18-35% for PUE_{herd} around the year 2000, Powell et al., 2006).

Nutrient use efficiency of the manure management system is defined here as the fractions of N and P excreted that were recycled to cropland or exported to other farms (also known as manure recycling rate). In 2010, only about 37% of the N and 55% of the P excreted in dairy cattle manure were recycled to cropland in China (Bai et al., 2013 & 2016). Our estimates indicate that 50±22% of the N and 89±22% of the P excreted by dairy cattle were applied to the cropland of the farm or exported to other farms. The apparent increase in NUE and PUE of the manure management systems during the last 10 years may be attributed in part to policy effects; there is a formal ban on manure discharge to surface waters since 2014, and the government encourages cooperation between livestock and crop farms, to exchange feed and manure (Report of Dairy Herd Genetic Improvement in China, 2020). Yet, there is still a huge variation in manure NUE and especially PUE among farms (Figure 4.3).

Farm level NUE (53±20%) and PUE (84±22%) were defined as the ratio of total nutrient exported (via animal and crop products and manure exportation) divided by imported feed nutrients. Most of the required feed was purchased and most of the manure N and P were exported to other farms, which indicates that large parts of the N and P use (in)efficiencies in feed production and large parts of the (in)efficiencies associated with manure N and P utilization were excluded from our analysis. The externalization of feed production and manure utilization greatly increases NUE_{farm} and PUE_{farm} (Hristov et al., 2006; Quemada et al., 2020; Oenema & Oenema, 2021). Additional calculations indicate that the earlier estimated farm level NUE_{farm} (53±20%) would decrease to 26±10% and the earlier estimated farm level PUE_{farm} (84±22%) would decrease to 60±19%, when assuming a NUE of 50% and a PUE of 75% for the production of the purchased feed (Figure S4.4). Evidently, mean NUE_{farm} and PUE_{farm} of our farms were high when compared to mean NUE and PUE of grassland-based dairy farms in New Zealand and Western Europe, because of the externalization of the inefficiencies associated with feed production and manure utilization.

About 40% of the farms (54 out of the 141 surveyed farms) were fully landless (did not have any cropland). As a consequence, manure had to be exported to other farms. Manure applications on dairy farms with cropland were very high: on average 1364 kg N and 281 kg P per ha per year, i.e., 9-fold higher than the estimated average manure N and P loadings in Shandong and Hebei in 2006 (Wang et al., 2010), and much higher than the mean N and P withdrawal with harvested crops (86-158 kg N and 16-36 kg P per ha per year, Ma et al., 2010). Some dairy farms rented cropland just for manure disposal. Notably the liquid fractions were applied to on-farm cropland; these liquids partially seeped in the ground and partially evaporated into the air (because of the high evaporative demand in the North China Plain (Wu et al., 2019). Intensive grassland-based dairy farms in the EU, North America and New Zealand commonly use targeted combinations of manure and synthetic N fertilizers for the fertilization of the grassland and cropland (Powell et al., 2007; Fangueiro et al., 2008; de Klein & Monaghan, 2011; Oenema & Oenema, 2021). In contrast, intensive dairy farms in China used the cropland largely for the purpose of manure disposal and silage maize production; they did not use synthetic fertilizers. Evidently, there is need for N and P application limits, similar to those in for example European Union (Velthof et al., 2014). In addition, there is need for adequate control and enforcement mechanisms.

4.4.3 Options for decreasing N and P losses

With current management practices, 50±22% of the total feed N intake by the cattle was ultimately lost, with gaseous N emissions being the major loss pathway (42±20% of the total losses) and housing systems and manure storages being the main loss stage (64±20% of the total losses). Losses from animal housings occurred notably on the unsheltered playground where manure was not collected frequently and where floors were mostly unpaved. Mitigating N and P losses from the housing stage therefore requires changes in floor type and manure collection technology and frequency.

Lowering feed protein is often seen as a most cost-effective measure to mitigate N losses via NH_3 emissions (Reijs, 2007; Hou et al., 2015; Zhang et al., 2019), but our study indicates that low-protein feeding would increase NUE_{herd}, NUE_{manure}, and NUE_{farm} by only 1.2±0.8%, 0.4±0.5% and 1.1±1.0%, respectively. The mean protein content of the ration was already rather low, because of the large proportion of silage maize in the ration (~34% of total DM intake). Moreover, soybean was considered to be expensive by most of the dairy farmers. In contrast, a combination of increased manure storage capacity, covered manure storages to reduce NH_3 emissions, and a strict ban on manure discharge would raise NUE_{manure} and NUE_{farm} by 12.2±11.9% and 7.6±8.0%, respectively. Further, manure N and P application limits as function of soil fertility level and crop N and P demand would also greatly increase the utilization efficiency of manure N and P. Interestingly, the latter improvement in manure management will not show up through increases of NUE_{manure} and NUE_{farm}, unless the 'saved' manure is exported to other farms, indicating the limitations of NUE_{manure} and NUE_{farm} as defined in our study. Further, NUE and PUE were not related to cropland area of the dairy farms, despite the fact that manure application on own farm land increased with an increase of the cropland area (Figure 4.4). A better picture of the N and P utilization of these intensive dairy farms will be obtained if changes in soil N and P accumulation of the cropland are considered too. Therefore, NUE and PUE should be combined with soil fertility indices to assist management decision (Gourley et al., 2012).

Our calculations indicate that changing the current open lagoons and open yard manure storages to closed (covered) basin storages, combined with solid-liquid separation, would increase NUE_{farm} by 12.3±13.1% and PUE_{farm} by 2.7±8.9% (Figure 4.5C). Though these increases in mean NUE_{farm} and PUE_{farm} are not remarkably high, 65 farms (46% of total) show relatively large increases in NUE_{farm} (range 10-49%), and 17 farms show relatively large increases in PUE_{farm} (range 5-69%). Note the wide ranges; the large differences between farms in the effectiveness of measures reflect that single-measure policies may not be effective. Instead, farm-specific technologies and measures will be needed, targeted to the specific characteristics and management level of the farms.

The results of the global uncertainty and sensitivity analyses confirmed the relative importance of manure management and technology for decreasing nutrient losses. Improving manure storages, solid-liquid separation technology and composting were highly instrumental for decreasing N and P losses and improving NUE and PUE. However, anaerobic digestion turned out to be not important. A combination of sufficiently large and covering manure storages, exportation of surplus manure to other farms, and a ban on manure discharge to surface waters have much greater effect on manure utilization than manure treatment technologies that do not consider the destination of the treatment products, as currently is being done in governmental regulations (Wei et al., 2021). Meanwhile, our suggested measures and techniques require not much investment and may be more acceptable by farmers (Bittman et al., 2014; Zhang et al., 2019). Also, there is need for measures that decrease manure N and P losses from cropland.

Our study provides new data and insights on the key factors that contribute to the variations in NUE and PUE of dairy farms at herd, manure management and farm system levels. There is a great scarcity in practical farm data, which limit a comprehensive understanding of the N and P cycling and use efficiencies of dairy farms in China. Previous studies focused on the uncertainties in GHG emissions (Zhu et al., 2016) and ammonia emissions (Zhang et al., 2019), but a synthesis of N and P use efficiencies at herd, manure management system and farm levels was lacking. Our study reveals critical entry points and measures for decreasing N and P losses and improving NUE and PUE in dairy production in China.

4.5. Conclusions

Our comprehensive analysis of empirical data from 141 intensive dairy farms in China showed that N and P losses and NUE and PUE at herd, manure management system and whole farm levels greatly varied among farms. These efficiency values are significantly higher than previous studies suggested, which were based on general statistical data and model calculations. The relative high NUE and PUE indicate that current intensive dairy farms perform much better that the average dairy farms did before 2010, even when considering a possible overrating of our estimations due to excessive manure applications to cropland. Farm-level NUE can be increased further to 60±19% through improved manure management. However, the effect of the manure management measures varies greatly between farms, suggesting that these industrial livestock farmers need to rank the priority of management options individually. The huge variations among farms also indicate that current broad-brushed polices aimed at enhancing manure treatment may not efficiently decrease N and P losses efficiently. Instead, farm-specific approaches are needed, targeted to improved manure collection, low-emission manure storage, and effective manure N and P utilization in cropland. Policies aiming at improved manure management must consider the final destination of manure and include also appropriate limits for manure applications.

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Supplementary information for Chapter 4

This supplementary information contains three main parts:

I. Description of the estimation of nutrient flows and losses;

II. Tables and figures;

III. Description of the uncertainty and sensitivity analyses.

I. Description of the estimation of nutrient flows and losses

Feed and nutrient Intake.

Feed intake by cattle was calculated based on energy requirements for maintenance, milk production, and live weight gain (LWG) (see Eq.S4.4), largely following the IPPC Tier 2 procedures (IPCC, 2006), but transferred to feed dry matter intake, while assuming a mean energy content of 7 MJ/kg. Total N and P intake by cattle per farm was calculated on the basis of the total feed intake, N and P content in the rations, and the number of animals in different groups (Eq.S4.5).

$$NE_{intake,i,j} = NE_{maintenance,i,j} + NE_{milk,i,j} + NE_{LWG,i,j} \qquad \textit{Eq.S4.4}$$

$$NU_{intake,i} = \sum_j NE_{intake,i,j}/7 \times NU_{diet,i,j} \times Number_{i,j} \qquad \textit{Eq.S4.5}$$

Where i refers to a dairy farm and j to animal categories, i.e., calves, heifers and milking cows. $NE_{intake,i,j}$ is the total energy intake at farm i for cattle j (MJ/head/year). $NE_{maintenance,i,j}$ is the energy needed for maintenance at farm i for cattle j (MJ/head/year), as function of body weight (derived from the farm survey) and a maintenance coefficient (constant parameter, Table S4.1). $NE_{milk,i,j}$ is the energy needed for milk production at farm i for cattle j (MJ/head/year), calculated with the milk yield and milk fat, which were derived from the farm survey. $NE_{LWG,i,j}$ is the energy needed for live weight gain at farm i for cattle j (MJ/head/year); the liveweight gain was derived from the farm survey, while an overall mean feed conversion ratio for liveweight gain was used (constant parameter, Table S4.1). $NU_{intake,i}$ is the total N or P intake at farm i (kg/farm/year). $NU_{diet,i,j}$ is the N or P content of the rations for cattle j at farm i (kg/kg diet), which were derived from the analysis results of feed samples. $Number_{i,j}$ is the number of cattle j at farm i (heads), as derived from the farm survey.

Energy requirements and allocation to the production of milk, beef and body maintenance were estimated for three distinguish categories (i.e., dairy, heifers, calves). Energy requirement for body maintenance per category was estimated using the following equation:

$$NE_{maintenance,i,j} = a \times weight_{i,j}^{0.75} \qquad \textit{Eq.S4.3}$$

Where $NE_{maintenance,i,j}$ is the amount of energy needed for maintenance of cattle j at farm i (MJ/head/year). a is maintenance coefficient (MJ/kg metabolic weight) and $weight_{i,j}$ is the yearly average weight of cattle j at farm i.

Energy requirement for live weight gain (LWG) is calculated as:

$$NE_{LWG,i,j} = b_j \times LWG_{i,j} \qquad \textit{Eq.S4.4}$$

Where $NE_{LWG,i,j}$ is the amount of energy needed for LWG of cattle j at farm i (MJ/head/year). b_j is an empirical constant for cattle j depending on health and feed management (MJ/kg LWG).

While feed required for milk production depends on the milk yield and milk fat, i.e.,

$$NE_{milk,i,j} = \left(1.47 + 0.40 \times Milk_{fat_{i,j}}\right) \times Milk_{yield_{i,j}} \qquad \textit{Eq.S4.5}$$

Where $NE_{milk,i,j}$ is the energy needed for milk production of cattle j at farm i (MJ/head/year). $Milk_{fat_{i,j}}$ is the fat content of milk at farm i of cattle j (%). $Milk_{yield_{i,j}}$ is the milk yield of cattle j at farm i (kg/head/year). For calves and heifers, $Milk_{yield_{i,j}}$ is 0, therefore $NE_{milk,i,j}$ is also 0.

Nutrient retention

Nutrient (N and P) retention was calculated at the herd level per animal category (calves, heifers and milking cows, represented by j in following equations). In simple form, the equation for estimating retention is:

$$NU_{retention,i} = \sum_j \left(Yield_{milk,i,j} \times NU_{milk,i} + LWG_{i,j} \times NU_{LW}\right) \times Number_{i,j} \qquad \textit{Eq.S4.6}$$

Where $NU_{retention,i}$ is the total nutrient retention at farm i; $Yield_{milk,i,j}$ is the milk yield of milking cows on yearly basis at farm i (kg/head/year); $NU_{milk,i}$ is the nutrient content of milk at farm i. $LWG_{i,j}$ is the live weight gain of animals j at farm i (kg/head/year); NU_{LW} is the nutrient content of the live weight and is assumed to be a constant (Table S4.1); $Number_{i,j}$ is the number of animals of animal j at farm i.

Nutrient excretion and losses in housing

Nutrient excretion was estimated from the difference between total nutrient intake and nutrient retention in milk and LWG. Nitrogen excretion was further divided into total ammoniacal nitrogen (TAN) and fecal-N excretion based on the protein digestibility (PD) of the feed (derived from farm-specific analyses of the feed sample) . Thus:

$$TAN_{excretion,i,j} = N_{intake,i,j} \times PD_{i,j} - N_{retention,i,j} \quad \textit{Eq.S4.7}$$

$$Fecal\ N_{excretion,i,j} = N_{excretion,i,j} - TAN_{excretion,i,j} \quad \textit{Eq.S4.8}$$

Where $TAN_{excretion,i,j}$ is the TAN excretion of cattle type j at farm i (kg/head/year); $N_{intake,i,j}$ is the N intake of cattle type j at farm i (kg/head/year); $PD_{i,j}$ is the PD of rations of cattle type j at farm i (kg/kg); $N_{retention,i,j}$ is the N retention of cattle type j at farm i (kg/head/year); $Fecal\ N_{excretion,i,j}$ is the fecal-N excretion of cattle type j at farm i (kg/head/year).

Dairy barns usually consists of a sheltered free-stall feeding barn and a unsheltered playground (open lot). All sheltered barns had concrete floors (there were no slatted floors with slurry pits underneath). Floor type of the open lots and slurry cleaning frequency varied, therefore we estimated the N and P excretion and losses in the sheltered barns and the open lots separately. Manure excretion in the barn and on the playground were estimated according to the fraction of time spent on each type. Thus:

$$NUF_{barn,i} = \sum_j NUF_{excretion,i,j} \times \left(1 - Time_{playground,i,j}\right) \times Number_{i,j} \quad \textit{Eq.S4.9}$$

$$NUF_{playground,i} = \sum_j NUF_{excretion,i,j} \times Time_{playground,i,j} \times Number_{i,j} \quad \textit{Eq.S4.10}$$

Where NUF represents different forms of nutrients, i.e., N, P, TAN, and fecal-N. $NUF_{barn,i}$ is the nutrient excretion in barn at farm i (kg/farm/year); $NUF_{excretion,i,j}$ is the nutrient excretion of cattle j at farm i (kg/head/year); $Time_{playground,i,j}$ is the fraction of time spent on playground by cattle j at farm i, as derived from the farm survey.

Nutrient losses from the barn and playground were also calculated separately based on the floor type and cleaning frequency. Each floor type and cleaning frequency had specific emission factors (EFs) for ammonia, nitrous oxide, di-nitrogen and nitrogen oxides. For ammonia emissions, we used a combination of an upper emission factor and emission reduction factors (ERF, see below and Table S4.1). There were also floor type specific leaching factors (LF, Table S4.1).

Emissions of NH_3 are triggered by urea hydrolysis and are proportional to the amount of TAN in the excreta. Losses of N via leaching were also assumed to be proportional to the amounts of TAN, but depending on floor type and manure storage system. Emissions of N_2O, N_2 and NO_x (abbreviated as 'non-NH_3') are produced through nitrification-denitrification processes and were assumed to be proportionally to total nitrogen (TN).

We assumed that as much as 65% of TAN will be lost through NH_3 emissions from the housing systems for farms with concrete floors and a slurry collection frequency (cleaning frequency) less than 1 time per week. In this type of housing system, cattle walk in slurry layers of 0 to 10 cm deep, and thereby mix and stir the slurry nearly continuously. These conditions are highly conducive to NH_3 emissions. We applied emission reduction factors (ERF) for farms with more frequent (better) slurry collection.

The specific equations for calculating N and P losses are therefore as following:

$$NH_{3_{barn,i}} = \sum_j TAN_{barn,i,j} \times (0.65 - ERF_{barn\,floor,i,j} - ERF_{barn\,clean,i,j}) \times Number_{i,j} \qquad \textit{Eq.S11}$$

$$N_{other,barn,i} = \sum_j N_{barn,i,j} \times EF_{barn,i,j} \times Number_{i,j} \qquad \textit{Eq.S4.12}$$

$$N_{leach_{barn,i}} = \sum_j TAN_{barn,i,j} \times LF_{N,barn,i,j} \times Number_{i,j} \qquad \textit{Eq.S4.13}$$

$$P_{leach_{barn,i}} = \sum_j P_{barn,i,j} \times LF_{P,barn,i,j} \times Number_{i,j} \textit{Eq.S4.14}$$

Where $NH_{3_{barn,i}}$, $N_{other,barn,i} N_{leach_{barn,i}}$ and $P_{leach_{barn,i}}$ are the NH_3 emission, non-NH_3 emissions, N leaching and P leaching from the barn at farm i (kg/farm/year), respectively; $TAN_{barn,i,j}$ is the TAN excretion of cattle type j in the barn at farm i (kg/head/year); $ERF_{barn\,floor,i,j}$ is the emission reduction factor of the floor type of the barn for cattle j at farm i; $ERF_{barn\,clean,i,j}$ is the emission reduction factor of the manure cleaning frequency of the barn for cattle j at farm i; $N_{barn,i,j}$ is the N excretion in the barn by cattle j at farm i (kg/head/year); $EF_{barn,i,j}$ is the non-NH_3 emission factor of the barn for cattle j at farm i (Table S1); $LF_{N,barn,i,j}$ is the N leaching factor of the floor type of the barn for cattle j at farm i; $P_{barn,i,j}$ is the P excretion in the barn by cattle j at farm i (kg/head/year); $LF_{P,barn,i,j}$ is the P leaching factor of the floor type of the barn for cattle j at farm i.

Equations for losses from the playground are analogous to Eq.S4.11-Eq.S4.14, but barn was replaced by playground.

The amounts of nutrients that can be collected in the barn or on playground at farm i are therefore:

$$TAN_{barn\,remain,i} = TAN_{barn,i} - NH_{3\,barn,i} - N_{other,barn,i} \times \frac{TAN_{barn,i}}{N_{barn,i}} - N_{leach\,barn,i} \qquad Eq.S4.15$$

$$Fecal\ N_{barn\,remain,i} = Fecal\ N_{barn,i} - N_{other,barn,i} \times \frac{N_{barn,i} - TAN_{barn,i}}{N_{barn,i}} \qquad Eq.S4.16$$

$$P_{barn\,remain,i} = P_{barn,i} - P_{leach,i} \qquad Eq.S4.17$$

The amounts of nutrients that can be collected on playground are calculated analogous to Eq.S4.15-Eq.S4.17.

The total amounts of nutrients that remain in the barn and playground are collected for storage, treatment, exportation, application on farm or for discharge. Manure collection in housing can be either as slurry (i.e. urea and feces mixed together) or as liquids (which typically run directly to lagoons over a sloping floor) and solids (by scraping). If manure is collected as liquid and solid separately, we assumed that 70% of the remained TAN and 10% of the remained fecal-N and P were in the liquid fraction. The proportions of collected manure being stored, treated, exported, applied or discharged are derived from farm survey.

Nutrient losses from manure storages

The amounts of TAN, fecal N and P entering manure storages were estimated as follows:

$$TAN_{store,i} = \sum_k TAN_{k\,remain,i} \times \left(F_{k,slurry,store,i} + 0.7 \times F_{k,liquid,store,i} + 0.3 \times F_{k,solid,store,i}\right) = TAN_{slurry\,store,i} + TAN_{liquid\,store,i} + TAN_{solid\,store,i} \qquad Eq.S4.18$$

$$Fecal\ N_{store,i} = \sum_k Fecal\ N_{k\,remain,i} \times (F_{k,slurry,store,i} + 0.1 \times F_{k,liquid,store,i} + 0.9 \times F_{k,solid,store,i}) = Fecal\ N_{slurry\,store,i} + Fecal\ N_{liquid\,store,i} + Fecal\ N_{solid\,store,i} \qquad Eq.S4.19$$

$$P_{store,i} = \sum_k P_{k\,remain,i} \times (F_{k,slurry,store,i} + 0.1 \times F_{k,liquid,store,i} + 0.9 \times F_{k,solid,store,i}) = P_{slurry\,store,i} + P_{liquid\,store,i} + P_{solid\,store,i} \qquad Eq.S4.20$$

where k represents either barn or playground, e.g., $TAN_{k\,remain,i}$ is the TAN remained on barn or playground at farm i (kg/farm/year); F represent fraction of manure, i.e., $F_{k,slurry,store,i}$ is the fraction of collected slurry manure from k (barn or playground) to be stored at farm i, $F_{k,liquid,store,i}$ is the fraction of collected liquid manure from k (barn or playground) to be stored at farm i, $F_{k,solid,store,i}$ is the fraction of collected solid manure from k (barn or playground) to be stored at farm i. It was assumed that 1% of the fecal-N is transferred to TAN per month through mineralization of organically bound N.

Emission of NH_3 from manure storages were assumed to be a function of the amount of TAN (kg/farm/year), the storage type induced ERF, storage duration (D, month) and a time factor (TF) limiting the maximum amount of TAN that can be lost as NH_3 for a certain period, thus:

$$NH_{3_{store,i}} = NH_{3_{solid\ store,i}} + NH_{3_{liquid\ store,i}} + NH_{3_{slurry\ store,i}} = \sum_l \left(TAN_{l\ store,i} + Fecal\ N_{l\ store,i} \times 0.01 \times D_{l,i}\right) \times \left(1 - ERF_{l\ store,i}\right) \times D_{l,i} \times TF_{l,i} \quad Eq.S4.21$$

Where l represents solid, liquid or slurry.

Emissions of non-NH_3 from storages depend on the total amount of N (kg/farm/year), the storage type induced emission factor (EF_{store}, Table S1), and the storage duration.

$$NonNH_{3_{store,i}} = NonNH_{3_{solid\ store,i}} + NonNH_{3_{liquid\ store,i}} + NonNH_{3_{slurry\ store,i}} = \sum_l \left(TAN_{l\ store,i} + Fecal\ N_{l\ store,i}\right) \times EF_{l\ store,i} \times D_{l,i} \quad Eq.S4.22$$

Leaching losses of N during storage were calculated as the total amount of TAN multiplied by the N leaching factor ($LF_{N,store}$, Table S1) and storage duration, i.e.,

$$N_{leach_{store,i}} = N_{leach_{solid\ store,i}} + N_{leach_{liquid\ store,i}} + N_{leach_{slurry\ store,i}} = \sum_l \left(TAN_{l\ store,i} + Fecal\ N_{l\ store,i} \times 0.01 \times D_l\right) \times LF_{N_{l\ store,i}} \times D_{l,i} \quad Eq.\ S4.23$$

Similarly, P leaching during storage was calculated as the amount of P multiplied by a P leaching factor ($LF_{P,store}$, Table S1) as function of storage duration, thus:

$$P_{leach_{store,i}} = P_{leach_{solid\ store,i}} + P_{leach_{liquid\ store,i}} + P_{leach_{slurry\ store,i}} = \sum_l P_{l\ store,i} \times LF_{P_{l\ store,i}} \times D_{l,i} \quad \text{Eq.S4.24}$$

Nutrients losses from manure treatment

Manure can be treated directly after their collection from the housing systems, or following a short storage. Three types of manure treatment techniques were used in the surveyed dairy farms: solid-liquid separation (SL), anaerobic digestion (AD), and composting (CM). Taking m to represent these techniques, nutrients entering technique m is calculated as:

$$TAN_{m,i} = \sum_k TAN_{k\ remain,i} \times \left(F_{k,slurry,m,i} + 0.7 \times F_{k,liquid,m,i} + 0.3 \times F_{k,solid,m,i}\right) + \sum_l TAN_{l\ remain,i} \times F_{l\ m,i} \quad Eq.S4.25$$

$$Fecal\ N_{m,i} = \sum_k Fecal\ N_{k\ remain,i} \times \left(F_{k,slurry,m,i} + 0.1 \times F_{k,liquid,m,i} + 0.9 \times F_{k,solid,m,i}\right) + \sum_l Fecal\ N_{l\ remain,i} \times F_{l\ m,i} \quad Eq.S4.26$$

$$P_{m,i} = \sum_k P_{k\ remain,i} \times \left(F_{k,slurry,m,i} + 0.1 \times F_{k,liquid,m,i} + 0.9 \times F_{k,solid,m,i}\right) + \sum_l P_{l\ remain,i} \times F_{l\ m,i}$$ *Eq.S4.27*

Nutrient losses from solid-liquid separation (SL)

Solid-liquid separation occurred through a screw press in the surveyed farms. With this type of separation, 90% of total N (100%TAN) and 15% of P were separated to the liquid fraction (Hou et al., 2017). It was assumed that no loss occurred during the separation process (because of the short duration, and most separators were indoors), but losses may occur during the post-storage of the separated solid and separated liquid fractions. As the solid fraction only contains little TAN, NH_3 emission was assumed to be negligible during the storage of the solid fraction. For NH_3 emission factor of the liquid fraction during storage was assumed to be 0.1; hence, total emissions from the liquid fraction during storage were estimated as follows:

$$NH_{3_{SL,i}} = TAN_{SL,i} \times F_{liquid\ storage,i} \times 0.1$$ *Eq.S4.28*

Where $F_{liquid\ storage,i}$ is the fraction of separated liquid being post-stored at farm i.

The non-NH_3 emission factor was set at 0.05 for both separated solid and liquid part and non-NH_3 emission is based on the total N, i.e.,

$$NonNH_{3_{SL,solid,i}} = \left(TAN_{SL,i} + Fecal\ N_{SL,i}\right) \times 0.1 \times F_{solid\ storage,i} \times 0.05$$ *Eq.S4.29*

$$NonNH_{3_{SL,liquid,i}} = \left(TAN_{SL,i} + Fecal\ N_{SL,i}\right) \times 0.9 \times F_{liquid\ storage,i} \times 0.05$$ *Eq.S4.30*

As the storage of separated solid and liquid were all with concrete floors, N and P leaching of SL were negligible.

Nutrient losses from anaerobic digestion and composting

Emissions of NH_3 and non-NH_3 from anaerobic digestion (AD) and composting were estimated as follows:

$$NH_{3_{m,i}} = TAN_{m,i} \times EF_{a,m}$$ *Eq.S4.31*

$$NonNH_{3_{m,i}} = \left(TAN_{m,i} + Fecal\ N_{m,i}\right) \times EF_{b,m}$$ *Eq.S4.32*

where m represents AD or composing, $EF_{a,m}$ is the ammonia emission factor for AD or composting (Table S4.1), $EF_{b,m}$ is the non-NH_3 emission factor for AD or composing (Table S4.1).

Leaching of N and P from AD and composting were considered to be negligible, because these treatment systems were closed underneath.

II. Tables and Figures

Table S4.1. Parameter values used in the calculation of nutrient flows and losses

Parameter	Description	Value	Unit	Source
a	Maintenance coefficient in Eq.S3	0.386	MJ/kg metabolic weight/year	IPCC, 2006
b	Feed conversion ratio of liveweight gain in Eq.S4	38.5 for dairy cows and heifers; 27.0 for calves	MJ/kg LWG	Bai et al., 2013
P_{milk}	P content in milk in Eq.S6	0.001	kg/kg milk	Galama et al., 2015
N_{LW}	N content in liveweight in Eq. S6	0.027	kg/kg LW	Galama et al., 2015
P_{LW}	P content in liveweight in Eq. S6	0.0074	kg/kg LW	Galama et al., 2015
$ERF_{barn\ floor}$ & $ERF_{playground\ floor}$	NH_3 emission reduction factor of floor type in Eq.S11	0.25 for concrete sloping floor; 0.2 for unpaved sloping floor; 0.1 for unpaved flat floor; 0 for concrete flat floor	-	Klimont & Brink, 2004*
$ERF_{barn\ clean}$ & $ERF_{playground\ clean}$	NH_3 emission reduction factor of cleaning frequency in Eq.S11	0.25 for 2 times per day; 0.2 for 1 time per day; 0.1 for 1 time per week; 0 for <1 time per week	-	Klimont & Brink, 2004*
EF_{barn} & $EF_{playground}$	Non-NH_3 emission factor in Eq.S12, depending on floor type	0.2 for unpaved flat floor; 0.05 for other type of floor	-	Klimont & Brink, 2004*
$LF_{N,barn}$	N leaching factor of barn in Eq.S13, depending on floor type of barn	0.05 for unpaved flat floor; 0 for other type of floor	-	Klimont & Brink, 2004*
$LF_{N,playground}$	N leaching factor of playground, depending on floor type of barn	0.1 for unpaved flat floor; 0 for other type of floor	-	Klimont & Brink, 2004*
$LF_{P,barn}$ & $LF_{P,playground}$	P leaching factor in Eq.S14, depending on floor type	0.01 for unpaved flat floor; 0 for other type of floor	-	Klimont & Brink, 2004*
ERF_{store}	NH_3 emission reduction factor of the storage type in Eq.S21	0.95 for closed basin storage; 0.5 for open lagoon storage; 0.2 for open yard storage	-	Klimont & Brink, 2004*

TF	Time factor or NH_3 emission in Eq.S21	0.3 for <=3 days; 0.4 for <=1 week; 0.5 for <=0.5 month; 0.75 for <=1 month; 0.9 for <=3 months; 1 for >3 months		Klimont & Brink, 2004*
EF_{store}	Non-NH_3 emission factor during storage in Eq.S22	0.03 for open yard storage; 0.01 for other storage	-	Klimont & Brink, 2004*
$LF_{N,store}$	N leaching factor during storage in Eq.S23	0.01 for unpaved floor storage; 0 for sealed floor storage	-	Klimont & Brink, 2004*
$LF_{P,store}$	P leaching factor during storage in Eq.S24	0.01 for unpaved floor storage; 0 for sealed floor storage	-	Klimont & Brink, 2004*
$EF_{a,AD}$	Ammonia emission factor of anaerobic digestion in Eq.S31	0.02	-	Klimont & Brink, 2004*
$EF_{a,CM}$	Ammonia emission factor of composting in Eq.S31	0.1733	-	Yang et al., 2019

* Adjusted with additional expert knowledge.

Table S4.2. Characterization of the dairy herd; table used in the farm survey questionnaire.

Question	Unit	Value
1-1 Dairy breed		
1-2 Number of calves	Heads	
1-3 Average weight of calves at 1 year old	kg	
1-4 Number of heifers	Heads	
1-5 Average weight of heifers at 2 years old	kg	
1-6 Number of high yield milking cows	Heads	
1-7 Number of medium yield milking cows	Heads	
1-8 Number of low yield milking cows	Heads	
1-9 Daily milk yield	t/day	
1-10 Content of milk fat	%	
1-11 Content of milk protein	%	

Table S4.3. Characterization of the feed management of the dairy herd; table used in the farm survey questionnaire.

Feed ingredients	Calves	Heifers	High-yield milking cows	Medium-yield milking cows	Low-yield milking cows	Dry cows
Maize silage						
Alfalfa						
Hay						
Oat						
Commercial feeding						
Soybean meal						
Other 1:						
Other 2:						
Other 3:						
Other 4:						
Other 5:						
Other 6:						
Other 7:						
Other 8:						
Other 9:						

Table S4.4. Characterization of the housing system of the dairy herd; table used in the farm survey questionnaire.

	Calves	Heifers	High-yield milking cows	Medium-yield milking cows	Low-yield milking cows	Dry cows
In barn						
• Bedding material						
• Floor type						
• Floor sloping						
• Cleaning method						
• Cleaning frequency						
• Where goes solid manure after cleaning						
• Where goes liquid manure after cleaning						
• Where goes slurry manure after cleaning						
On playground						
• Fraction of time spent on playground						
• Floor type						
• Floor sloping						
• Cleaning frequency						
• Where goes solid manure after cleaning						
• Where goes liquid manure after cleaning						
• Where goes slurry manure after cleaning						

Table S4.5. Characterization of the manure storage systems of the dairy farm; table used in the farm survey questionnaire.

		Solid manure	Liquid manure	Slurry manure
Storage area (m^2)				
Storage depth (m)				
Bottom type（0-soil， 1-anti-leakage bottom）				
Cover (0-without cover， 1-with cover)				
Storage duration (months)				
Where goes manure after storage	Export (%)			
	Applied on own cropland (%)			
	Composting (%)			
	Anaerobic digestion (%)			
	Solid-liquid separation (%)			
	Discharge (%)			
	Other (%)			

Table S4.6. Characterization of the manure composting; table used in the farm survey questionnaire.

Composting type	1-windows composting; 2-trough composting； 3-closed reactor composting; 4-other type composting
Coverage during composting	0-no coverage; 1-closed coverage
Volume of the composting (m^3)	
Where goes the compost product?	Export: %; Applied on own cropland: %; Discharge: %; Further processing: %, specifically:

Table S4.7. Characterization of the anaerobic digestion of cattle manure; table used in the farm survey questionnaire.

Volume of the anaerobic digestion (m^3)	
Days of operating per year (days)	
Gas yield (m^3/day)	
Gas used for	Export: %; Applied on own cropland: %; Discharge: %; Further processing: %, specifically:

Table S4.8. Characterization of the solid-liquid separation of cattle slurry; table used in the farm survey questionnaire.

Type of separation	1- centrifugation and sedimentation； 2- screw and filter pressing； 3-belt pressing; 4-other type
Capacity of separation (m^3/h)	
Where goes the separated solid	Export: %; Applied on own cropland: %; Discharge: %; Further processing: %, specifically:
Where goes the separated liquid	Export: %; Applied on own cropland: %; Discharge: %; Further processing: %, specifically:

Table S4.9. Characterization of the management of the cropland of the dairy farm; table used in the farm survey questionnaire.

Total cropland area managed by the farm (ha)	
Type of the crop cultivated	1-cereal; 2-vegetable; 3-fruit; 4-other type of crops, please specify:
Main purpose of the crop production	1-for domestic usage; 2-for animal production; 3-for selling on the market; 4-other purpose, please specify:
Times of manure application per year	
Amount of manure application per time (m^3/ha)	
Method of solid manure application	1-surface application 2-deep application
Tillage after solid manure application	0-without tillage 1-with tillage
Method of liquid manure application	1-surface application 2-deep application
Irrigation after liquid manure application	0-without irrigation 1-with irrigation

Table S4.10. Summary description of possible measures to improve manure management, NUE and PUE.

Nr	Description of the measures
O1	Diets with higher CP reduced to 159 g/kg for lactating dairy cows, 119 g/kg for heifers and 131 g/kg for calves
O2	Original deep lagoon storage or open field storage changed to leak-tight and covered storage
O3-1	Enlarged manure storage to allow the directly discharged manure to be stored for 1 month, with the assumption that 20% of the stored manure can be exported after storage.
O3-2	Enlarged manure storage to allow the directly discharged manure to be stored for 3 month, with the assumption that 40% of the stored manure can be exported after storage.
O3-3	Enlarged manure storage to allow the directly discharged manure to be stored for 6 month, with the assumption that 80% of the stored manure can be exported after storage.
O4-1	Enlarged solid-liquid separation to allow directly discharged manure to be separated, with assuming that all separated products can be efficiently utilized.
O4-2	Enlarged composting capacity to allow directly discharged manure to be composted, with assuming that all composts can be efficiently utilized.
O4-3	Enlarged anaerobic digestion capacity to allow directly discharged manure to be digested, with assuming that all digestate can be efficiently utilized.
O5-1	O1 & O2 & O3-3
O5-2	O1 & O2 & O4-1

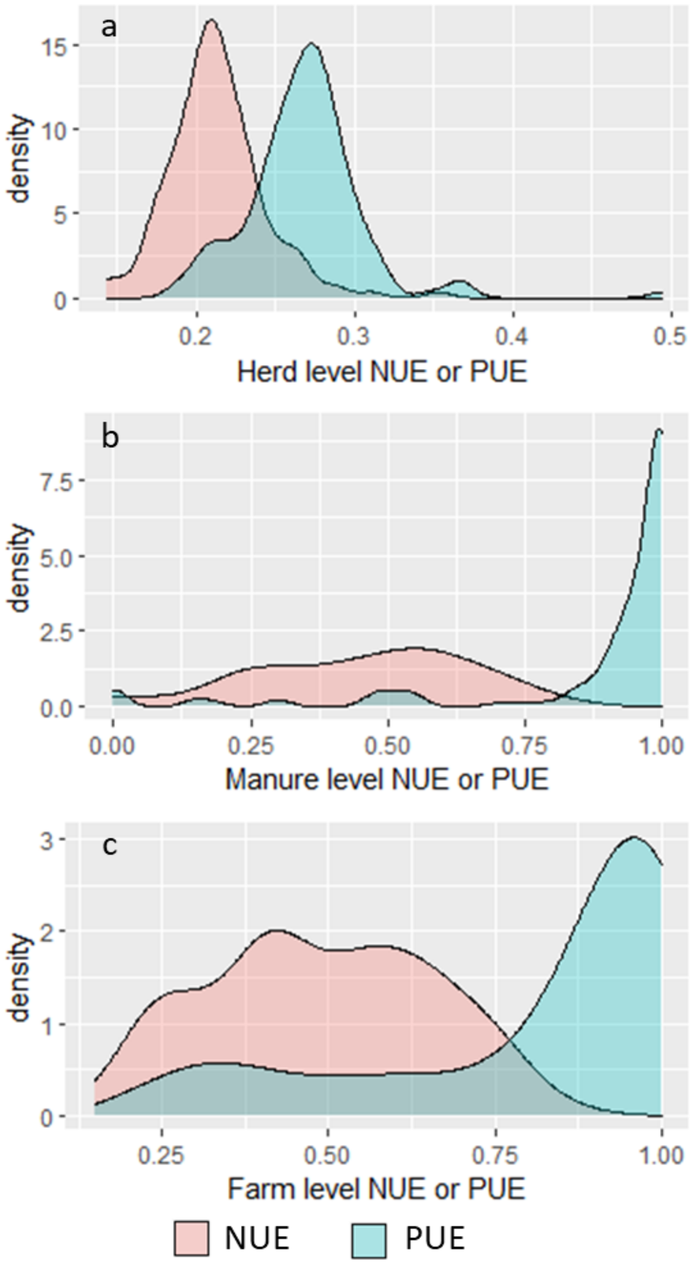


Figure S4.1. Density distribution of NUE and PUE at herd (a), manure (b) and farm (c) level.

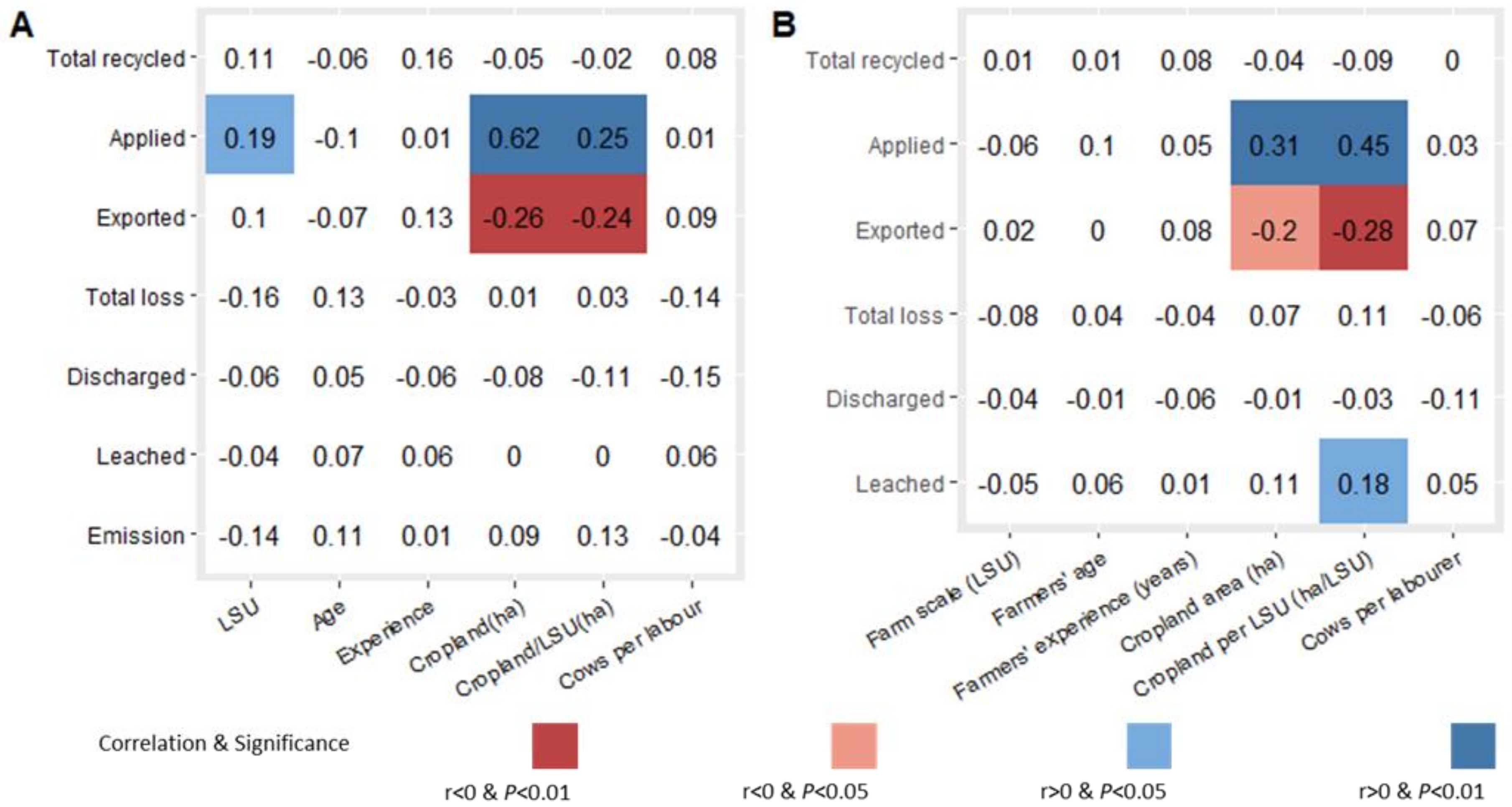


Figure S4.2. Correlation matrix of farm and farmers' characteristics (x-axis) and (A) N flows in kg per 1000 kg FPCM; (B) P flows in kg per 1000 kg FPCM.

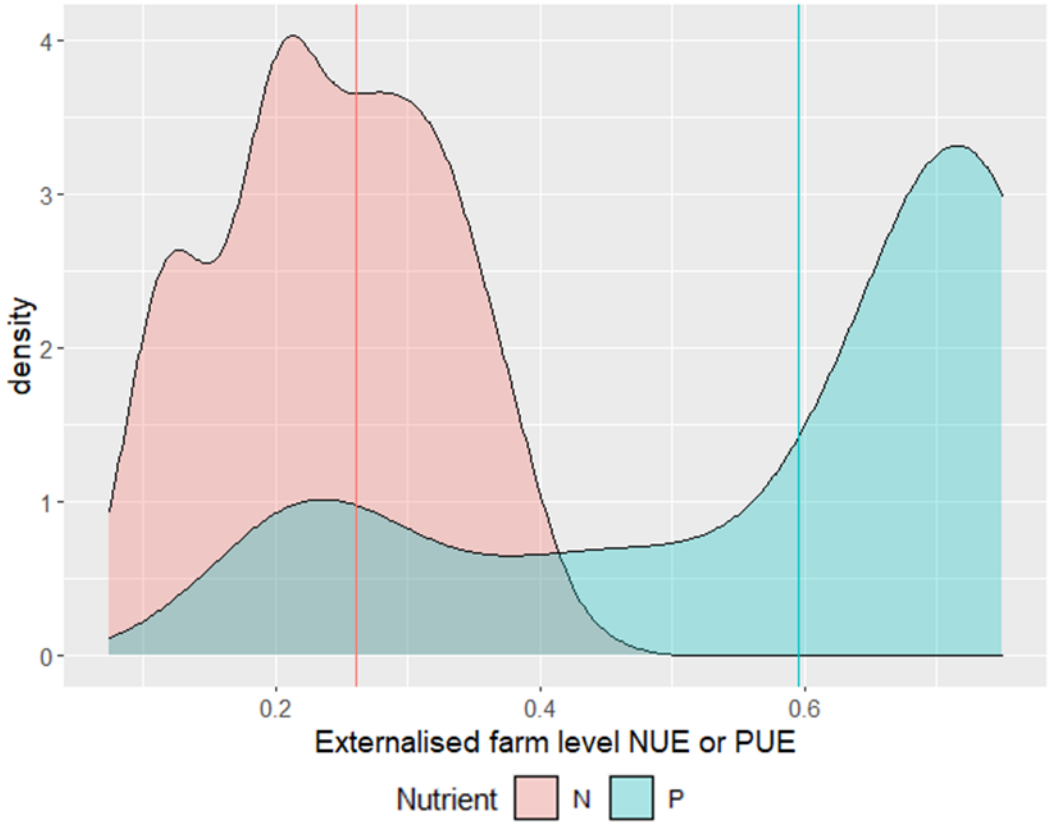


Figure S4.4. Density distribution of externalized farm level NUE and PUE. Lines indicate LSU weighted average of NUE (red line) and PUE (blue line).

III. Detailed description of the uncertainty and sensitivity analyses

To assess the uncertainty of the calculated NUE and PUE, and to explore which factors caused the main uncertainty in the outcome, Monte Carlo simulations were performed using @RISK software (Palisade Corporation). The causes for uncertainty of model outputs are mainly from the inputs and parameters (Zhu et al., 2016). In the context of our model, model inputs refer to farm activity data, such as animal numbers, feed N and P contents, milk yield, housing conditions, manure distributions, etc. The model parameters refer to the excretion and emission factors listed in Table S1.

The analyses included uncertainty quantification (UQ) and sensitivity analysis (SA). The purpose of UQ is to quantify the model output uncertainty in response to input and parameter uncertainty, whereas SA aims to determine how much of the uncertainty of inputs and parameter contributes to the model output uncertainty. Within SA, local and global SA can be distinguished (Hoops et al., 2016). A local SA addresses sensitivity relative to a change of a single parameter value by changing selected parameters by a certain range (for instance ±10%) like Hou et al., 2016 and Sefeedpari et al., 2019 have done. It assumes that the model is approximately linear and the variation of one parameter is not associated with any other parameter. A global analysis examines sensitivity with regard to the entire inputs and parameter distribution according to their distribution function as Uwizeye et al., 2017 have done, and is often used to determine how much each parameter explains the model output variance. A global analysis is also appropriate when it is important to explore a wider span of the input parameter space, or model inputs have combined effects that cannot be reduced to the sum of the individual responses precluding a linear description (Saltellie et al., 2000). Global SA is a central tool in SA since it provides a quantitative and rigorous overview of how different inputs and parameters influence the output.

In our model, there are 110 inputs and 41 parameters and many of these are connected values. Therefore a global sensitivity analysis is more suitable for our study than a local SA. The value of an input or parameter can be sampled from its minimum to maximum value, not in the range of mean ± sd because not all of the parameters fitted a normal distribution. Dependency and logistic relationship were considered in the setting of the inputs and parameters. For example, the fraction of collected slurry from stable being exported, stored, discharged, applied and treated should all have a value from 0-1, at the same time their sum should also be 1. We used our survey data to determine the distribution of the input variables, to ensure that the input variable package is reasonable (Table S11). In addition, we used information from the literature to determine the distribution of coefficients (Table S11).

Table S4.11. Distribution and sources of the parameters and input data for the Monte Carlo (uncertainty) analysis.

Parameters description	**Group[a]**	**Category**	**Distribution type**	**Mean**	**SD**	**min**	**max**	**p**	**source**
Number of dairy cows	LAD	Input	Lognormal	306	480	50	5400		Survey data
Numbers of heifers	LAD	Input	Lognormal	148	247	15	2742		Survey data
Number of calves	LAD	Input	Lognormal	151	174	13	1596		Survey data
Weight of dairy cows	EXE	Input	Normal	649	31	500	800		Survey data
Weight of heifers	EXE	Input	Normal	554	44	350	680		Survey data
Weight of calves	EXE	Input	Normal	312	36	240	500		Survey data
Milk yield per farm	EXE	Input	Normal	8383	1508	3923	14000		Survey data
Milk fat	EXE	Input	Normal	39.7	2.5	33	47		Survey data
Milk protein	EXE	Input	Normal	33.3	1.4	30	38		Survey data
Feed protein content of dairy cows	EXE	Input	Normal	159	16	90	203		Survey data
Feed protein content of heifers	EXE	Input	Normal	137	23	72	195		Survey data
Feed protein content of calves	EXE	Input	Normal	139	25	72	217		Survey data
Feed digestibility of dairy cows	EXE	Input	Normal	0.693	0.073	0.505	0.854		Survey data
Feed digestibility of heifers	EXE	Input	Normal	0.625	0.052	0.487	0.798		Survey data

Feed digestibility of calves	EXE	Input	Normal	0.632	0.058	0.500	0.826	Survey data
Feed P content	EXE	Input	Normal	4.0	0.4	2.0	5.0	Survey data
Maintenance coefficient	EXE	Parameter	Normal	22	4	15	30	Estimation
Feed conversion coefficient	EXE	Parameter	Normal	5.5	1	3	8	Estimation
Liveweight gain of dairy cows	EXE	Parameter	Normal	45	4.5	40	50	Estimation
Fraction of manure dropping on playground of heifers and calves	EFH	Input	General			0	1	Survey data
NH_3 emission reduction factor of playground floor	EFH	Parameter	Normal	1	0.25	0.7	1.3	Hou et al., 2017
NH_3 emission reduction factor of stable floor	EFH	Parameter	Normal	1	0.25	0.7	1.3	Hou et al., 2017
NH_3 emission reduction factor of cleaning frequency	EFH	Parameter	Normal	1	0.25	0.7	1.3	Hou et al., 2017
N and P leaching factors in housing	EFH	Parameter	Normal	1	0.25	0.7	1.3	Hou et al., 2017
Non-ammonia N emission factor	EFH	Parameter	Lognormal	1	0.34	0.7	1.3	Hou et al., 2017; Zhang et al., 2019
Fraction of manure stored	TAD	Input	General			0	1	Survey data
Fraction of manure discharged, exported, applied to cropland, and treated	TAD	Input	Uniform			0	$1\text{-}F_{store}$	Estimation

NH_3 emission reduction factor of manure storage	EFS	Parameter	Normal	1	0.25	0.7	1.3	Hou et al., 2017
Duration of manure storage	EFS	Input	General			0	1	Survey data
Time factor of NH_3 emission from storage	EFS	Parameter	Normal	1	0.25	0.7	1.3	Estimation
N and P leaching factor of storage	EFS	Parameter	Normal	1	0.25	0.7	1.3	Hou et al., 2017
Non-ammonia N emission factor of storage	EFS	Parameter	Lognormal	1	0.34	0.7	1.3	Hou et al., 2017; Zhang et al., 2019
Fraction of total nitrogen in separated liquid	EFT	Parameter	Uniform			0.63	0.9	Hou et al., 2017; Zhang et al., 2019
Fraction of total ammonic nitrogen in separated liquid	EFT	Parameter	Uniform			0.7	1	Hou et al., 2017; Zhang et al., 2019
Fraction of phosphorus in separated liquid	EFT	Parameter	Normal	0.15	0.0375	0.105	0.195	Hou et al., 2017; Zhang et al., 2019
Fraction of separated solid stored, exported and applied	EFT	Input	Uniform			0	1	Estimation
NH_3 emission factor of separated products	EFT	Parameter	Normal	0.1	0.05	0.07	0.13	Hou et al., 2017; Zhang et al., 2019
N_2O emission factor of separated products	EFT	Parameter	Normal	0.05	0.025	0.035	0.065	Hou et al., 2017; Zhang et al., 2019

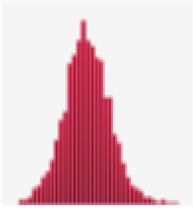
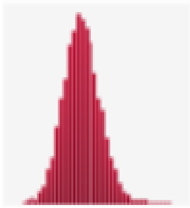
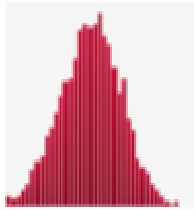
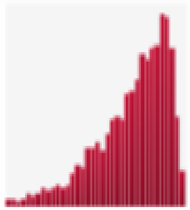
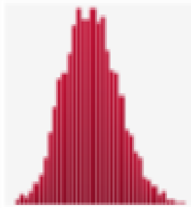
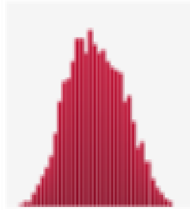
Fraction of separated products applied, discharged and exported	TAD	Input	Uniform			0	1		Estimation
NH_3 emission factor of digestate	EFT	Parameter	Normal	0.02	0.01	0.014	0.026		Hou et al., 2017; Zhang et al., 2019
Non-ammonia N emission factor of digestate	EFT	Parameter	Lognormal	0.05	0.017	0.035	0.065		Hou et al., 2017; Zhang et al., 2019
Fraction of digestate applied, discharged and exported	TAD	Input	Uniform			0	1		Estimation
NH_3 emission factor of compost	EFT	Parameter	Normal	0.1733	0.1022	0.1213	0.2253		Hou et al., 2017; Zhang et al., 2019
Non-ammonia N emission factor of compost	EFT	Parameter	Normal	0.03	0.012	0.021	0.039		Hou et al., 2017; Zhang et al., 2019
Cropland/LSU ratio	EFA	Input	Expon			0	0.37	0.01	Survey data
NH_3 emission factor of applied slurry from housing	EFA	Parameter	Normal	0.4	0.1				Mattila & Joki-Tokola, 2003; Hou et al., 2017
NH_3 emission factor of applied solid from housing	EFA	Parameter	Normal	0.132	0.033				da Silva Cardoso et al., 2019; Hou et al., 2017
NH_3 emission factor of applied liquid from housing	EFA	Parameter	Normal	0.0888	0.0222				Singh et al., 2013; Hou et al., 2017

NH_3 emission factor of applied stored slurry and solid	EFA	Parameter	Normal	0.2	0.05			Rotz, 2004; Hou et al., 2017
NH_3 emission factor of applied stored liquid	EFA	Parameter	Normal	0.264	0.066			Whitehead & Raistrick, 1993; Hou et al., 2017
NH_3 emission factor of applied stored separated solid	EFA	Parameter	Normal	0.1	0.025			Estimation
NH_3 emission factor of applied separated liquid	EFA	Parameter	Normal	0.255	0.063			Thompson et al., 1987; Hou et al., 2017
NH_3 emission factor of applied composting product	EFA	Parameter	Normal	0.59	0.15			Mattila & Joki-Tokola, 2003; Hou et al., 2017
NH_3 emission factor of applied digestate	EFA	Parameter	Normal	0.143	0.036			Saunders et al; 2012; Hou et al., 2017
N_2O emission factor of applied slurry and solid from housing	EFA	Parameter	Lognormal	0.0033	0.001	0.002	0.005	Thorman et al., 2020
N_2O emission factor of applied liquid from housing	EFA	Parameter	Lognormal	0.0165	0.005	0.01	0.025	Singh et al., 2013

N_2O emission factor of applied stored slurry and solid	EFA	Parameter	Lognormal	0.0046	0.0014	0.003	0.006	Thorman et al., 2020
N_2O emission factor of applied stored liquid	EFA	Parameter	Lognormal	0.0175	0.01	0.007	0.025	Pelster et al., 2012
N_2O emission factor of applied separated solid and composting product	EFA	Parameter	Lognormal	0.005	0.0018	0.003	0.007	Estimation
N_2O emission factor of applied separated liquid	EFA	Parameter	Lognormal	0.069	0.023	0.045	0.09	Thompson et al., 1987
N_2O emission factor of applied digestate	EFA	Parameter	Lognormal	0.03	0.009	0.02	0.04	Saunders et al., 2012

[a] LAD: livestock production data (i.e. animal numbers); EXE: parameters or inputs used for calculating nutrient excretion; EFH: parameters or inputs used for calculating losses from housing; EFS: parameters or inputs used for calculating losses from manure storages; EFT: parameters or inputs used for calculating losses during manure treatment; EFA: parameters or inputs used for calculating losses during manure application to land.

Table S4.12. Uncertainty analysis of the nutrient use efficiencies at herd, manure and farm levels.

	NUE_{herd}	PUE_{herd}	NUE_{manure}	PUE_{manure}	NUE_{farm}	PUE_{farm}
Graphs						
Min	0.08272	0.10026	0.00198	0.00325	0.13909	0.17259
Max	0.37376	0.50416	0.73443	0.99445	0.77251	0.99965
Mean	0.20651	0.26174	0.36119	0.70816	0.42289	0.58465
SD	0.04046	0.04818	0.12415	0.19654	0.09981	0.14839
CV(%)	20	18	34	28	24	25
Percentile						
5%	0.13962	0.18528	0.14730	0.31106	0.26765	0.35546
95%	0.27349	0.34274	0.55969	0.93939	0.59508	0.83815

This table shows the uncertainty range of the NUE and PUE at various levels, as obtained from our model calculations. The x-axis of the graphs indicates the value of NUE or PUE while the y-axis of the graphs indicates the frequency; the total area of the red bars in a graph is 1. Results indicate that PUE_{manure} is skewed to the right while PUE_{system} is skewed to the left. Other NUEs and PUEs are generally normally distributed. This table indicates the ranges of NUE and PUE at a dairy farms, from very poorly managed farms to a very good managed farms.

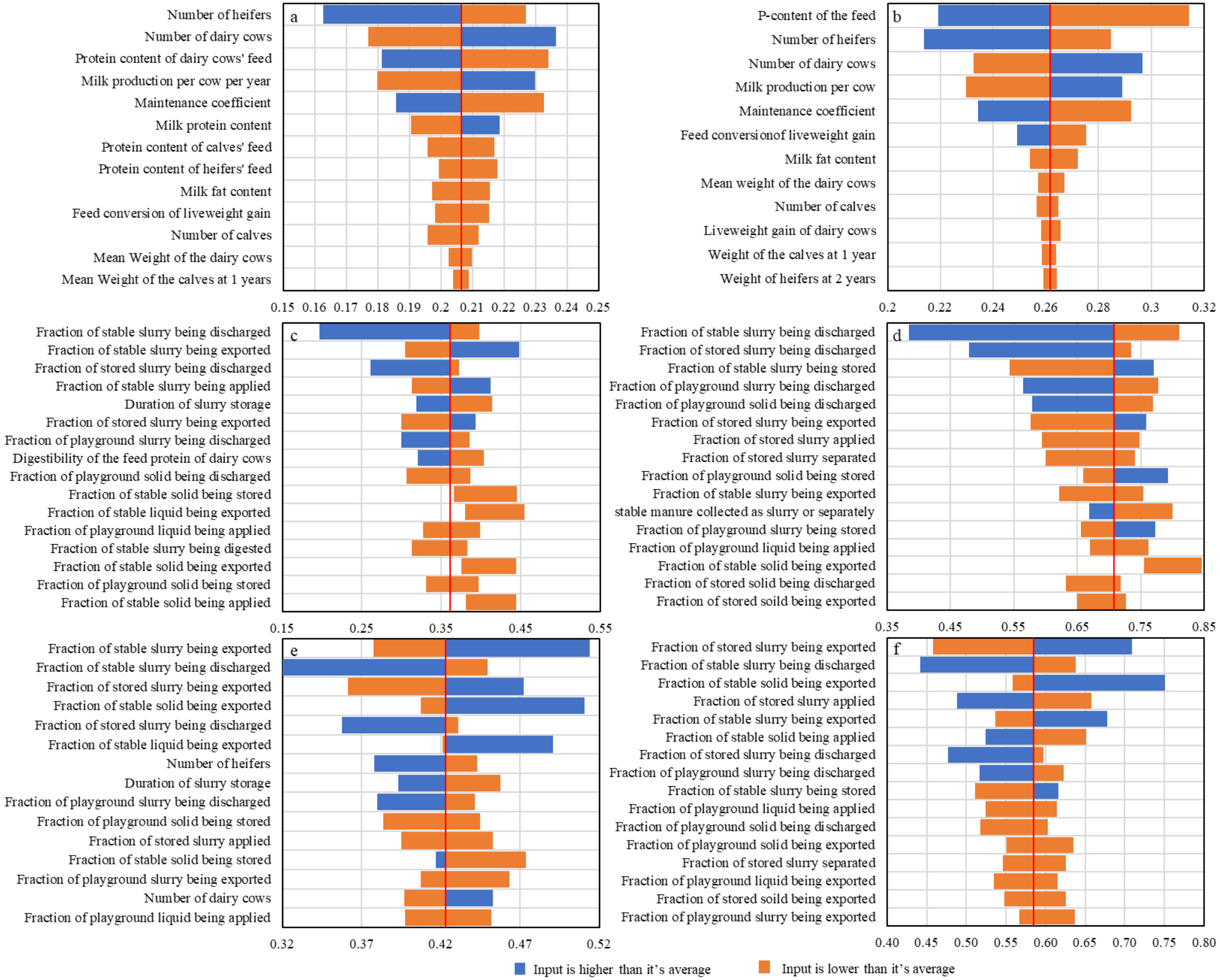

a
Number of heifers
Number of dairy cows
Protein content of dairy cows' feed
Milk production per cow per year
Maintenance coefficient
Milk protein content
Protein content of calves' feed
Protein content of heifers' feed
Milk fat content
Feed conversion of liveweight gain
Number of calves
Mean Weight of the dairy cows
Mean Weight of the calves at 1 years
0.15 0.16 0.17 0.18 0.19 0.2 0.21 0.22 0.23 0.24 0.25
b
P-content of the feed
Number of heifers
Number of dairy cows
Milk production per cow
Maintenance coefficient
Feed conversionof liveweight gain
Milk fat content
Mean weight of the dairy cows
Number of calves
Liveweight gain of dairy cows
Weight of the calves at 1 year
Weight of heifers at 2 years
0.2 0.22 0.24 0.26 0.28 0.3 0.32
c
Fraction of stable slurry being discharged
Fraction of stable slurry being exported
Fraction of stored slurry being discharged
Fraction of stable slurry being applied
Duration of slurry storage
Fraction of stored slurry being exported
Fraction of playground slurry being discharged
Digestibility of the feed protein of dairy cows
Fraction of playground solid being discharged
Fraction of stable solid being stored
Fraction of stable liquid being exported
Fraction of playground liquid being applied
Fraction of stable slurry being digested
Fraction of stable solid being exported
Fraction of playground solid being stored
Fraction of stable solid being applied
0.15 0.25 0.35 0.45 0.55
d
Fraction of stable slurry being discharged
Fraction of stored slurry being discharged
Fraction of stable slurry being stored
Fraction of playground slurry being discharged
Fraction of playground solid being discharged
Fraction of stored slurry being exported
Fraction of stored slurry applied
Fraction of stored slurry separated
Fraction of playground solid being stored
Fraction of stable slurry being exported
stable manure collected as slurry or separately
Fraction of playground slurry being stored
Fraction of playground liquid being applied
Fraction of stable solid being exported
Fraction of stored solid being discharged
Fraction of stored soild being exported
0.35 0.45 0.55 0.65 0.75 0.85
e
Fraction of stable slurry being exported
Fraction of stable slurry being discharged
Fraction of stored slurry being exported
Fraction of stable solid being exported
Fraction of stored slurry being discharged
Fraction of stable liquid being exported
Number of heifers
Duration of slurry storage
Fraction of playground slurry being discharged
Fraction of playground solid being stored
Fraction of stored slurry applied
Fraction of stable solid being stored
Fraction of playground slurry being exported
Number of dairy cows
Fraction of playground liquid being applied
0.32 0.37 0.42 0.47 0.52
f
Fraction of stored slurry being exported
Fraction of stable slurry being discharged
Fraction of stable solid being exported
Fraction of stored slurry applied
Fraction of stable slurry being exported
Fraction of stable solid being applied
Fraction of stored slurry being discharged
Fraction of playground slurry being discharged
Fraction of stable slurry being stored
Fraction of playground liquid being applied
Fraction of playground solid being discharged
Fraction of playground solid being exported
Fraction of stored slurry separated
Fraction of playground liquid being exported
Fraction of stored soild being exported
Fraction of playground slurry being exported
0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80
Input is higher than it's average
Input is lower than it's average

Figure S4.3. Results of the sensitivity analysis of the effects of uncertainties in inputs and parameters on the nutrient use efficiencies at herd, manure and farm level. a: NUE at herd level; b: PUE at herd level; c: NUE at manure level; d: PUE at manure level; e: NUE at farm level; f: PUE at farm level. The x-axis indicates the value of NUEs and PUEs (expressed in fractions, i.e. kg/kg). The red lines indicate the average mean of the NUEs and PUEs from the 5000 iterations. The sensitivity decreases from top to bottom. The blue bars indicate that the minimum or maximum efficiency was derived at a value that is higher than the average of the factor, while the orange bars indicate that the minimum or maximum efficiency was derived at a value that is lower than the average of the factor. So a blue bar at the right and orange bar at the left indicates the positive influence of the factor and vice versa. Orange bars at both sides indicate that both the minimum and the maximum efficiency are derived with values lower than the average of the factor.

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Chapter 5 Relationships between livestock density and soil phosphorus contents - County and farm level analyses

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Abstract

Soil fertility of cropland depended in part on the local availability of livestock manure, and vice versa, until cheap synthetic fertilizers arrived on the market. The relationship between soil fertility and livestock density at farm and regional levels became further entangled through spatial decoupling of intensive livestock and crop farms, notably in developed countries. Understanding this relationship is important for spatial planning of livestock farms and for manure management and treatment. This paper addresses the relationships between livestock density and soil phosphorus content at farm and regional levels in Hebei (CN), which experienced very rapid developments in livestock production systems. County level relationship were explored using existing databases with livestock density and statistics on Olsen-P contents. Farm level relationships were explored on the basis of a farm survey among 80 livestock farms and 480 crop farms, and analyses of total phosphorus (TP) and oxalate-extractable phosphorus (Pox) in topsoil (0-15 cm) and subsoil (15-30 cm) of 562 fields. Results indicate that mean Olsen-P (range: 9 to 41 mg/kg) did not have clear relationships with mean livestock density (range 0.4 to 16.0 LSU/ha) in the 167 counties. There was also no clear relationship between livestock density and TP and OP contents of topsoil and subsoil at farm level. However, livestock farms with cropland tended to have higher TP and Pox contents in soil than crop farms without livestock. Most livestock farms had little cropland; they applied excessive amounts of manure N and P to on-farm cropland and exported manure to nearby crop farms, within a distance of 5 km. Manure application on crop farms depended on crop types; 21% of cereal fields, 31% of cotton fields, 58% of the orchards, and 65% of the vegetable fields received manure regularly. In total, 21% of the fields from livestock farms and 41% of the fields from crop farms had higher TP contents in the subsoil than topsoil, suggesting P leaching. In conclusion, we did not find clear relationships between mean livestock density and mean TP contents in the topsoil and subsoil of cropland at farm and county levels, likely due to confounding factors. Our results indicate that livestock manures are not well utilized. There is a need for manure application limits, especially on livestock farms, and incentives for improved manure distribution and utilization.

5.1 Introduction

The global food system has to transform to a more sustainable system, with healthy diets and healthy food production systems, through radical improvement of technology and management, to be able to realize the United Nations Sustainable Development Goals (SDGs) under the expected global population growth (Willett et al., 2019). This mission includes unprecedented challenges for soils and soil management. Soils play a key role in realizing the SDGs related to food, water, climate health and biodiversity (Bouma and Montanarella, 2016; Keesstra et al., 2016), and for the functioning of terrestrial ecosystems (Blum, 2005; Bünemann et al., 2018). The functioning of the soil itself depends on its composition, the surrounding environmental conditions, and its management. Soil tillage, fertilization, irrigation and drainage, crop rotation and pest management are among the most critical soil management factors (Rietra et al., 2022), influencing the realization of the SDGs related to food, water, climate health and biodiversity.

Phosphorus (P) is an essential nutrient for plants, animals and humans, and the second most limiting nutrient (after nitrogen) in global crop production (Janssen & De Willigen, 2006; Mueller et al., 2012). Phosphorus is often also a main culprit for water eutrophication (Lajtha & Jarrell, 1999; Carpenter, 2005). Phosphorus enrichment or depletion in soil depend on the balance between input (mainly through application of organic and inorganic fertilizers) and output (mainly through P withdrawal with harvested crops). Since the primary resources for synthetic P fertilizers in the world are finite and non-renewable (Cordell et al., 2009), and its losses may threaten ecosystem health, increasing phosphorus recycling and reducing phosphorus losses are essential elements for sustainable intensification of global food systems (Schröder et al., 2011 Jordan‐Meille et al., 2012; Willett et al., 2019)

Farmers relied heavily on animal manure for maintaining or increasing soil P contents, until affordable synthetic fertilizers arrived on the market. This holds as well for other nutrients essential for plant growth. As P is rather immobile in soil, application of P in excess of the amount of P withdrawn with harvested crop results in soil P accumulation. Thus, farms and regions with high livestock density usually have high soil P contents, especially when the livestock farms import animal feed from elsewhere (Reijneveld, 2013; Tóth et al., 2014). Commonly, there is also a gradient in the soil P content of cropland around the homestead, because farmers preferentially allocate animal manure and wastes nearby to save labour (Tittonell et al, 2005; Giller et al., 2011). The surplus manure P accumulates in the topsoil (Smith et al., 1998), but when the soil P level increases, the risk of P leaching to the subsoil and to surface waters following run-off and erosion also increases (Djodjic et al., 2004; Hussain et al., 2021). This raises the question of how intensive livestock farms can manage livestock manures in a sustainable manner. The 1991 EU Nitrates Directive demands for application limits of animal manure and fertilizers, especially when nutrient leaching losses pollute groundwater and/or surface waters (e.g., Schröder & Neeteson, 2008; Sommer and Knudsen, 2021), but many developing countries with increasing livestock density do not have such regulations yet.

Chinese agriculture experienced a seismic transformation as regards manure and fertiliser use during the last few decades. Farmers relied on animal excreta for supplementing soil nutrients before synthetic fertilizers became widely available, from the 1980s (Chadwick et al., 2015). Since then, crop farmers increasingly used synthetic fertilizer and disregarded animal manure, because synthetic fertilizers are relatively cheap and easy to handle, and farmers preferentially allocate labour to off-farm work and give no priority to manure use (Jin et al., 2021; Chadwick et al., 2015). Application of synthetic P fertilizer increased from 1.2 Tg P per year in 1980 to 6.2 Tg P per year in 2010 (FAOSTAT, 2022). At the same time, livestock production and thus manure production greatly increased, especially in densely populated areas; a total of 4.6 Tg manure P was produced by 2010, but only half was recycled to cropland (Bai et al., 2013). Manure became a main source of ammonia volatilization, greenhouse gas emission, and water eutrophication (Steinfeld, 2006; Huang et al., 2014; Strokal et al., 2016). The new intensive livestock farms became nearly landless and spatially decoupled from crop farms, and manure became a burden for both livestock farms and the society. Recent governmental policies encourage farmers to treat manure and to recycle it to cropland, so as to partially replace synthetic fertilizers, increase crop yields, prevent soil degradation and mitigate pollution (Zhang et al., 2019a; Zhang et al., 2020; Du et al., 2020). However, implementation of these policies in practice is still limited (Tan et al., 2021).

Spatial planning of livestock production has been suggested recently as strategy to tackle air and water pollution caused by nitrogen (N) from surplus amounts of manure in China (Bai et al., 2022) and Europe (Van Grinsven et al., 2018). Such a strategy may be equally relevant for regions coping with risks of soil P leaching and runoff following excessive applications of manure P. Possible alternative strategies for these regions include manure treatment and export, and low protein and low P animal feeding (Powell et al., 2002; Withers et al., 2015). The need for such strategies depends in part on soil P contents and the risk of soil P leaching and runoff. Previous studies reported that manure and fertilizer application differs among crop types, with cash crop (e.g. vegetable, fruit, cotton, etc) receiving high nutrient inputs (Ju et al., 2006; Chadwick et al., 2015). Zhang et al., (2021) reported that a higher percentage of cash crop farmers applied manure than cereal farmers. However, the current spatial variations of soil P contents and their relationship with livestock density have not been examined yet.

The general purpose of our study was to reveal the relationships between livestock density, manure distribution and soil phosphorus content at farm and regional levels in Hebei, China, so as to define the needs for improved manure distribution and/or spatial planning of livestock farms. We hypothesized (i) that regions and farms with high livestock density have higher P content in the topsoil and possibly also in the subsoil (because of P leaching) than regions and farms with low livestock density; (ii) that cropland of livestock farms has higher P contents than cropland of crop farms, and iii) that cropland with cash crops have higher P content than cropland with cereal crops. We analyzed data from existing databases to explore the relationship mean between livestock density and mean Olsen-P of the topsoil in the 167 counties in Hebei, and we conducted a farm survey with soil sampling campaign on 80 livestock farms and 480 crop farms in 8 counties, to analyze the relationship between livestock density and total P content in the topsoil and subsoil at farm level, as function of farm type and crop type. The results of our study will be helpful to understand the cause of variations in soil P contents and to guide nutrient management planning at farm and regional levels.

5.2 Materials and methods

5.2.1 Description of the study area

Hebei province surrounds Beijing, China, and is one of the main crop and livestock production areas in China. The topography of the province is characterized by mountain ridges and tablelands in the northwest and low plains in the southeast. It is in the temperate-continental monsoon climate zone with cold, dry winters and hot, humid summers. Mean annual temperature ranges from −16 to −3 °C in January to 20 to 27 °C in July. Mean annual precipitation ranges from 300 to 800 mm, of which 70-80% occurs in June to September (Gu et al., 2013; Ma et al., 2021). Yearly evapotranspiration ranges from 215 mm to 615 mm, depending on geographic location (Wang et al., 2018). There are 21 soil types, with Cinnamon soils, Fluvo-aquic soils, Brown earths, and Castanozems predominating (Gu et al., 2013). In 2018, Hebei had 74.3 million inhabitants (population density 396 km^{-2}). Administratively, there are 11 cities, which together have 167 counties (i.e., a city has on average 15 counties). Each county has on average 292 villages, each with on average 318 farm households. In total there were about 15.5 million farm households in 2018.

Total cropland area was 6.6 Mha, with 76% cereals (mainly wheat and maize), 10% vegetables, and 7% fruits in 2018 (National Bureau of Statistics). Total cropland area has kept stable since 2007; however the area of cereals slightly increased and that of fruit slightly decreased, also because the government encourages farmers to grow water-saving crops (Figures S5.1, S5.2; Li et al., 2021). These changes mainly showed up in southeast counties (Figures S5.3, S5.4). Most crop farmers are part-time farmers; on average 0.48 ha of cropland was managed by a single family in 2016, with several smaller fields scattered around villages (Statistic Bureau of Hebei, 2018).

Livestock production has been increasing since 1950 (Chadwick et al., 2015). Statistics show a drop in the number of animals in 2006, due to a change of the accounting method; very small farms were excluded from the accounting from 2007 onwards (Figure S5.1). There are significant differences among counties: for example, some counties showed strong increases in poultry production and decreases in sheep (& goat) production, while other counties showed increases in sheep (& goat) production (Figures S5.5, S5.6). Mean livestock density was 4.4 LSU/ha at provincial level in 2016, ranging from 0.06 LSU/ha to 38.6 LSU/ha at the county level (Figure S5.7). The number of counties with relatively low livestock density (≤4.00 LSU/ha) increased while the number of counties with high livestock density (>4.00 LSU/ha) decreased when comparing the years 2016 and 2006 (Figures S5.7, S5.8), indicating that livestock density has become more uniform at county level (but note the neglect of small farms from 2007 in the accounting). Mean livestock density at farm level increased greatly. The percentage of animals in intensive livestock farms doubled between 2007 and 2017 (the percentage dairy cows in intensive dairy farms increased even 4 times, Table S5.1). Unfortunately, there is a lack of high-resolution livestock data and fertilizer input data over longer time periods.

5.2.2 Collection of county-level data

To test the hypothesis that counties with high livestock density have higher P content in the topsoil than counties with low livestock density, county-level livestock number and soil phosphorus data were collected. The number of animals and the area of cropland per county in 2016 were derived from the Statistical Yearbooks 2017 from each city, and used to calculate mean livestock density. Soil phosphorus data (Olsen-P contents) were derived from the national database of scientific fertilization (http://kxsf.soilbd.com/); this database provides means, standard deviations, and 5 and 95 percentile values of Olsen-P contents of the topsoil from 157 counties. The database is an aggregation of results from the second national soil survey and scientific research during the past four decades. The number of soil samples ranged from 10 to 10582 per county, with an average of 3349 per county. The reasons for this wide variation are not well-known; variations likely reflect differences in activity between agriculture bureaus per city/county, and experimental field studies conducted by universities and agricultural bureaus in some counties/cities.

5.2.3 Collection of farm-level data – a case-study

5.2.3.1 Selection of counties and farms

For testing the hypothesis that livestock density and crop type influences manure application and soil P content in topsoil and subsoil, the 167 counties in Hebei were divided into 8 groups according to (i) high/low livestock density; (ii) high/low areas of cereals; (iii) high/low areas of cash crops in 2016. For each group one county was selected to examine the relationship between livestock density and soil P content at farm level, and as function of farm type and dominant crop type. The 8 counties were selected in close proximity, so as to keep the environmental conditions and soil type approximately similar. Mean livestock density and changes over time in livestock density in the selected counties are provided in Figure S5.9. Within each county, 10 livestock farms were selected randomly. To test the hypothesis that cropland of livestock farms had higher soil P content than the cropland of crop farms, we selected and examined 6 crop farms per livestock farm randomly around the livestock farm (note that crop farms are much smaller than livestock farms). In total 80 livestock farms and 480 crop farms were visited and examined (Figure S5.10).

5.2.3.2 Farm survey

To collect information on manure production and use, livestock farmers were asked for the categories and numbers of animals, the areas of cropland and type of crops, the changes over time in animals and cropland, and manure use and exportation. Crop farmers were asked for the area of cropland, crop types, manure and fertilizer uses, and changes over time in manure and fertilizer use. The geographic location of the fields where soil was sampled was recorded, as well as the distance to the nearest livestock farms.

5.2.3.3 Soil collection and analyzing

Soil samples were collected from the largest land plots of the farms in December 2020 (during this time no manure or fertilizers were applied and no precipitation occurred). For farms planting two or more types of crops, two plots were sampled, for other farms just one plot per farm was sampled. Ten soil cores (0-30 cm depth) were collected from each plot by using a 3-cm-diameter auger, when walking in a “W”-like pattern over the plot. Samples were separated into 0-15 cm (topsoil) and 15-30 cm (subsoil) layers, because tillage depth is usually 10 to 15 cm in Hebei. Subsamples were bulked and carefully mixed (after removing visible stones and plant residues) to form two composite samples per field. In total 1124 soil samples (562 topsoil and 562 subsoil samples) were collected for testing.

The samples (about 1 kg) were air-dried and sieved at 2 mm in Quzhou experimental station of China Agricultural University in Hebei. The sieved samples were then transported to the Netherlands for testing soil properties using standard and certified procedures at Eurofins Agro (https://www.eurofins-agro.com). All samples were analyzed for texture, soil organic matter, total phosphorus (TP), and oxalate-extractable phosphorus (Pox) using near-infrared spectroscopy (NIRS). The NIRS-spectra were calibrated to the results of conventional soil analyses using a large database and advanced statistical calibration techniques (Reijneveld et al., 2014a; Reijneveld et al., 2022). In addition, a selection of 195 soil samples was extracted with 0.01 M $CaCl_2$ (1:10 soil to solution ratio; w/v) followed by discrete analysis and ICP-AES / ICP-MS under controlled conditions for assessing plant available nutrients. Further, selections of 150 to 200 samples were analyzed according to conventional procedures, to validate the results of NIRS for texture, soil organic matter, total N, and oxalate extractable phosphorus (Pox) (Reijneveld et al., 2022). Relationships between results obtained with NIRS and conventional methods for texture, SOM, pH, total N, were linear, with regression coefficients ranging between 0.92 to 1.00, and correlations coefficients (R^2) ranging from 0.88 to 0.97. Relationships were less good for Pox (regression coefficient = 1.12; R^2 = 0.72).

5.2.4 Data processing and statistical analysis

County level relationship between mean Olsen-P content and mean livestock density were analyzed using Pearson correlation. Mean TP and Pox contents of fields from livestock farms were statistically compared to mean TP and Pox contents of fields from nearby crop farms. To test whether manure application frequency was influenced by the nearby availability of manure, Spearman ranking correlation was conducted between manure application frequency and the distance to nearest livestock farm. Differences in the TP and Pox contents among farm types and crop types, and among different distances to livestock farms were analyzed using Tukey

HSD (honestly significant difference) test. Relationships between soil nutrient content and livestock density were analyzed using linear regression based on ordinary least squares (OLS). All of the data processing and analysis were performed in R programming language (R core team, 2021).

5.3 Results

5.3.1 Relationship between mean livestock density and mean Olsen-P at county level

Mean Olsen-P contents of the topsoil of counties were normally distributed and ranged from 8.9 mg/kg to 41.4 mg/kg with a skewness of 0.22. The 95 percentile values of Olsen-P contents of the topsoil of counties were also normally distributed and ranged from15.2 mg/kg to 98.3 mg/kg with a skewness of 0.23 (Figure S5.11). There was no clear spatial pattern of mean Olsen-P contents (Figure S5.12), and also no clear relationship between mean livestock density and mean Olsen-P content at county level (Figures 5.1, S5.13). Yet, there was a positive correlation between mean Olsen-P and mean livestock density according to the Pearson Correlation analysis ($r=0.21$, $P<0.05$), which indicates that Olsen-P tended to increase with livestock density. This is somewhat a surprising result, given the wide ranges in mean livestock density and mean Olsen-P contents. However, the Olsen-P results in the database were derived from different sources and the samples were collected over a time span of nearly 40 years, with most of the samples likely collected during the last one or two decades. Unfortunately, we have no access to the underlying data and sampling protocol.

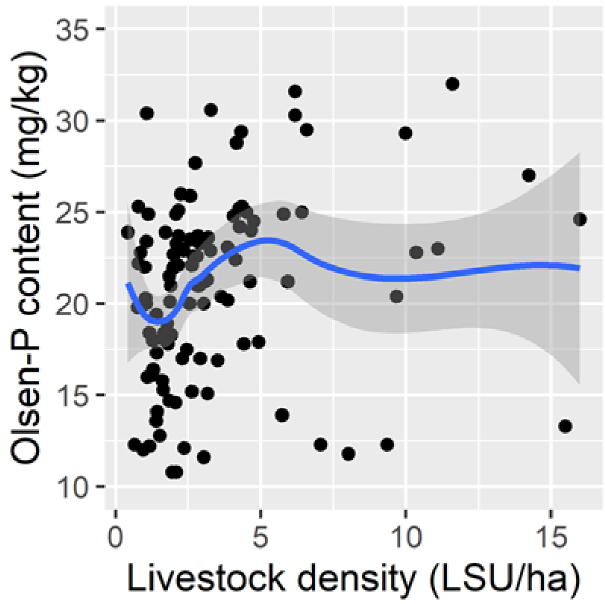

Figure 5.1. Relationship between mean livestock density and mean Olsen-P contents at county level. Each dot represents a county. The blue line and shadow are locally weighted regression lines and their 95% confidence intervals, respectively, generated by R programming language. Data derived from existing databases as described in section 5.2.2.

5.3.2 Manure use on surveyed crop and livestock farms

The 80 livestock farms had on average 9.5 ha cropland, but 24 farms had no cropland (were landless). About 87% of the cropland area on livestock farms was used to produce cereals (mainly wheat and maize) and 9% was used to produce vegetables. Mean livestock density at farm level was 50 LSU/ha. Most livestock farms produced more manure than could be disposed of on on-farm cropland, and thus exported manure to nearby crop farms (Table S5.2), mostly within 5 km distance (Figure 5.2a). Almost all fields of the livestock farms received manure at least once a year, regardless of crop type (Figure 5.2b). Unfortunately farmers did not know how much manure was applied to on-farm cropland and how much manure was exported to crop farms.

The 480 crop farms had on average 1.7 ha cropland. Most of the cropland (54%) was used to grow cereals, 25% to grow vegetables, 11% to grow fruit, and 11% was used to grow other crops (cotton, nuts, etc, Table S5.2). Manure application frequency was not significantly related to the distance between livestock farms and crop farms (Figure 5.2c, $P>0.05$). Amounts of manure applied to cropland are not known by farmers, but fields at a distance of ⩾5 km from livestock farms received manure less frequently than fields at ⩽5 km distance from livestock farms (Figure 5.2c). Meanwhile, 65% of the fruit orchards and 58% of the vegetable fields of crop farms received manure, while cereal fields (21%) and cotton fields (31%) received manure less frequently (Figure 5.2b). Manure was applied less frequently on fields from crop farms than on fields from livestock farms (Figure 5.2b).

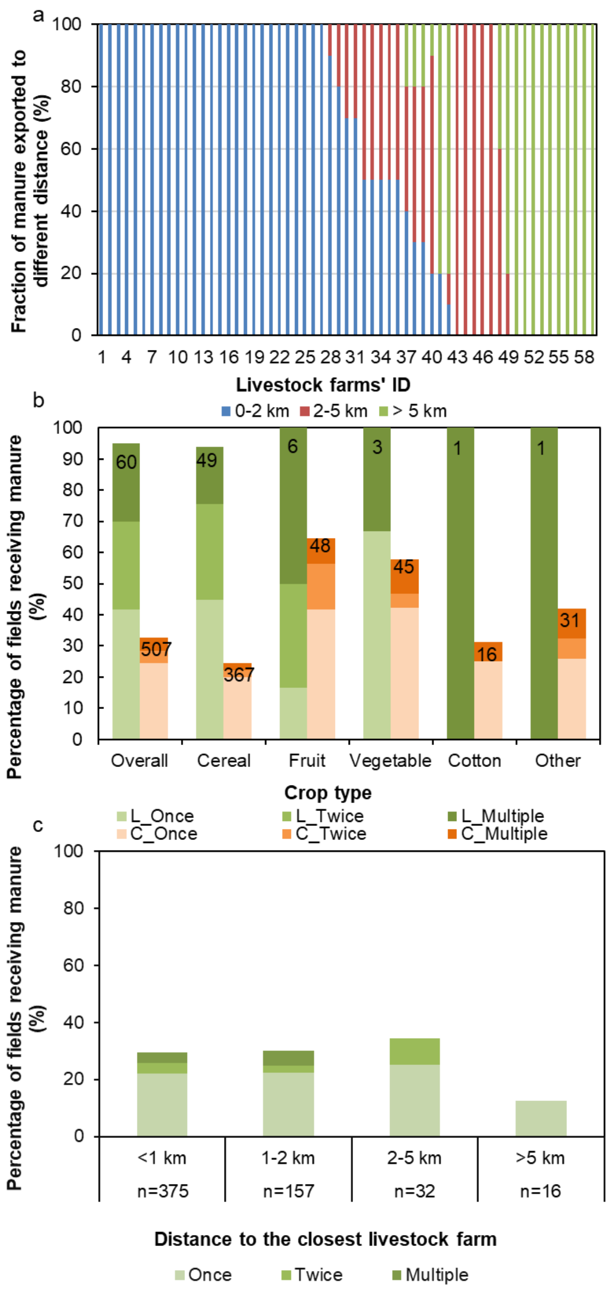

Figure 5.2. Results from the farm survey. Manure utilization on livestock and crop farms. (a) Distance of manure exportation from livestock farms to crop farms; (b) Annual manure application frequency on fields from livestock farms (green columns) and crop farms (orange columns), with number of fields indicated on the top of columns; (c) Annual manure application frequency on crop farms at different distances from livestock farms.

5.3.3 Soil P contents on livestock farms and crop farms

Cereals (mainly winter wheat - summer maize double cropping system) were the dominant crops in Hebei, both on crop and livestock farms, and were therefore chosen to compare soil P contents of crop and livestock farms. For the topsoil, 39% of the livestock farms had significantly higher TP contents than nearby crop farms, while 22% of livestock farms had significantly lower TP contents than nearby crop farms (Figure 5.3a). Rather similar results were obtained for oxalate-extractable P (Pox; Figure S5.14a).

For the subsoil, 26% of livestock farms had higher TP contents than nearby crop farms, while 24% of the livestock farms had lower TP contents than nearby crop farms (Figure 5.3b). Again, rather similar results were obtained for Pox (Figure 5.14b). Hence, more livestock farms had relatively high TP and Pox contents in topsoil than crop farms, but this was not true for the subsoil (Table S5.3).

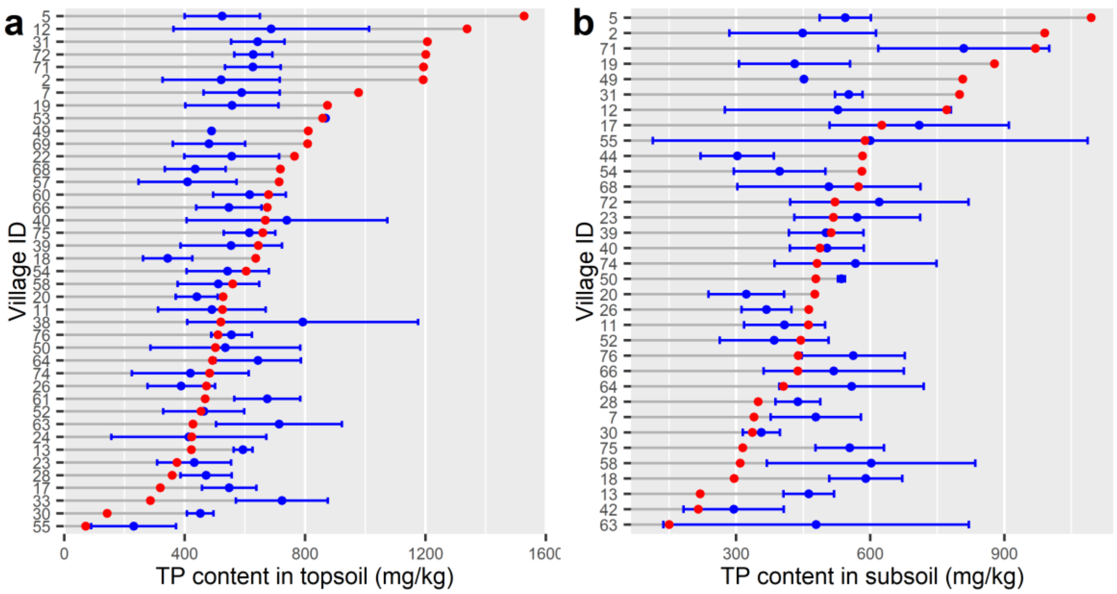

Figure 5.3. Total phosphorus (TP) content in the topsoil (0-15 cm, panel a) and subsoil (15-30 cm, panel b) of cereal fields on livestock farms (red dots, plotted in descending order, with village ID number on the left), and on six nearby crop farms (blue dots with blue bars). Dots indicate mean values; error bars indicate 95% confidence intervals of the mean of the six crop farms per livestock farm. Results from the soil sampling campaign.

5.3.4 Relationships between farm characteristics and soil P contents

Manure users had on average slightly higher TP contents in the topsoil than non-manure users (Figure 5.4), but there were no significant differences for the subsoil. Fields nearby livestock farms had slightly higher TP (Figure 5.4a) and Pox (Figure S5.15a) contents of the topsoil than fields further away. Surprisingly, there were on average no significant differences between crop types in the TP content of the topsoil; yet cereal fields had lower TP content of the subsoil compared to fruit orchards. There were significant differences between counties in TP and Pox contents of the topsoil and subsoil (Table S5.3). The TP content of the topsoil was positively related to manure application frequency (Table S5.3).

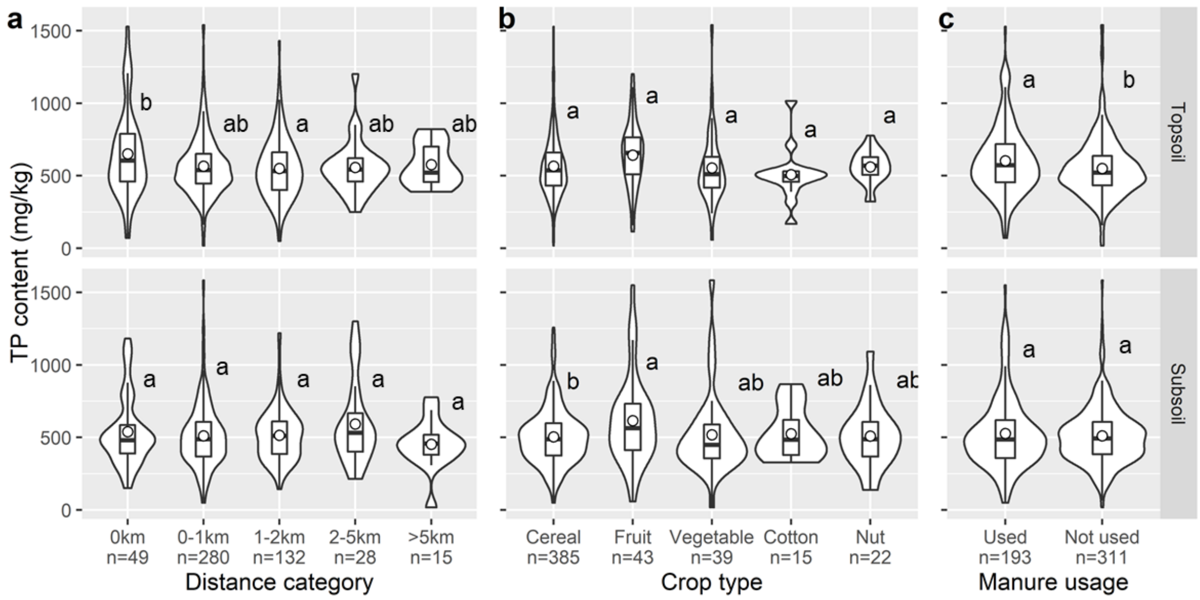

Figure 5.4. Results of the soil sampling campaign. Frequency distributions (outlines of the violins) of total phosphorus (TP) contents in the topsoil (0-15 cm; upper three panels) and subsoil (15-30 cm; lower three panels) in fields at different distances (in km) to livestock farms (a), with different crop types (b) and manure usage (c). Boxes inside the violins indicate the 25 percentile (lower border) and 75 percentile values (upper border), while the line in the box represents the median and the circle represents the average TP content. Vertical lines indicate the 5 and 95 percentile values. The number of observations are indicated at the x-axis (similar for topsoil and subsoil). Different letters near violins indicate statistically significant ($P<0.05$) differences between mean TP contents (Tukey HSD analysis).

Contents of TP and Pox were related to soil clay and sand contents, according to the Pearson correlation analysis (Figure 5.5). TP and OP contents increased with clay content, and decreased with sand content. This suggest that part of the P in soil has a geo-genetic origin, and is associated with the clay fraction.

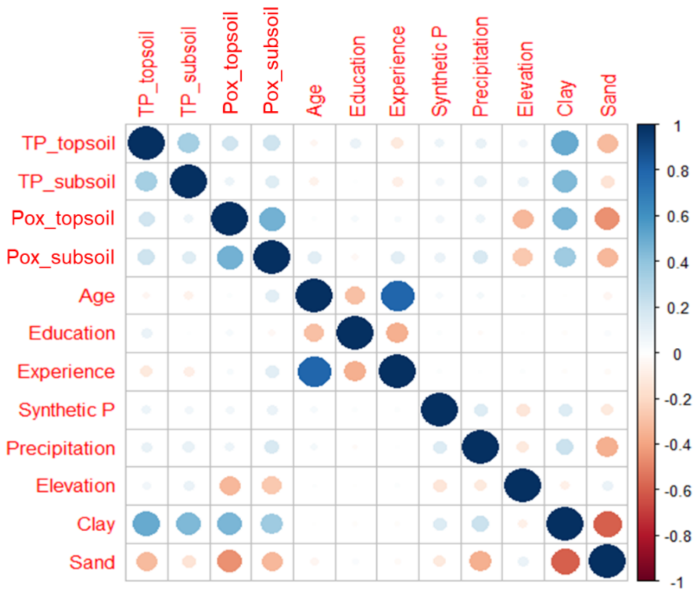

Figure 5.5. Results of the farm survey, soil sampling campaign and analysis. Correlation matrix of soil phosphorus (TP and Pox) contents and soil properties (clay and sand contents), environmental conditions (mean precipitation and altitude), farmers' characteristics (age, years of education and experience with manure use), and synthetic P fertilizer use.

5.3.5 Differences between topsoil and subsoil in P contents

Pair-wise t-tests revealed that the TP contents of the topsoil were in general higher than the TP contents of the subsoil. However, this was not observed for fields planted with non-cereal crops. Three out of the eight counties had higher TP contents in topsoil than subsoil and five counties had similar TP content in the two layers. In contrast, the Pox contents of the topsoil tended to be higher than the Pox contents of the subsoil, for all crop types (Table S5.3).

Surprisingly, a slightly greater percentage of crop farms (41%) compared to livestock farms (21%) had higher TP contents in the subsoil than in the topsoil (Figure 5.6a). However, the percentage of crop farms (17%) and livestock farms (13%) with higher Pox contents in the subsoil than in the topsoil was rather similar (Figure S5.16a).

Differences between crop types were small in the percentage of fields with higher TP contents in the subsoil than in the subsoil (range 35 to 40%; Figure 5.6b). The percentage of fields with higher Pox contents in the subsoil compared to topsoil decreased in the following order: vegetable 36% > nut 24% > fruit 22% > cereal 14% > cotton 13% (Figure S5.16b). There were no clear differences between manure users and non-manure users (Figure 5.6d).

Differences between counties in the percentage of fields with higher TP contents in the subsoil compared to the subsoil were relatively small (range 27 to 45%). The percentage of fields with higher Pox contents in the subsoil than in the subsoil was 5 times higher in Zanhuang county than in Zhaoxian county (Figure S5.16c).

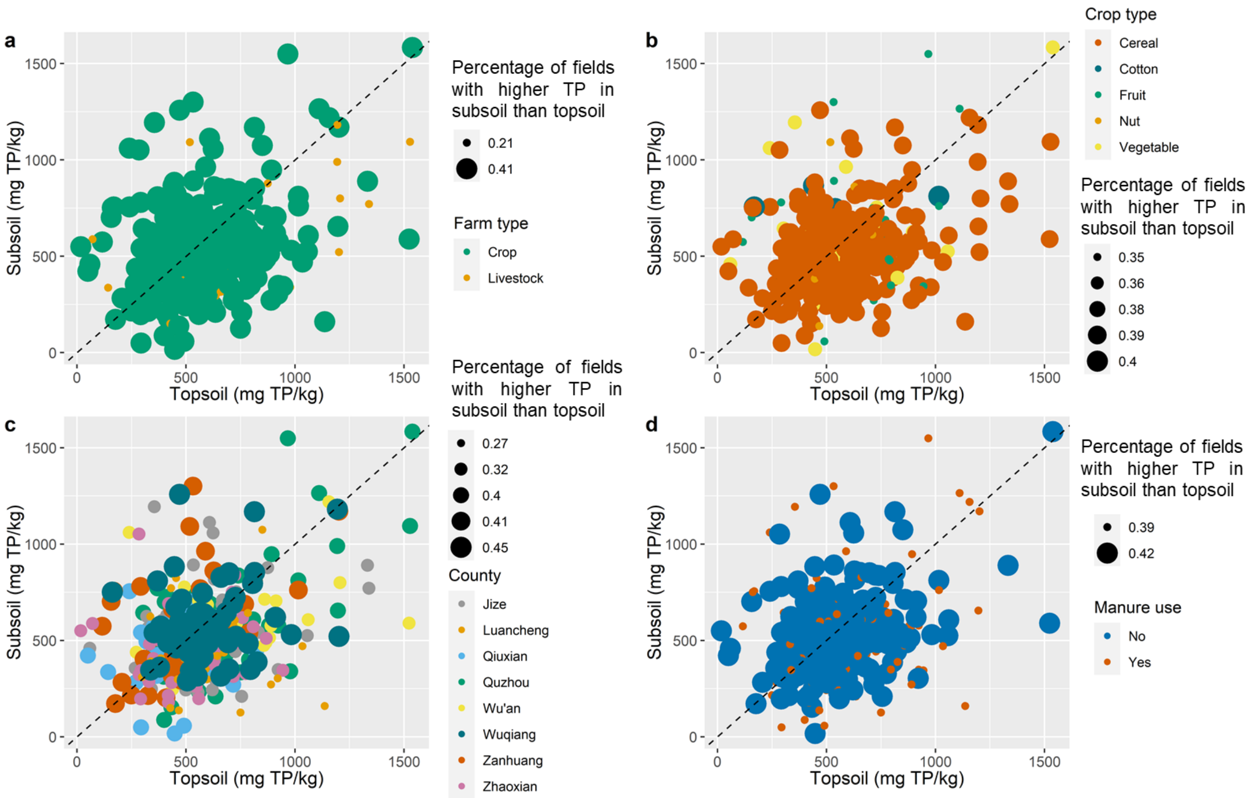

Figure 5.6. Results of farm survey, soil sampling campaign and analysis. Relationships between TP contents of the topsoil (0-15 cm) and subsoil (15-30 cm) as function of farm type (a), crop type (b), county (c) and manure users at farm level (d). Dot size indicates the proportion of fields with higher TP content in subsoil than topsoil per category.

5.4 Discussion

5.4.1 Overall nutrient management practices

Nutrient management in China can be characterized as a "high input - high output - low nutrient use efficiency strategy". This strategy has been effective for enhancing crop and animal productivity, but at the same time has created large environmental pollution. The strategy and the overall results have been attributed to governmental incentives, a low knowledge level of farmers, farmers' risk aversion tendency, and market confusion (Shen et al., 2013; Zhang et al., 2016). Science, industry and agricultural bureaus (as extension services) have important roles here, where the latter serve as intermediates between the more than 200 million farmers and governments, science and industry. The agricultural bureaus are part of the ministry of Agriculture; they have offices at each administrative level. An agricultural bureau at sub-county level (<10 staff) has to ‘manage’ on average 6627 households for a wide range of issues, including crop/livestock disease control, quality and safety control, and policy implementation, including nutrient management (National Statistics, 2012). The fertilizer industry also has an important role through providing many different, subsidized fertilizers (Li et al., 2013); there were more than two dozen fertilizer products in the market with neither streamlined nor user-friendly labelling (Zhang et al., 2016). Fertilizer companies normally cooperate with local retailers who sell various fertilizer products from different brands at the same time. Farmers' purchase decisions were mainly influenced by price and marketing schemes of the fertilizer brand (Zhang et al., 2016). Independent, science-based guidelines for nutrient management are hardly available to farmers. Farmers often asked for suggestions for fertilizer use during our farm survey.

The large use of synthetic P fertilizer use by crop farmers is probably one of the main reasons why we did not find clear relationships between livestock density, manure use and soil P contents, unlike our initial hypothesis. Consumption of synthetic P fertilizer has increased 100-fold during the last five decades, from 0.05 Mt in 1960 to 5.3 Mt in 2010 (Li et al., 2015; Zhang et al., 2019b). From 2015, synthetic P fertilizer production and consumption tend to plateau, in response in part to the policy ‘zero-growth in synthetic fertilizer and pesticide use’ (Zhang et al., 2019b). Recently, an increasing percentage of farmers can get access to information from Science and Technology Backyards, which is a collaboration of universities, industry, and governmental agencies, aimed at improving farming practices, especially nutrient management (Zhang et al., 2016; Jiao et al., 2019).

Another factor obscuring the expected relationship between livestock density, manure use and soil P contents is the large transformation of agriculture and especially livestock production systems in China during the last decades (Jin et al., 2021; Bai et al., 2018). A significant fraction of small mixed farms became specialized crop farms; while abandoning livestock production, farmers found a better-paid job in the city (particularly young people) and managed the farm part-time. Meanwhile, new industrial-scale farms with intensive livestock production were build, linked in part to feed and/or animal-source food processing companies. The share of traditional mixed farms decreased sharply from 71% in 1986 to 12% in 2017 (Jin et al., 2021), while livestock density on farms with livestock ranged from 3 LSU/ha to 1560 LSU/ha in 2017

(Figure S5.17). Livestock and crop production became spatially decoupled, making it difficult for livestock farms to recycle manure to cropland. The mean ratio of manure N to fertilizer N input to cropland declined from 18% in 1995 to 10% in 2017 (Jin et al., 2021; Zhang et al., 2021). Meanwhile, a significant fraction of the produced animal manure on livestock farms ended up in evaporation lagoons, landfill, backyards or was discharged into surface waters (Bai et al., 2016). The low recycling of manure to cropland may also explain the weak relationship between livestock density and soil Olsen-P content at county level (Figure 5.1), and between livestock density and the TP content of the topsoil at farm level (Figure 5.4). In contrast, intensification of livestock production in EU and North America has led to soil P build-up in close relationship with livestock density (Sims et al., 2000; Tóth et al., 2014). However, manure application limits and manure processing in combination with manure redistribution through contractors (middlemen) are halting a further build-up of P in soils or are reversing the soil P build-up in some countries (e.g. Schröder & Neeteson, 2008; Oenema and Oenema, 2021). Though there are no evident signs of excessive soil P accumulation through manure application on the surveyed crop and livestock farms (Figure 5.4), the accelerating intensification of livestock production in China (e.g., Bai et al., 2018) suggests that manure application limits and manure redistribution will be needed, likely with the help of contractors (Zhang et al., 2021).

The surveyed livestock farms had a high livestock density (half of the farms had >100 LSU/ha). Part of the manure produced on livestock farms was exported to crop farms, mostly within 5 km distance (Figure 5.2a), far-distance transport was limited by the high transportation cost and lack of proper transportation vehicles (Chadwick et al., 2015). Market demand for manure has seasonal variation, as influenced by the crop growing seasons, and many livestock farms had difficulties to export manure to crop farms during the growing season. The surplus manure was then discharged or applied to on-farm cropland. Livestock farms with cropland (54 out of the 80 farms) applied manure to on-farm cropland multiple times per year, regardless of the crop type (Figure 5.2b). Livestock farmers often applied large amounts of manure as the only source of nutrients, also to compensate for the presumed low availability of manure nutrients (Smith et al., 1998), and simply to get rid of a burden (Tan et al., 2021). Results of another farm survey in Hebei and Shandong provinces indicated the mean manure application rate equaled 1364 kg N and 281 kg P per ha per year on the cropland of 87 intensive dairy farms (Tan et al., submitted).

Crop farms applied manure to cropland less frequently per year than livestock farms. Depending on crop types, 21-65% of the fields from crop farms received manure (Figure 5.2b). Many crop farmers were not willing to use manure because 1) it requires high labor input; 2) there is a lack of application machines; and 3) farmers don't have enough knowledge about the manure nutrient content and their effectiveness (Ma et al., 2013; Chadwick et al., 2015; Zhang et al., 2016; Zhang et al., 2021). The crop farmers that do use manure, often apply excessive amounts of manure as a supplement to synthetic fertilizer, and pay little attention to the potential environmental risks (Li et al., 2011).

5.4.2 Soil phosphorus content and influencing factors

County-level average Olsen-P contents were marginally correlated with mean livestock density ($r=0.21$, $P<0.05$, Figure 5.1). Standard deviations of mean Olsen-P per county were relatively large (Figure S5.17), which indicates large variations in practices between farms but not between counties, despite large differences in mean livestock density. In contrast, Meng et al., (2017) found that livestock density accounted for 35 to 76% of the variance in P inputs in South China, and that livestock density was the most important factor explaining variations in soil TP and Olsen-P contents in cropland. Li et al., (2011) reported that Olsen-P in North China Plain increased from a mean of 6.4 mg/kg in 1980 to a mean of 20.7 mg/kg in 2006, indicating that Olsen-P increased quickly over time. The results of the database with county-level mean Olsen-P contents do not discriminate between years of the soil sampling, and although most results relate to samples taken during the last one or two decades, it is very likely that these means do not provide actual means. Another possible disturbing factor is sampling bias; likely, cropland from livestock farms was neglected or not adequately sampled, also because agricultural bureau officers tend to focus on crop farms.

Several livestock farms had higher TP and Pox contents in the topsoil of their cropland than the nearby crop farms, which is in line with our second hypothesis. Yet, the TP and Pox contents of cropland were not significantly correlated with livestock density at farm level (Figure S5.18). There are a number of possible reasons for this apparent anomaly. First, we did not sample obvious manure dumping sites on livestock farms, such as farm yards and manure dumping fields. Second, crop farmers commonly use large amounts of synthetic P fertilizer in Hebei province (Shuchang et al., 2008; Yan et al., 2013). Third, most intensive livestock farms are of recent age; these relatively large farms have replaced many small mixed farms, which became specialized crop farms. Fourth, there are obvious differences in soil texture between fields, and TP and Pox were associated with the clay fraction of the soil (Olsen et al., 1963). Further, differences in climate, topography, irrigation practices and crop residue management may also obscure the expected relationship between livestock density and soil P contents (Hou et al., 2018; Page et al., 2005; Zhao et al., 2005; Tittonell et al., 2007). We did not attempt to filter these confounding factors out through multiple linear regression analysis, as our database turned out to be not appropriate for doing so.

Commonly, contents of P and some other immobile nutrients in soil decrease with soil depth (Powell et al., 1998; Jobbagy & Jackson, 2001; Reijneveld et al., 2014a; Dikgwatlhe et al., 2014; Martínez et al., 2016). Farmers apply manure and fertilizers to the topsoil, which is confined to the upper 10 to 15 cm by the common soil cultivation practices in the North China Plain. Also, plant roots take up nutrients from the topsoil and subsoil, while most nutrients in crop residues are returned to the topsoil. A rainfall surplus and excessive irrigation may leach mobile nutrients from the topsoil to the subsoil, but less so for immobile nutrients such as P. However, as soil P contents increase, the risk of P leaching from topsoil to subsoil also increases (Schoumans, 2015; Wang et al., 2012; Jalali & Jalali, 2017).

Soil P contents of the subsoil were relatively high in our study area, compared to the P contents of the topsoil. Some 21% of fields from livestock farms and 41% of fields from crop farms had equal or higher TP contents in the subsoil than in the topsoil (Figure 5.6a). Manure use was not clearly related to the TP contents of topsoil and subsoil (Figures 5.4, 5.6), suggesting that manure use did not influence soil P distribution over depth. This is in accordance with findings of Sharpley et al (1993) and Lindo et al (1993), but contrasts with findings of Liu et al (2012), Edmeades (2003) and Goulding et al (2000). We did not include unfertilized land in our sampling campaign, and therefore do not know the TP contents of topsoil and subsoils of unmanaged sites. The positive relationship between clay content and TP content indicates that at least part of the P in the subsoil has a geo-genetic origin. Another fraction likely is from P leaching from the topsoil. Leaching of P in soil is a complex process, and influenced by various factors such as soil properties, climate and agronomic management (Djodjic et al., 2004; Hesketh & Brookes, 2000; Bergström et al., 2015). The molar ratio of oxalate extractable P over the sum of oxalate extractable Fe and Al has been used as indicator for the risk of soil P leaching in acidic (pH $\leqslant 6$) soils (Van der Zee & Van Riemsdijk, 1986; Schoumans & Groenendijk, 2000). However, our soils are alkaline with pH$\geqslant$7.5, indicating that P likely accumulates as calcium phosphates (apatite) and not as iron and aluminum phosphates. Results of the NIRS analyses indicated that the molar ratio of Pox/(Alox+Feox) was 0.34±17, which would suggest that a significant fraction of the available Al and Fe binding sites could have been saturated with P. Evidently, further studies are needed to spread more light on the spatial variations in TP and Olsen-P in the topsoil, and on the factors that may explain the relatively high TP in the subsoil.

5.4.3 Limitations of our study and outlook

Land management history is an important factor influencing soil phosphorus enrichment or depletion over time (MacDonald et al., 2012). It takes tens of years to establish an equilibrium level after a change of land use (Yang & Janssen, 1997; Martínez et al., 2016). Unfortunately the history of our sampling locations is unknown; this relates to the data from the database as well as to the locations of our soil sampling. Most farmers do not keep written records of manure and fertilizer use. Agricultural bureaus record mean fertilizer use (but no manure use) at provincial level annually, which is too coarse for the purpose of our study. Most data related to fertilizer use and manure use are collected through farm surveys (e.g., Zhang et al.2021), but these surveys have neglected variations in soil fertility and soil P contents so far. Our study made a first attempt to relate livestock density to manure use and soil P contents, but due to the uncertainties in the land management history and in the representativeness of the soil sampling sites, we cannot draw firm conclusions yet. The potential changes emphasize the importance of long-term data collection on land management and soil fertility, as for example the Netherlands has been doing (Reijneveld, 2013).

Possible soil sampling biases and the chosen soil testing approach have also weaken the confidence of our results. The sampling and soil analysis protocols underlying the database with county-level mean Olsen P values are unknown, and access to this database is limited for various reasons that are beyond the scope of this study. Our original aim was to use this database to select areas for further research through farm surveys, which turned out to be not useful/possible. Further, we observed that some statistical data on livestock numbers at county level may not be as accurate as expected. Also, most Chinese farmers do not keep records and have no good data management; as a result some farm data may not be very precise.

We used NIRS as a broad-spectrum and rapid soil test, together with 0.01 M $CaCl_2$ extractions of plant-available nutrients, given also the large number of soil samples collected (~1200). The transport of the dried samples from China to Wageningen was troublesome, due to restrictions related to the Covid-19 pandemic. In the end, only 990 samples were analyzed with NIRS and some 150-200 with 0.01 M $CaCl_2$ extractions and ICP analyses. The NIRS is well-calibrated for samples from European agriculture (Reijneveld et al., 2022), but less well for soils from China. Validation of the Pox results obtained by NIRS with the classic wet-chemical method for 166 samples showed that the NIRS had a NRMSE (normalized root-mean-square error) of 0.33 and R^2 of 0.7 which indicate medium good fitness (Ritter & Munoz-Carpena, 2013). The NIRS tended to overestimate Pox when Pox was <396 mg/kg and underestimated Pox when it exceeded this value (Figure 5.7). Unfortunately we don't have data to validate the TP results.

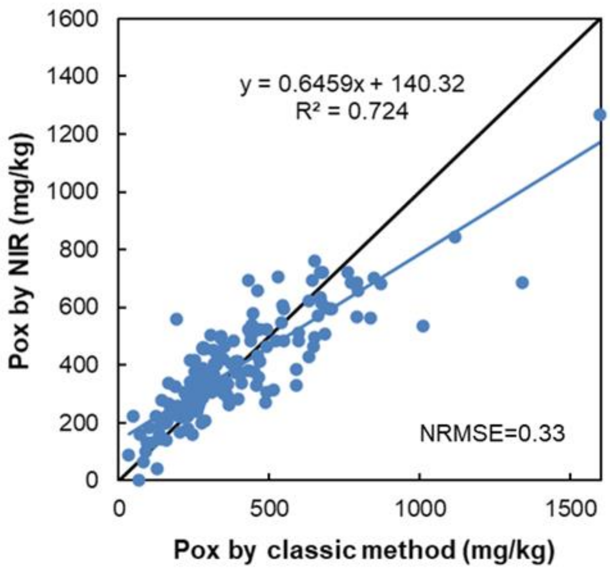

Figure 5.7. Comparison of results obtained with NIRS and with classical wet-chemistry method for Pox. Based on a selection of 166 soil samples from Hebei.

So far Pox has not been used much in China, and its usefulness and interpretation as indicator for the long-term availability of soil P has not been tested. Guo & Yost (1999) found that Pox was unsuitable for quantifying the available P pool in calcareous, high-pH soils. Hooda et al (2000) found that Pox explained only 20% of the variance in the amounts of soil P desorbed, and that Pox was not a reliable estimator for the fraction of soil P that can potentially be released to water.

Recently, Chinese government launched the third national soil survey (National Council, 2022), which provide a good opportunity to collect representative samples from both crop and livestock farms. The new dataset may become available by 2025 and the results may be compared with the results of the second national soil survey, to better understand the changes in soil P, and to develop plans for improved land use, nutrient management, and nature conservation. This national survey should also consider taking samples from the subsoil, and include multi-nutrient soil tests, given the increasing importance of micro nutrients (Reijneveld et al., 2014b), but also some heavy metals, including Cu, Zn and Cd. Special attention should be paid also to the relationship between soil (land tenure and functioning) and livestock.

Conclusions

The relationships between livestock density and soil P contents in topsoil and subsoil were analysed at county and farm/field levels. The large variations in mean livestock density at county level (range 0.4-16.0 LSU/ha) and farm level (range 3-1560 LSU/ha) suggest that the availability of animal manure greatly differed among farms and regions, and that manure P applications also greatly differed, and hence soil P contents. However, the differences in livestock densities were not clearly reflected in differences in soil P status between farms and between counties, likely because of the large amounts of synthetic P fertilizer use, the inappropriate manure use and the recent changes in land use and livestock density. Thus, no clear relationship was found between livestock density and soil P content at county and farm levels.

Yet, differences can be observed between livestock farms and crop farms in the manure management and also in soil P contents. In total 95% of the fields from livestock farms received manure regularly, while only 33% of the fields from crop farms received manure. Manure from livestock farms was partly transported to nearby crop farms within 5 km distance. The differences in manure management between livestock farms and crop farms resulted in somewhat higher mean TP and mean Pox contents in cropland of livestock farms compared to crop farms. Further, 21% of the fields from livestock farms had higher TP contents in the topsoil than in the subsoil, while 41% of the fields from crop farms had higher TP contents in the topsoil compared to the subsoil. Higher TP and Pox contents in the subsoil than in the topsoil may indicate P leaching from the topsoil to the subsoil. However, other explanations for high TP content of subsoils cannot be excluded, including a different geo-genetic origin. Our results point at large spatial variations in the accumulation of P in both topsoil and subsoil. These spatial variations are not yet well-understood, and underscore the need for further studies, as well as the need for improved manure management. Notably on intensive livestock farms, there is a need for manure application limits and for improved manure distributions to crop farms.

ACKNOWLEDGMENT

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Supplementary information for Chapter 5

Table S5.1. Total number of farms and relative numbers of intensive farms and animals in intensive farms in Hebei province.

		Pig	Broiler	Laying Hen	Dairy cow
2007	Total number of farms	3117018	266162	2583292	458374
	Fraction of intensive farm (%)	0.22	0.11	0.05	0.27
	Fraction of animal number in intensive farms (%)	19	12	5.78	15
2017	Total number of farms[1]	12751	1487	3682	1984
	Fraction of intensive farm (%)	1.2	1.0	0.4	2.4
	Fraction of animal number in intensive farms (%)[2]	38	25	17	76

[1]the tremendous decrease of farms numbers is partly due to the change of statistical method. In 2007, families with 1 dairy cow is accounted as a dairy farm, but in 2017, only families with >5 heads are accounted.

[2]this data for year 2011 because data are not available for later years. All data are derived from Statistical Yearbook of respective years.

Table S5.2. General information of the surveyed crop farms and livestock farms

	Crop farms	Livestock farms
Average cropland area (ha)	1.7	9.54 (56 out of 80 farms have cropland)
Average livestock unit		433
Percentage of farms with cropland scattered (%)	75	73
Average cereal area (ha)	0.91	8.35
Average fruit area (ha)	0.18	0.35
Average vegetable area (ha)	0.43	0.84
Average other area (ha)	0.18	0
Fraction of farms that apply manure	36	66
Fraction of farms that apply manure from nearby livestock farms	25	
Fraction of livestock farms selling/export manure		77.5

Table S5.3. TP content (g/kg) and Pox content (mg/kg) in the topsoil and subsoil of different farm types, crop types, counties and manure utilizations and the significance of differences between topsoil and subsoil.

	TP (mg/kg)			Pox (mg/kg)		
	Mean content in topsoil	Mean content in subsoil	p[1]	Mean content in topsoil	Mean content in subsoil	p[1]
Crop farm	557±203	518±214	<0.01	457±133	345±115	<0.01
Livestock farm	655±325	541±243	0.01	536±197	363±131	<0.01
Difference between farms[2]	p=0.07	p=0.57		p=0.02	0..39	
Cereal fields	564±217	508±193	<0.01	483±139	350±111	<0.01
Fruit fields	626±240	592±312	0.53	407±135	329±119	<0.01
Vegetable fields	546±260	528±301	0.73	425±135	370±150	0.01
Cotton fields	507±184	525±184	0.77	374±143	284±97	<0.01
Nut fields	560±96	560±219	0.99	382±106	308±132	0.03
Difference between crops[3]	p=0.388	p=0.222		p<0.01	p=0.06	
Jize	560±214	538±214	0.5	524±121	368±91	<0.01
Luancheng	602±179	464±184	<0.01	503±125	374±99	<0.01
Qiuxian	450±126	414±130	0.11	423±131	303±113	<0.01
Quzhou	631±263	560±276	0.02	483±169	381±113	<0.01
Wu'an	650±250	564±167	0.02	391±87	307±103	<0.01

Wuqiang	607±193	597±212	0.77	523±123	421±111	<0.01
Zanhuang	505±218	563±255	0.14	356±152	271±127	<0.01
Zhaoxian	526±208	448±179	0.07	474±98	311±97	<0.01
Difference between counties[3]	p<0.01	p<0.01		p<0.01	p<0.01	
With manure application	597±241	525±250	<0.01	467±160	345±123	<0.01
Without manure application	546±201	516±193	0.03	463±129	347±112	<0.01
Difference between manure utilization[2]	p=0.02	p=0.70		p=0.76	p=0.91	

[1] Tested with pair-wise student-test (t-test)

[2] Tested with non-pair-wise t-test

[3] Tested with Tukey HSD test

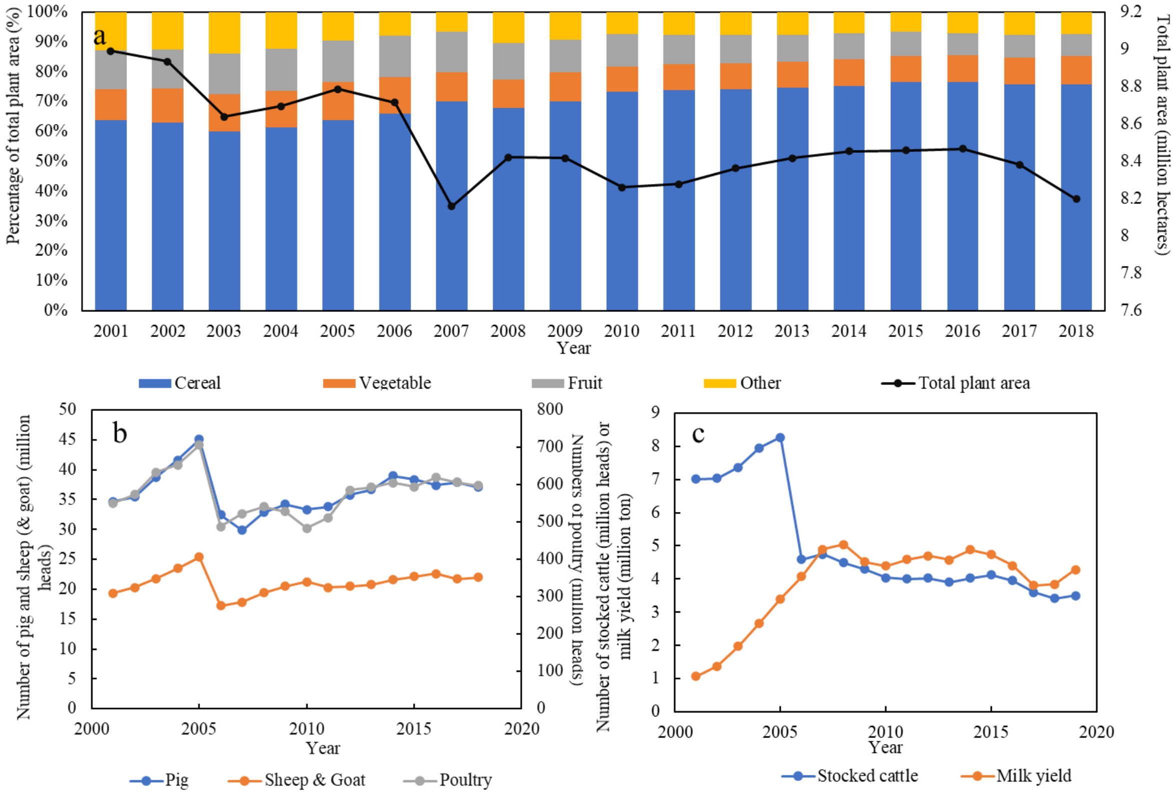

Figure S5.1. Changes of livestock number and crop areas over time. a: number of pig, sheep & goat, and poultry slaughtered; b: number of cattle and total milk yield; c: Total plant area and the shares of different types of crops). Note the drop in number of animals in 2005/2006 due to the discard of small farms with <5 animals from then onwards.

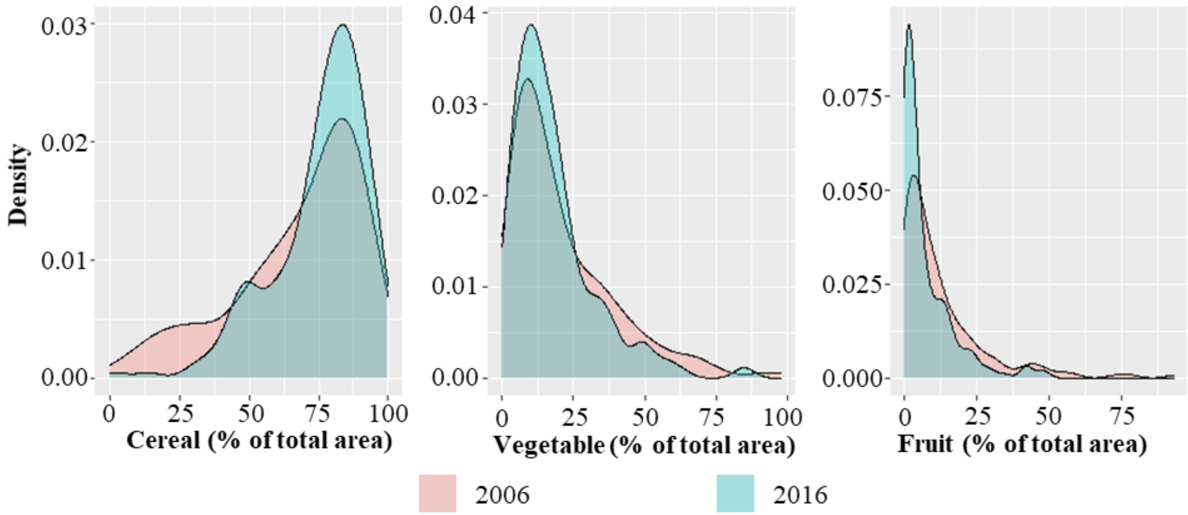

Figure S5.2. Density distribution of relative area of cereal, vegetable and fruit area to total cropland area per county in 2006 and 2016 (note there are 167 counties in Hebei). Compared to 2006, relative area of cereal condensed to the right while that of vegetable and fruit to the left, meaning that cropland area used for cereal production increased while for vegetable and fruit production decreased.

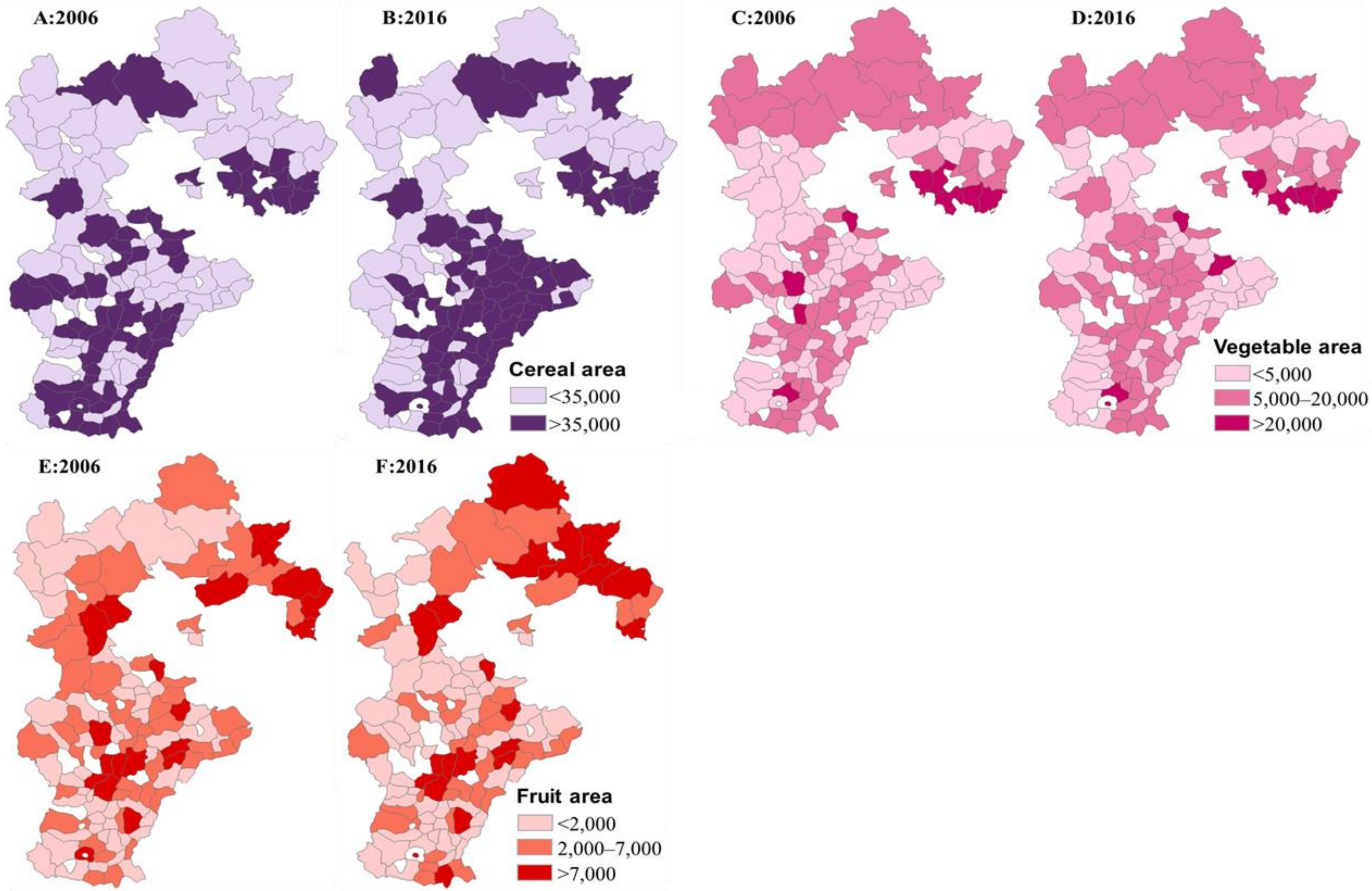

Figure S5.3. Crop production area at county level in Hebei province in 2006 and 2016 (unit: ha).

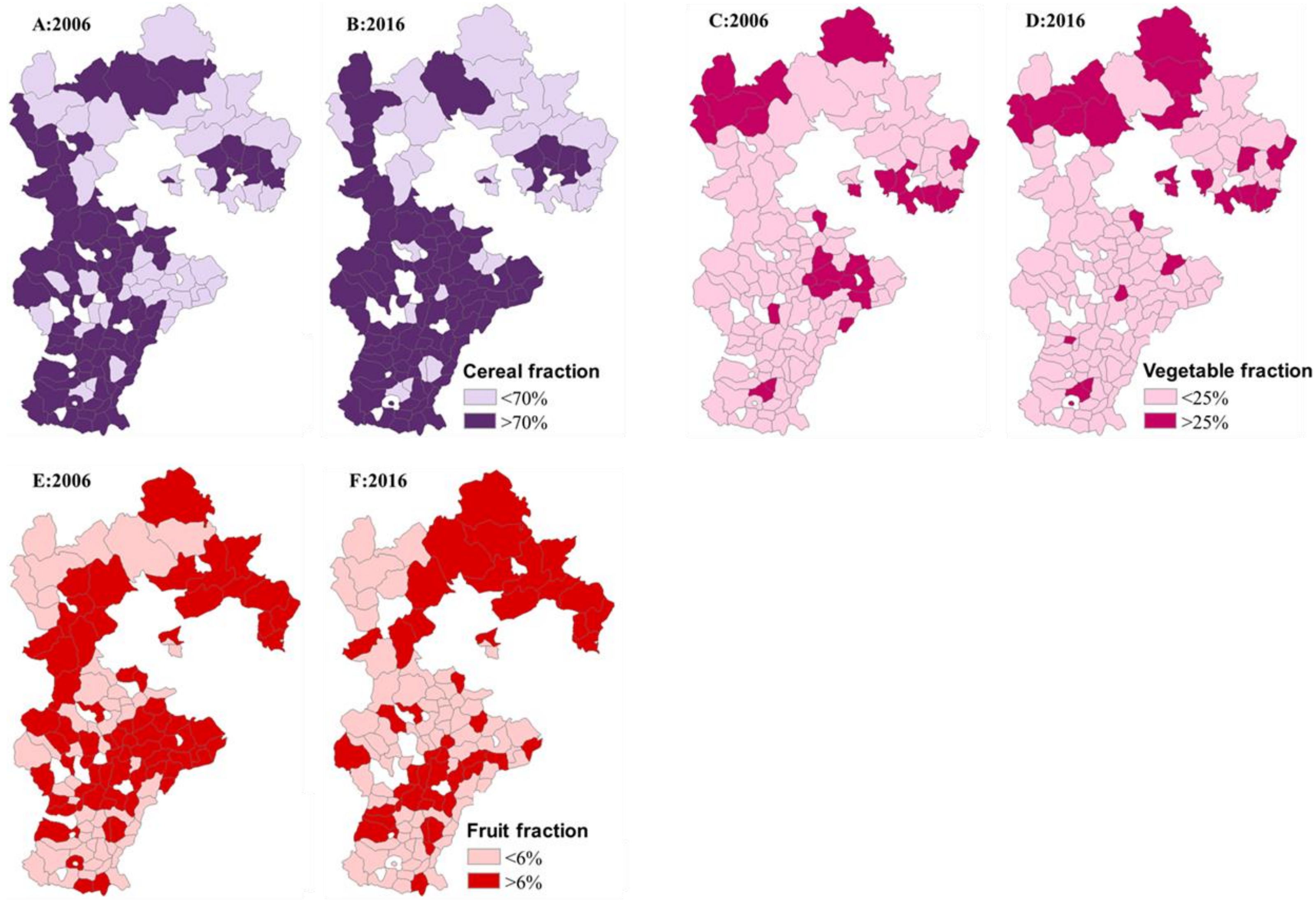

Figure S5.4. Relative area of crops at county level in Hebei province in 2006 and 2016 (unit: %).

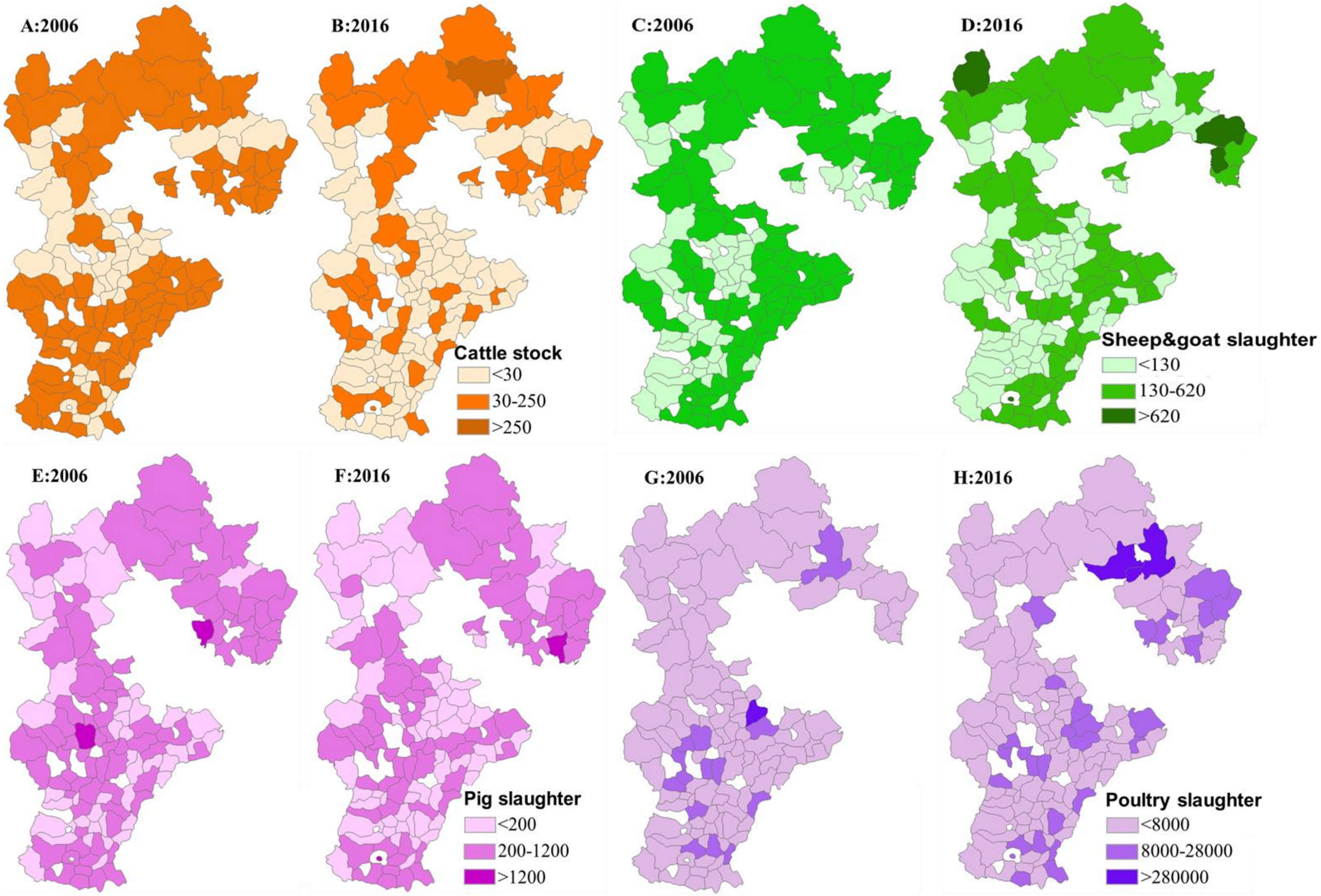

Figure S5.5. Number of animals at county level in Hebei province in 2006 and 2016 (unit: 1000 heads).

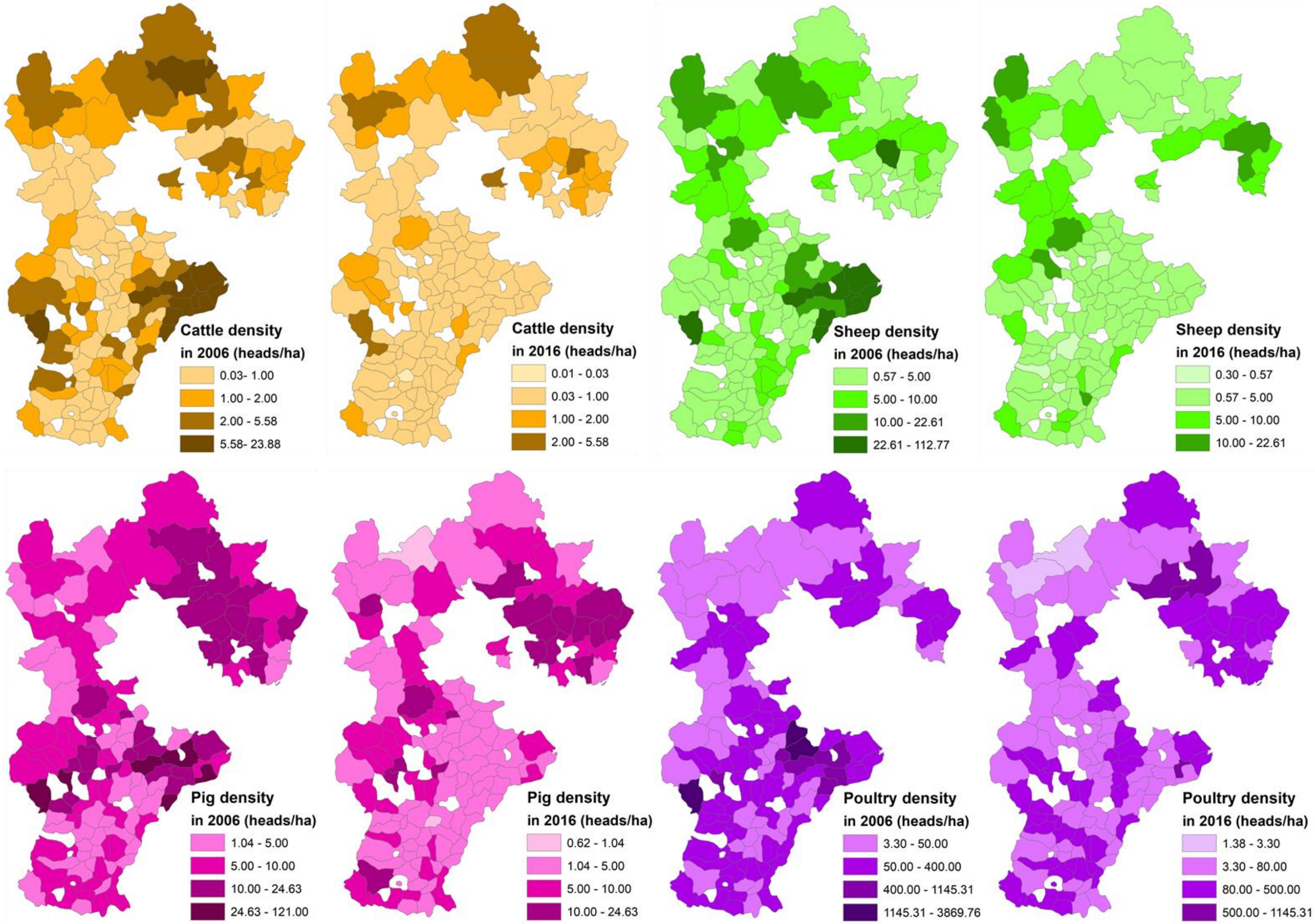

Figure S5.6. Density of animals at county level in Hebei province in 2006 and 2016 (unit: heads/ha)

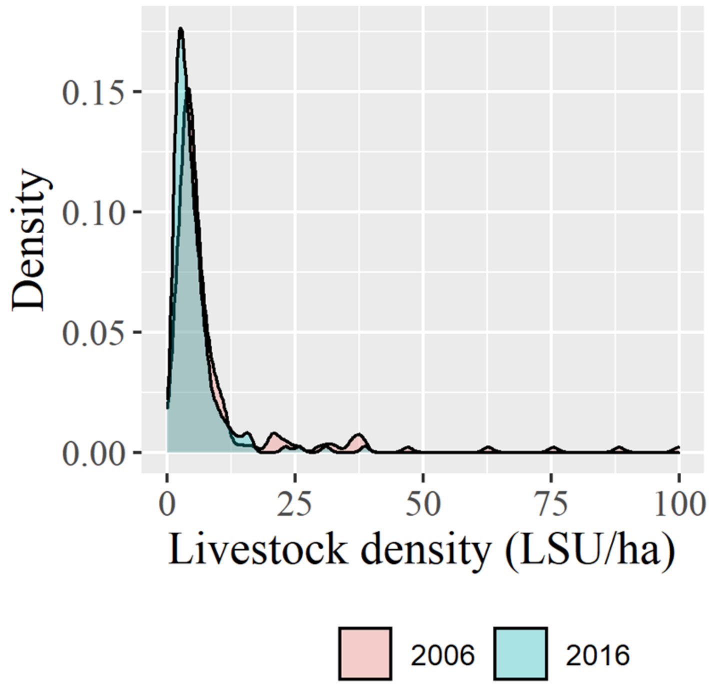

Figure S5.7. Density distribution of livestock at county level in 2006 and 2016 in Hebei province.

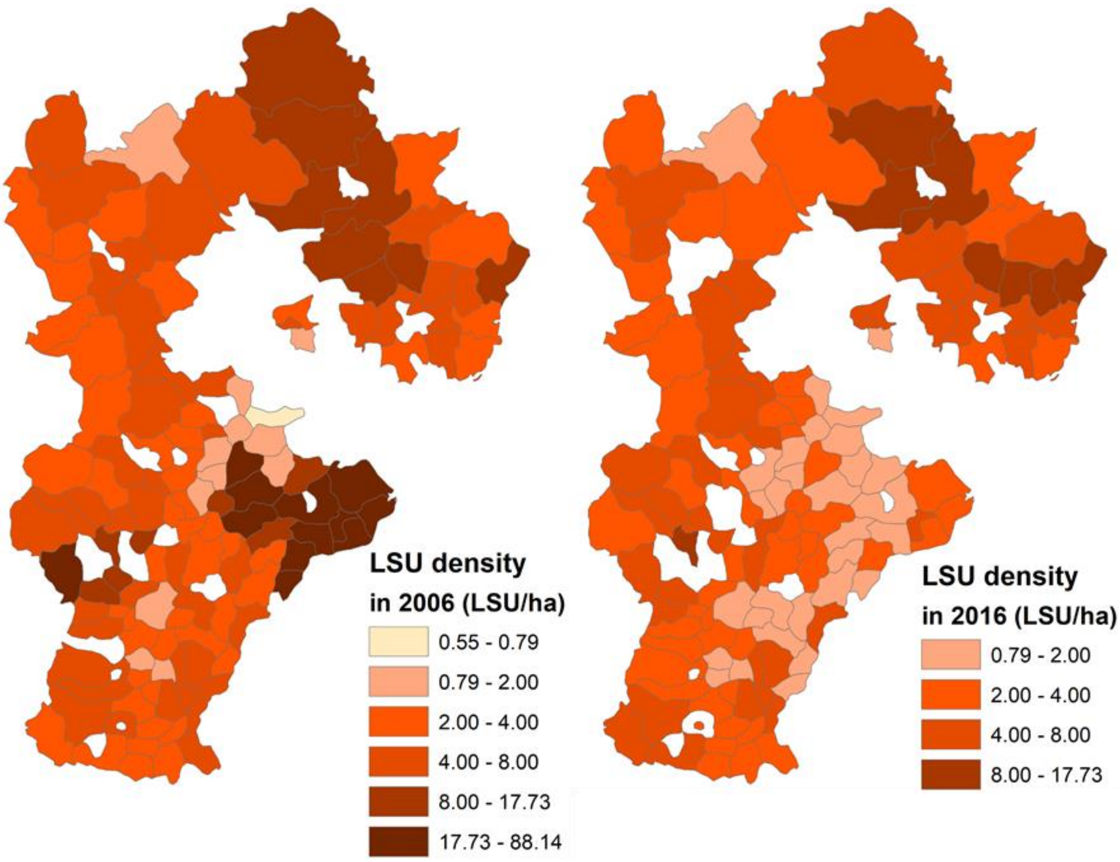

Figure S5.8. Spatial distribution of livestock density in 2006 and 2016 in Hebei province.

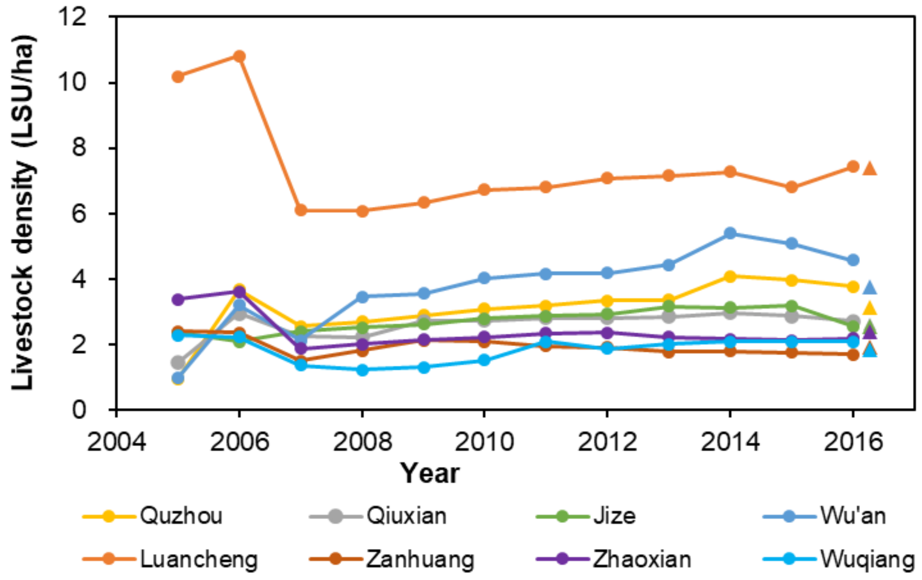

Figure S5.9. Changes of livestock density of the surveyed counties in recent years (lines with dots) and the average livestock density from 2005 to 2016 (small triangles at the right end of the lines).

Note the drop in number of animals in 2005/2006 is due to the discard of small farms from then onwards.

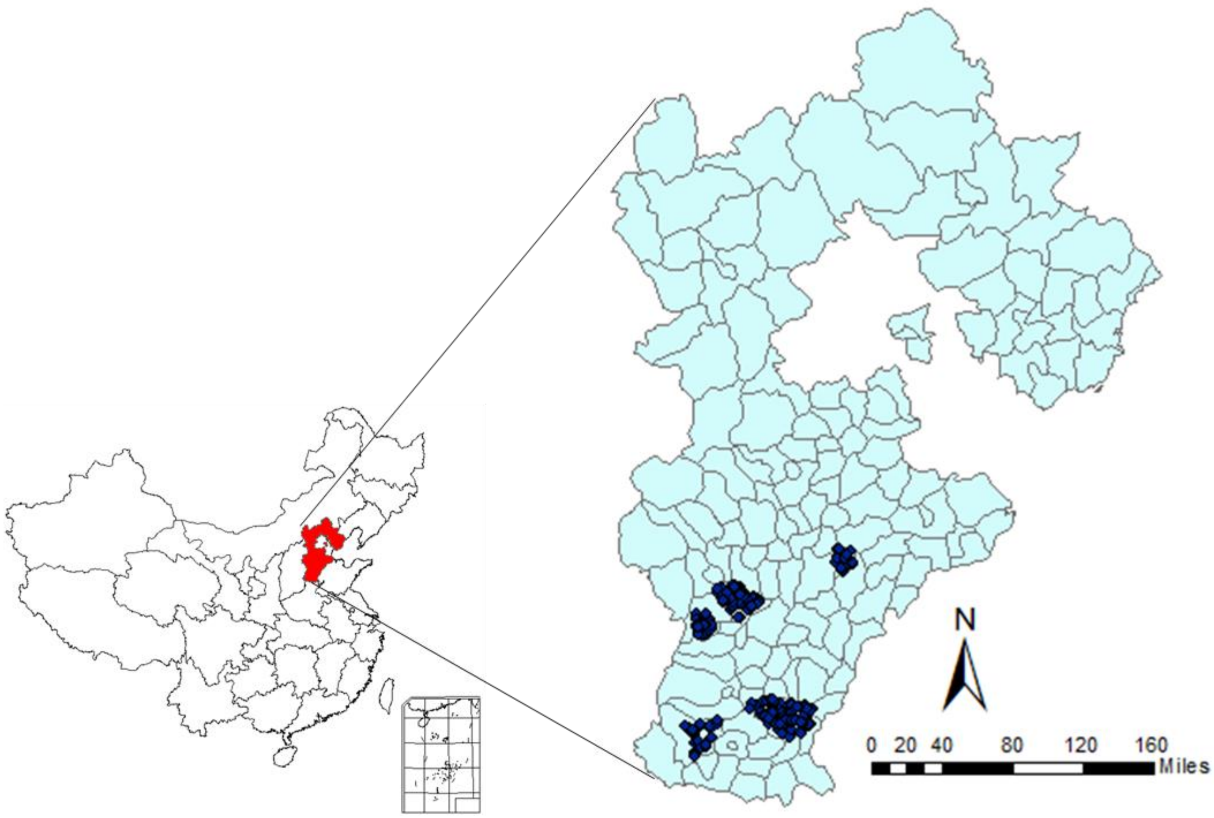

Figure S5.10. Geographical distribution of the counties selected for the farm survey and the soil sampling.

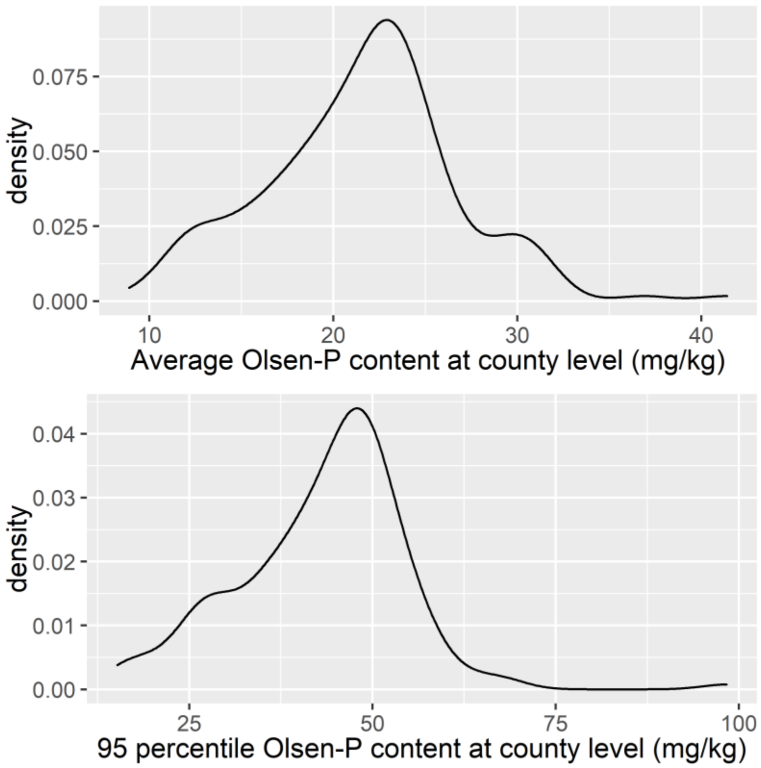

Figure S5.11. Density distribution of average and 95 percentile values of Olsen-P at county level.

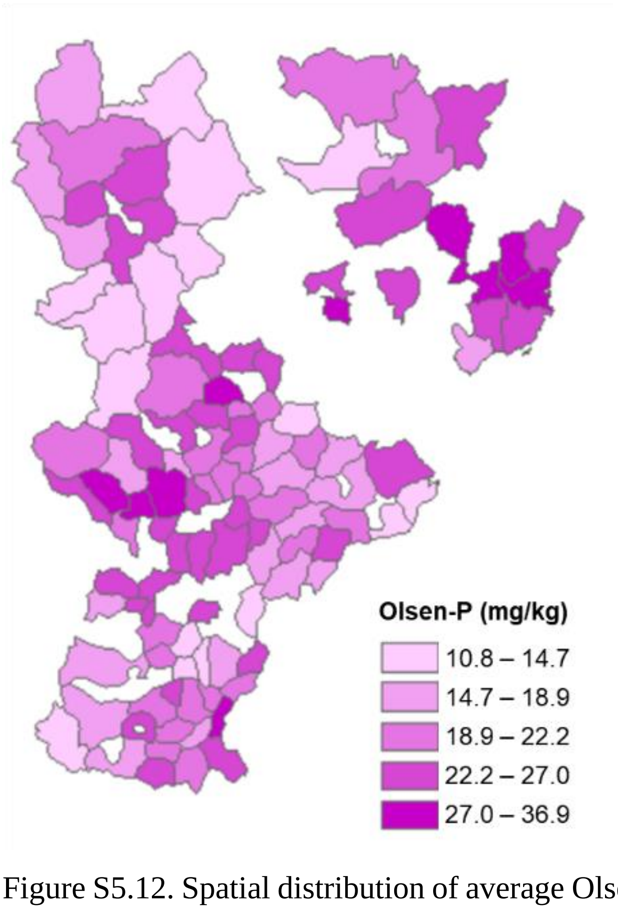

Figure S5.12. Spatial distribution of average Olsen-P content at county level in Hebei province.

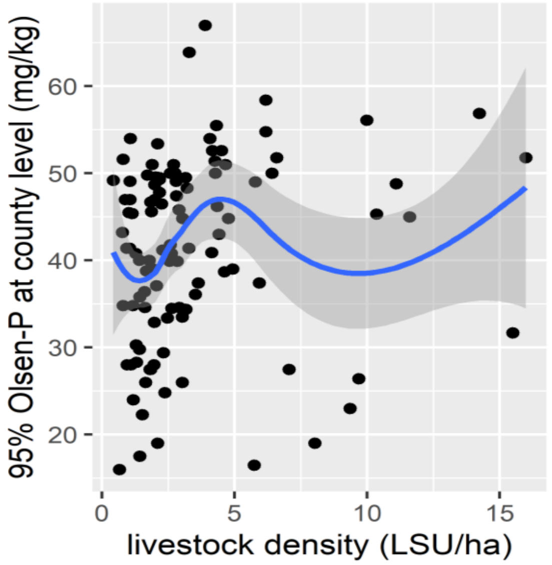

Figure S5.13. Relationship between livestock density and the 95 percentile values of Olsen-P content at county level. Each dots represents a county. The blue lines and shadows are loess regression (locally weighted regression) lines and their 95% confidence intervals generated by R programming language.

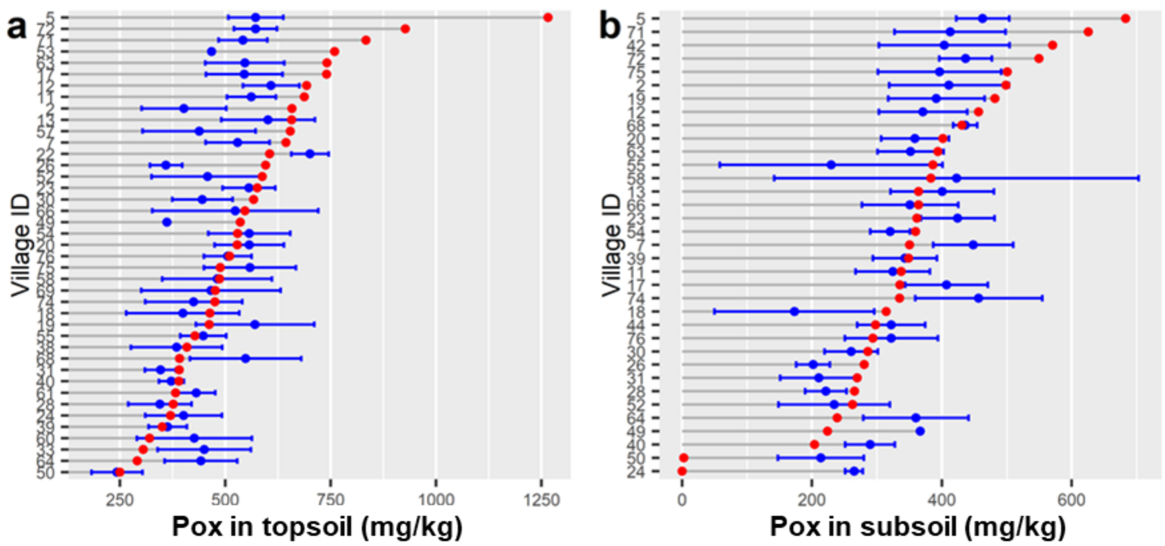

Figure S5.14. Oxalate extractable phosphorus (Pox) content of cereal fields from crop farms (blue dots with blue bars) and from livestock farms (red dots). Points show average values; error bars indicate 95% intervals for the six crop farms per livestock farm (mean value $\pm$ $1.96 \times \frac{sd}{\sqrt{n}}$). When red dots are out of range of the blue coloured intervals, the chance is high that differences between livestock farms and crop farms were significant. (a) for topsoil and (b) for subsoil.

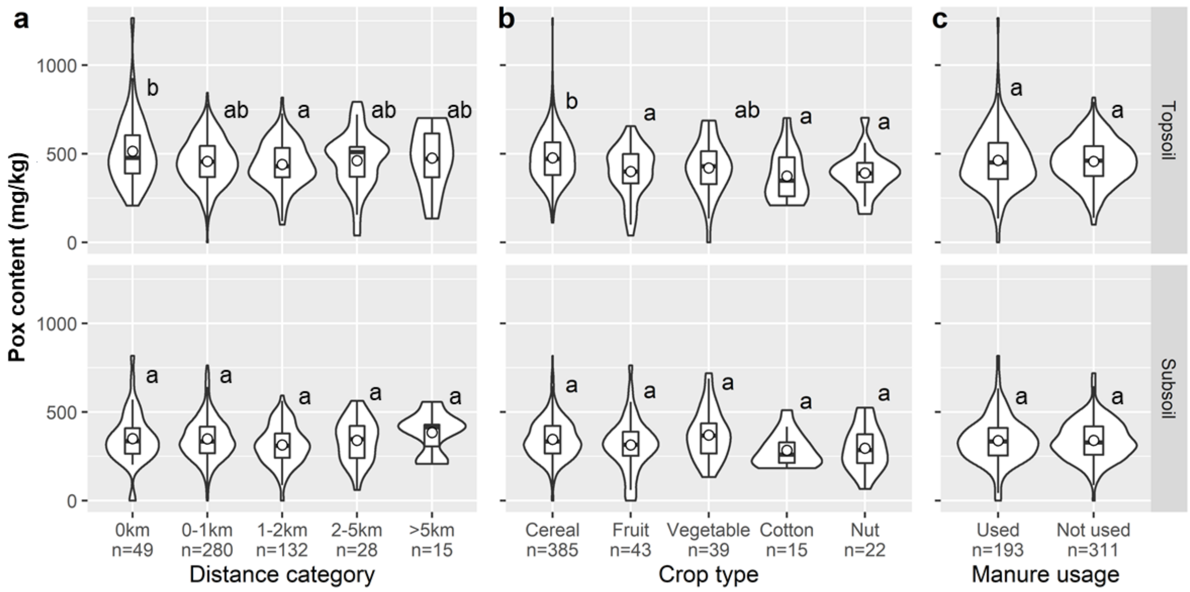

Figure S5.15. Comparison of oxalate-extractable phosphorus (Pox) content in fields with different distance to livestock farms (a), crop types (b) and manure application (c) in topsoil (upper panel) and subsoil (lower panel). The distance category of panel (a) represents livestock farms (0), within 1 km to nearest livestock farm (1), 1-2 km to nearest livestock farm (2), 2-5 km to nearest livestock farm (3) and more than 5 km to nearest livestock farm (4).

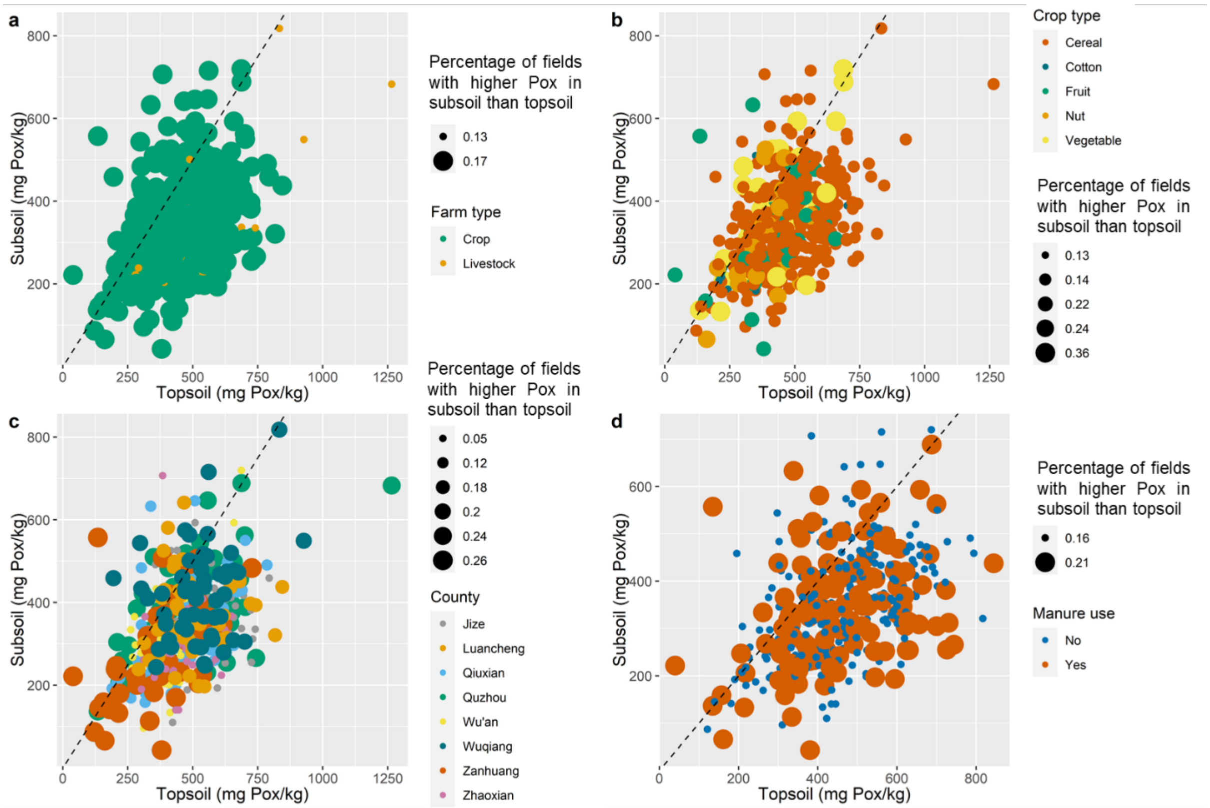

Figure S5.16. Results of soil sampling campaign. Relationships between Pox contents in the topsoil (0-15 cm) and subsoil (15-30 cm) as function of farm type (a), crop type (b), county (c) and manure use at farms (d). Dot size indicates the proportion of fields with higher OP content in subsoil than topsoil.

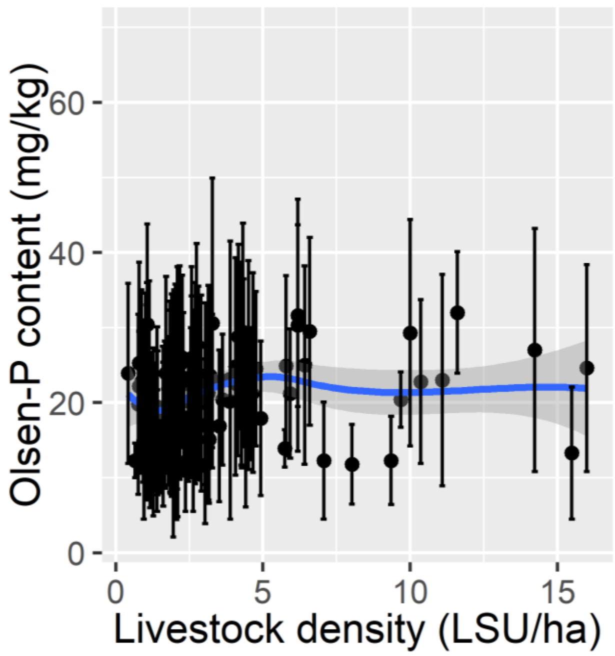

Figure S5.17. Relationship between livestock density and Olsen-P content at county level. Dots represent the average value of each county and error bars are the standard deviations. The blue line and shadow are loess regression (locally weighted regression) lines and their 95% confidence intervals using the average value generated by R programming language.

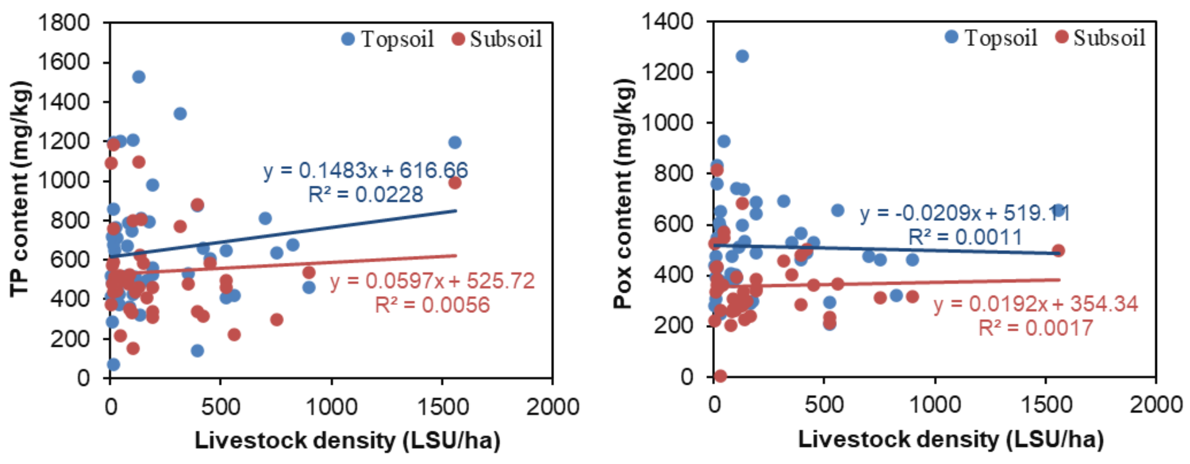

Figure S5.18. Relationship between livestock density and total phosphorus (TP; left figure) and oxalate-extractable phosphorus (Pox; right figure) in the topsoil and subsoil of cropland in livestock farms.

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Chapter 6 General discussion

The first field experiment testing farm yard manure as a soil amendment and nutrient source in the world started in Rothamsted, United Kingdom in 1848 and was continued for more than 150 years (Williams et al 1963; Goulding et al 2006). More systematic scientific research on manure and manure management in Europe can be dated back to the 1930s (e.g., Frankena, 1938). The early research mainly focused on manure's fertilizing effect on soil and crop (e.g., Künzli & Geering, 1973; Kolenbrander & De la Lande Cremer, 1967). From the 1980s environmental impacts, utilization efficiency of N, P, K and emission mitigation measures started to be examined seriously (MacNaeidhe et al., 1997; Dewes et al., 1993).

Scientific research on manure management in China started in the 1990s. Scientific reports tried to raise people's attention for the large amounts of manure produced and its potential threats to animal health (e.g., Xiang, 1993). Manure management methods were reviewed qualitatively based on literature and experiences from other countries (e.g., Jin et al., 1998). Quantitative examination of environmental impacts of animal manure started from 1995/1996, i.e., the effects of manure on GHG emissions (e.g., Erda, 1995; Hongmin et al., 1996). From 2000, more researches focused on estimating and reducing pollution from manure management and on the impacts of manure application to soil and crop (e.g., Geohring et al., 2001; Sandars et al., 2003). Research on the manure management chain started around 2010, largely based on budget calculations (Ma et al., 2010; Bai et al., 2013).

Chinese livestock production has been developing quickly. Within a few decades, the traditional, mixed, backyard systems have been and are being replaced by intensive, industrial production systems, and the intensive specialized livestock farms became spatially decoupled from cropland, from crop farms (Jin et al., 2021; Bai et al., 2018). Partly as a consequence of this intensification, China became the biggest livestock producer in the world, with pigs, cattle, and chicken as the dominant animal species (FAOSTAT, 2017). The new intensive livestock farms are often large in terms of the number of animals but have little or no cropland. The large amount of manure produced on intensive livestock farms can only be partly applied to on-farm cropland. Thus, intensive livestock farms have to treat the manure and export the surplus manure to crop farms. However, the implementation of adequate manure management, and the operation of manure treatment techniques are often limited because of serious social-economic and technical barriers which are not well revealed yet.

The overall objectives of my PhD thesis research were (i) to increase the understanding of the drivers and barriers for improving manure management on intensive livestock farms in China, and (ii) to explore options for and impacts of improved manure management techniques and practices. My PhD thesis research was part of the SURE+ subproject (Manure Management For Diminishing Environmental Pollution And Improving Soil Quality). In this subproject 5 PhD students have been doing research on various aspects of the manure management chain at different spatial scales. My thesis research focused on improving manure management at farm level in Hebei and Shandong provinces, with consideration of farmers' perceptions.

Unfortunately because of the outbreak of African Swine Fever at the beginning of my first farm survey, I had to give up investigating pig farms even though they are a very important livestock sector. Also, the planning and conduction of the second farm survey and soil sampling campaign was greatly delayed and had to be adjusted because of the spread of COVID-19. As a result, not all soil samples could be analyzed in time manner and not all results could be included in the thesis

6.1 Main findings

The most novel aspects of my PhD thesis research are

- A systematic investigation of drivers and barriers for adoption of manure treatment techniques on modern intensive livestock farms in Hebei and Shandong
- A survey on farmers' feed management and associated influencing factors on dairy and poultry farms
- A systematic analysis of variations in nutrient flows and nutrient use efficiencies at herd, manure, and farm level on dairy farms
- An exploration of measures to improve farm level manure management
- An assessment of the impacts of spatial variations in livestock density on manure utilization and soil phosphorus content at county and farm levels

These aspects are explained further in the three sections below, and discussed further in subsequent paragraphs 6.2, 6.3, 6.4 and 6.5.

6.1.1 Livestock farmers are struggling with manure management and treatment

- Current manure management and treatment practices on modern intensive livestock farms were relatively poor: almost all farms surveyed in Hebei and Shandong struggled with proper manure disposal, 70 out of the 338 surveyed farms were equipped with manure treatment facilities but less than half of the facilities were in operation.

- Farmers' adoption of manure treatment techniques was mainly driven by subjective norms from government agencies, by the awareness of environmental benefits of manure treatment, and by subsidies for investments in treatment techniques. Long-term operation of manure treatment techniques was hindered by the high operational costs and the low demand for and thus low price of manure products, which were not subsidized.

- Feed companies, rather than livestock farmers, define the crude protein content in animal rations. The average crude protein contents of the feed of dairy cows (159 g/kg), layers (184 g/kg) and broilers (245 g/kg for starter broilers) were close to recommended levels, and were on average relatively low.

6.1.2 Huge variation among farms in nitrogen and phosphorus use efficiencies

- Of the 141 dairy farms surveyed, 40% were landless and the other 60% had an average livestock density of 84 LSU/ha (range 3 to 554 LSU/ha).

- The average feed intake by dairy cows contained 248±50 kg N and 40 kg±8 P per cow per year, with 21±3% of the N intake and 28±4% of the P intake retained in milk and liveweight gain. The remainder was excreted in urine and feces. About half (50±22%) of the excreted N and 89±22% of the excreted P were applied to on-farm cropland and/or exported to nearby crop farms. The mean on-farm manure application to cropland was extremely high, i.e., 1364±1848 kg N and 281±437 kg P per ha per year.

- Farm level N use efficiency (NUE, 53±20%) and P use efficiency (PUE, 84±22%) of dairy farms were relatively high compared to grassland-based dairy farms in for example New Zealand and European Union, because of the export of manure and the import of most feed. Implementation of improved manure storage and treatment can increase NUE to 65±19% and PUE to 87±21%. By using covered manure storages and solid-liquid separation, 65 out of the 141 farms can increase farm NUE by 10 to 49 percent points.

6.1.3 Influence of manure availability on soil phosphorus contents is diffuse

- Results from the national soil database indicate that the mean Olsen-P content (range 9-41 mg/kg) of the topsoil of cropland was only weakly correlated ($r=0.21$, $P<0.05$) with the mean livestock density (range 0.4-16 LSU/ha) at county level.

- Almost all fields on livestock farms and one-third of the fields on crop farms received manure regularly; fields on livestock farms received manure more frequently than fields on crop farms. Surplus manure from livestock farms was mostly exported to nearby crop farms within 5 km distance. During the crop growing seasons, when manure could not be applied to cropland, surplus amounts of manure (especially the liquid fraction) were often discharged, especially when the manure storage capacity was limited.

- One third of the livestock farms had higher P contents in the topsoil of cropland than nearby crop farms.

- In total 21% of the fields from livestock farms and 41% of the fields from crop farms had higher total P content in the subsoil than in the topsoil, suggesting leaching of P from the topsoil to the subsoil.

6.2 Manure management in modern intensive farms and traditional mixed farms

Livestock production is becoming more intensive in many countries, including the Netherlands (Bos et al., 2013; Oenema & Oenema, 2021), America (Clay et al., 2020), Brazil (Dias et al., 2016), Ethiopia (Tadesse et al., 2018), mainly for economic reasons. Chinese livestock production started to burgeon in the1980s driven by fast economic growth and increasing demand for animal products (Chadwick et al., 2015; Bai et al., 2018). Nowadays, 68% of the animals are raised in intensive farms in China (NPC, 2021). Compared with traditional small farms, there are large differences as regard to herd and manure management (Table 6.1).

Table 6.1. Comparison of management aspects of intensive livestock farms and traditional mixed farms. Synthesis of results from my farm surveys and literature.

	Intensive livestock farms	Traditional mixed farms
Herd management	Division of herd groups; phase feeding • Dairy: calves, heifers, high-yielding cows, medium-yielding cows, low-yielding cows, dry cows (and even more); • Layers: chicks, pre-laying hens, laying hens (rations adjusted based on the age and production stage); • Broilers: 2-4 phase feeding stages based on the age.	Mixed herd groups; one ration[1]
Feed ingredients	Purchased, high-quality feed • Dairy: Concentrate feed, soybean, alfalfa, silage, ryegrass, oat, etc; • Layers: premix feed, soybean, corn (or full compound feed); • Broilers: full compound feed.	Kitchen waste, straw, bran, grass, etc[2]
Housing system	• Dairy: free-stall barn; zero-grazing • Layer: cage systems; • Broiler: littered houses or cage system	• Dairy: tie-stall and free range[1]; • Layer/broiler: free-range
Housing floor and cleaning	Concrete floor with frequent mechanical cleaning	Concrete or bare ground with low-frequent manual cleaning[1]
Manure storage	Open field or open lagoon storage with/without concrete floor	Open ground storage, with leaking losses
Manure treatment	21% dairy farms with manure treatment techniques	No treatment, apart from natural composting
Manure application	Solid fraction transported by trucks, spread by hand; liquid fraction evaporated or discharged; manure only partially utilized	By wheelbarrow and hand; available manure fully utilized[3]

1 Zhai et al., 2015;

2 Bai et al., 2018;

3 Bai et al., 2016

At the feeding stage, traditional mixed farms commonly use farm and household residues like straw, brans, and kitchen waste as main feed ingredients (Bai et al., 2018), while modern intensive farms use high-quality feed like soybean, corn, alfalfa, silage maize and concentrate feed. It has been suggested that financially powerful farmers tend to over-supply crude protein (CP) in the animal rations to avoid the risk of decreasing animal productivity (FAO, 2003; Kim et al., 2019), but such risk-avoiding strategy was not found in my research. Lowering the feed protein content has been advised by many studies and international governmental bodies to decrease N excretion in urine and feces and to mitigate NH_3 emission (e.g. Hou et al., 2015; Bittman et al., 2014; Santonja et al., 2017). Animal manures were responsible for about 54% of the total NH3 emissions in China (Huang et al., 2012), and this percentage will likely increase as total livestock production increases, while the use of synthetic N fertilizer tends to decrease. In a recent modelling study, Zhang et al (2019) assumed that the ration of dairy cows contained 170 g/kg CP and concluded that there was a large potential of reducing the CP content in feed (low protein feeding) to mitigate NH_3 emissions in China. This assumption and this conclusion are likely biased according to my results obtained through the farm survey and the feed sample analyses. The average CP content of the ration of dairy cow was 159±20 g/kg, which is close to the level recommended for low-protein feeding (Chapter 3). Therefore, lowering feed CP in the ration of dairy cows had little effect as NH_3 emission mitigation measure. Lowering the feed CP in the ration of dairy cows had also minor effects on herd NUE and farm NUE (Chapter 4).

The housing stage is where most NH_3 emissions occur in the manure management chain; the results presented in Chapter 4 confirm earlier findings (Velthof et al., 2009; Bai et al., 2016). I estimated that 24±6% and 4±4% of excreted N were lost as NH_3 and N_2O+N_2, respectively, in housing stage of intensive dairy farms, equivalent to 5.7±2.1 kg NH_3 and 1.0±0.9 kg N_2O+N_2 per 1000 kg FPCM (fat-protein corrected milk) produced (Table 6.2). The N_2O+N_2 losses are expected to be relatively high from the manure deposition in the playground of dairy farms, but my estimations are highly uncertain due to lack of in-situ measurements. Nutrient losses from the housing stage are influenced by various factors, including floor type, housing system, climate, and manure removal (floor cleaning) frequency (Poteko et al., 2019; Ivanova-Peneva et al., 2008). In traditional backyard systems, manure is manually removed around once a week (Zhai et al., 2015). I found that in modern intensive farms, manure is removed from the housing systems with shovels or scrappers once a day (on 90% of the dairy farms, 89% of the layer farms, and 69% of the broiler farms; Chapter 2). Yet, there are still large differences among intensive farms in China and in some developed countries in floor type and housing system. For instance, dairy cows in the Netherlands are kept mostly in cubicle houses with slatted floor and graze outside during summer months (Van Horne & Prins, 2002; Oenema & Oenema, 2021), whereas all dairy cows in my research were kept on concrete-floor barns with/without a small playground all-year round. Up to 65% of the laying hens are raised in aviary systems in Switzerland (Häne et al., 2000), 67% of the hens are in cage systems and the others largely in free-range systems in Belgium (Tuyttens et al., 2011), while 100% of hens were kept in cage systems in China. Housing systems in China are conducive to NH_3 volatilization and are not animal friendly (Pereira et al., 2011).

Table 6.2. Nitrogen (N) and phosphorus (P) losses during the housing, manure storage and manure treatment stages of the manure management chain of the surveyed intensive dairy farms, in percent of total N and P excreted and in kg per 1000 kg of fat-protein corrected milk (FPCM). Values indicate mean ± standard deviation. Synthesis of results presented in Chapter 4.

	Nitrogen and phosphorus losses (% of excretion)			Nitrogen and phosphorus losses (kg/1000 kg FPCM))		
	Housing	Storage	Treatment	Housing	Storage	Treatment
NH_3	24±6	10±10	1±1	5.7±2.1	2.4±2.4	0.1±0.3
N_2O+N_2	4±4	3±5	1±1	1.0±0.9	0.8±1.1	0.2±0.3
N leaching	1±1	0±0	0±0	0.2±0.3	0±0	0.3±1.5
N discharge*	3±12	2±7	1±7	0.8±3.1	0.5±1.8	0.3±1.5
P leaching	0±0	1±2	0±0	0±0	0±0	0±0
P discharge*	4±17	4±12	2±10	0.2±0.7	0.1±0.5	0.1±0.3

*The discharge is after manure removal from the housing, storage and treatment because of the limited storage capacity on most farms.

Manure storages are also a main stage of gaseous N emissions. I estimated that 15% of the excreted N was lost through NH_3, N_2O and N_2 emissions and N leaching from manure storages on dairy farms. In addition, 5% of the excreted P was lost (Table 6.2). Gaseous N losses during storage are influenced by the presence of a coverage on the storage, the duration of the storage, possible additives in the manure (including acids, to lower the pH), and environmental conditions during the storage (Hörnig et al., 1999; Portejoie et al., 2003; Petersen et al., 2013).

Leaching losses are influenced by the leakiness of the bottom of storages and lagoons, and by surface runoff and discharge. Nearly all animal farms in Belgium, Denmark and the Netherlands use covered manure storage facilities with leak tight sealing (Hou et al., 2016). However, only 3 out of the 98 layer farms visited, 2 out of the 99 broiler farms visited and none of the dairy farms visited used covered manure storages (Chapter 2). Evidently, there is large potential to increase the nutrient recovery through covered and leak tight manure storages in China. Through covering the current open-field manure storages, the current NUE at farm level of dairy farms can be increased from 53±20% to 59±20% (Chapter 3). The reduction of gaseous N emission and the increase of the nutrient use efficiencies depend in part on the type of coverages. Coverage of manure storages may increase CH_4 emissions, while straw coverages may increase the emissions of N_2O, indicating that there are some trade-offs among gases (Hou et al., 2015; Portejoie et al., 2003).

Manure treatment is become more important under the intensification of animal production and recent policy regulations, as manure treatment products have greater acceptance by crop farmers than raw slurries, and thus may facilitate improved utilization of manure nutrients and organic matter in cropland. Technologies such as solid-liquid separation and composting are not too difficult to manage at farm scale and are relatively low cost, thus are commonly seen on intensive livestock farms (Chapter 2). Composted manure is more stable in physical, chemical and biological characteristics compared to raw slurries. Anaerobic digestion has been promoted in rural area of China by the government (Qu et al., 2013), but most of the digestion plants on intensive livestock farms were not in operation, due to several limitations, discussed further in section 6.4. There are various other possible techniques to treat manure, such as manure acidification (Kai et al., 2008; Zhang et al., 2019), bio-drying (Avalos Ramirez et al., 2012), algal turf scrubber (Pizarro et al., 2006), but these are not found in practice in China.

At the application stage, manure injection appears to have the largest NH_3 emission abatement potential when using raw or digested slurries (Hou et al., 2016). Slurry injection reduces NH_3 emissions by up to 98% compared to surface broadcasting of slurry, but depending on the injection depth (Duncan et al., 2017; Webb et al., 2010). Surface broadcasting followed by direct incorporation into the soil may yield similar effects if the incorporation occurs directly. However, slurry injection and manure incorporation into the soil have the side effect of increasing N_2O emissions (IPCC, 2007). Only surface broadcasting of solid manures, and no low-emission approaches, were found on the farms in Hebei and Shandong during my surveys, partly because of lack of machines and/or contractors. In comparison, manure injection is used by 12% of the dairy farms in USA (Aguirre-Villegas & Larson, 2017) and by 56% of the farms in the Netherlands (Gebrezgabher et al., 2015).

There was a large variation in the manure management among livestock farms (Chapter 2). As a consequence, N and P losses and use efficiencies also varied largely among farms (Table 6.2). Particularly for discharge, the percentages of N and P discharged had coefficient of variances (sd divided by the mean) over 300%. The mean values indicate that on average there was little manure discharge, but still some farms discharged remarkable amounts of manure (especially the liquid fraction of solid-liquid separated slurries) to surface waters or landfill. The total on-farm cropland area was a main factor influencing the on-farm manure application and manure exportation: farms with more cropland area applied a larger percentage of excreted N and P to on-farm cropland and exported a smaller percentage of excreted N and P to crop farmers (Chapter 4). Consequently, cropland area didn't influence NUE and PUE significantly. The manure level NUE (i.e., manure N recycling rate) was found to be negatively correlated with farmers' age, suggesting that older farmers had less manure N recycled but more N lost, possible because of the shortage of labor, unwillingness to invest in cleaner techniques, or lack of cognition of manure pollution. However, manure discharge appeared to occur rather random among farms, I was not able to discern common farm and/or farmer' characteristics as most influencing factors.

To sum up, manure management requires a chain approach with several consecutive steps that affect each other. Modern intensive livestock farms have invested in improving animal feeding and animal housing, but investments in manure storage, manure treatment facilities and manure export are still limited. Farm NUE (53±20%) and PUE (84±22%) found in my study were higher than in the studies of Bai et al., (2013, 2016) and Zhao et al., (2017): these researchers found values of 10 to 44% for NUE and 12 to 69% for PUE. The farm-level NUE and PUE of the dairy farms in my study were also relatively high compared to (grassland-based) intensive dairy farms in North America, Australia and Western Europe (8 to 65% for NUE and 46 to 159% for PUE; Powell et al., 2010; de Klein et al., 2016; Scott & Gourley, 2016; Oenema & Oenema, 2021; Harrison et al., 2021), in part because of the externalization of feed production and manure utilization. However, there was large variations among farms, and there is still much potential to make improvements in each step of the manure management chain.

6.3 Drivers and barriers for improving manure management and farmers' perceptions

Chinese government has announced several action plans to facilitate manure treatment, to reduce the environmental pollution from animal manures, and to facilitate manure recycling to cropland, also to reduce the use of synthetic fertilizers (policies listed in Bai et al., 2018; Wei et al., 2021). However, the implementation of these policies in practice is still limited. Knowing the reasons for the limited implementation may lead to recommendations for more effective policy instruments and policy implementation. The research presented in Chapter 2 investigated the drivers and barriers for using solid-liquid separation, anaerobic digestion and composting as on-farm manure treatment techniques.

Subjective norms and perceived benefits to the environment were main drivers, and the low benefit-cost ratio was the main barrier for farmers to adopt these techniques (Table 6.3). Farmers' subjective norms are mainly perceptions of whether they are expected by governmental agencies to use manure treatment. Costs for manure treatment included depreciation of construction costs (capital, machine, and land) and operational cost (energy, labor, maintenance). Investments in manure treatment techniques are often subsidized by the government, but operational costs are not supported/compensated. The cost barrier (mainly operational costs) was also observed in other countries, for instance in European countries (Hou et al., 2018), USA (McCann et al., 2006), and Brazil (Kunz et al., 2009).

Table 6.3. Drivers and barriers for using solid-liquid separation, anaerobic digestion and composting to treat manure, synthesized from Chapter 2.

	Drivers	Barriers
Solid-liquid separation	• Perceived benefits to environment • Easier handling of treated products • Subjective norms (from government agencies)	• High construction costs, including the land area needed • Operational costs for energy and labor • Lack of functioning manure market • Technical failures, especially in winter
Anaerobic digestion	• Perceived benefits to environment • Less energy use • Better manure quality • Subjective norms (from government agencies) • Availability of construction subsidy	• Construction costs • Lack of subsidies for covering operation costs • Low price for biogas • Technical complexity and labor needed
Composting	• Increasing income through selling compost products • Less odor nuisance and cleaner environment	• Construction costs, including the land area needed • High operation costs, including labor cost • Low benefit-cost ratio because of a dysfunctional market for composts • Lack of financial support from government - local governments believe that open-air composting pollutes the environment.

The cost of solid-liquid separation of raw slurry strongly depends on the type of separator, the amount of slurry separated per year and the desired 'purity' of the liquid fraction (Møller et al., 2000; Melse & Verdoes, 2005; Schröder et al., 2009). The centrifuge is more expensive than the screw press separator, but the dry matter content of the solid fraction is higher with the former than with the latter, and hence the solid fraction from the centrifuge has lower transportation costs than the solid fraction from the screw press. Total cost (i.e., operational costs and depreciation costs) decrease exponentially with an increase of the amount of slurry separated; total costs are in the range of 2 to 5 €/m^3 when separating ~10,000 m^3 per year (Møller et al., 2000; Schröder et al., 2009). The liquid fraction may be treated further through ultrafiltration and/or reverse osmosis, which increase the total cost to about 12 €/m^3 (Melse & Verdoes, 2005). Anaerobic digestion costs about 1 €/m^3 slurry (55% depreciation and 45% operational costs) in Spain (Flotats et al., 2009), but the net cost-benefit ratio strongly depends on the total amount of manure digested, energy costs, and the subsidies provided for delivering 'green energy' (Gebrezgabher et al., 2010). Although the operational cost may be lower in China than in Europe, because of the low electricity price and low labor cost, the additional costs and labor needed for anaerobic digestion reduce marginal profits, which farmers do not accept easily. Meanwhile, there is a lack of functional markets for treated manure products and for the generated biogas.

Adoption of solid-liquid separation and anaerobic digestion as manure treatment techniques is also limited by the conditions in winter, i.e., a low temperature complicates the operation and reduces the treatment efficiencies. The solid-liquid separator may get frozen and stuck. The commonly used screw press separator is easily worn out by the sand (from bedding material) in the slurries. Once the separator is broken, farmers have difficulties to repair it. Other separation techniques may be able to solve this problem, but operational costs of these techniques are higher (Møller et al., 2000). Farmers find controlling the temperature and pH of the anaerobic digestion process complex, also because they usually lack the needed skills. Moreover, the production of biogas is relatively high in summer when little heat is needed, and low in winter, when heat is needed. Proper cleaning of digestate is another barrier because it needs specialized workers, as farmers reported. Several accidents have occurred during cleaning the biogas digesters in China (e.g., Zhu, 2020; Cai & Peng, 2005; Tan, 2010).

Drivers and barriers for improving manure management and treatment can be different among countries, depending on governmental support and regulations, amounts of manure produced and to be treated, and the energy price. In general, adoption increases with the perceived financial benefit (Bangalore et al., 2016). Low-protein feeding is generally perceived as a cost-effective measure for decreasing manure N production and NH_3 emissions. The ration of the animals on intensive livestock farms were mainly defined by feed companies through the Precision Livestock Farming program; the formulated rations turned out to be close to the recommended rations for low-protein feeding. This is somewhat in contrast with many livestock farms in Europe, which have difficulties with lowering the protein level in the animal feed to the level of low-protein feeding (Bittman et al., 2014; Oenema & Oenema, 2021).

In summary, adoption of manure treatment techniques was mainly driven by the perceived subjective norms and the perceived environmental benefit. But high operational cost and a poor functioning manure market resulted in high cost-benefit ratios that hindered farmers' intention for continuous operation. Farmers know little about low-protein feeding and relied on feeding/contracting companies for feed management. These feeding/contracting companies recommended low-protein animal feed because protein-rich feed was expensive.

6.4 Manure management for diminishing environmental pollution and improving soil quality

Improving manure management to mitigate environmental pollution and to improve soil quality is a crucial element of the circular economy and of sustainable agriculture. Manure management is highly relevant to 8 targets of the Sustainable Development Goals (SDGs), as defined by the United Nations. Additionally, 9 targets are moderately relevant and another 9 targets have minor relevance to this topic (Wang et al., 2022). Of all 17 SDGs, manure management is most relevant to SDG 2 "Zero hunger – End hunger, achieve food security and improved nutrition and promote sustainable agriculture".

Manure management influences air, water, and soil quality and thereby ecosystem and human health. Figure 6.1 synthesizes the main research topics related to manure management: 1. Management of macronutrients (N, P, K) in manure and their environmental impacts (e.g., Bai et al., 2016; Zhang et al., 2019); 2. Soil organic matter and soil biodiversity management through manure additions (e.g. Maillard & Angers, 2014; Li et al., 2021); 3. Contamination of soil and the environment through heavy metals, antibiotics and hormones in animal manure (e.g., Zhen et al., 2020; Odoemelam & Ajunwa, 2008); 4. Management of the emission of odorous volatile and possibly toxic gases from manure storages (e.g., greenhouse gas emissions, fatty acids, hydrogen sulfide, hydrogen cyanide, ammonia) (e.g. Trabue et al., 2019; Gay et al., 2003); 5. Innovations in manure treatment and management (e.g. Mulbry et al., 2008; Cao & Harris, 2010).

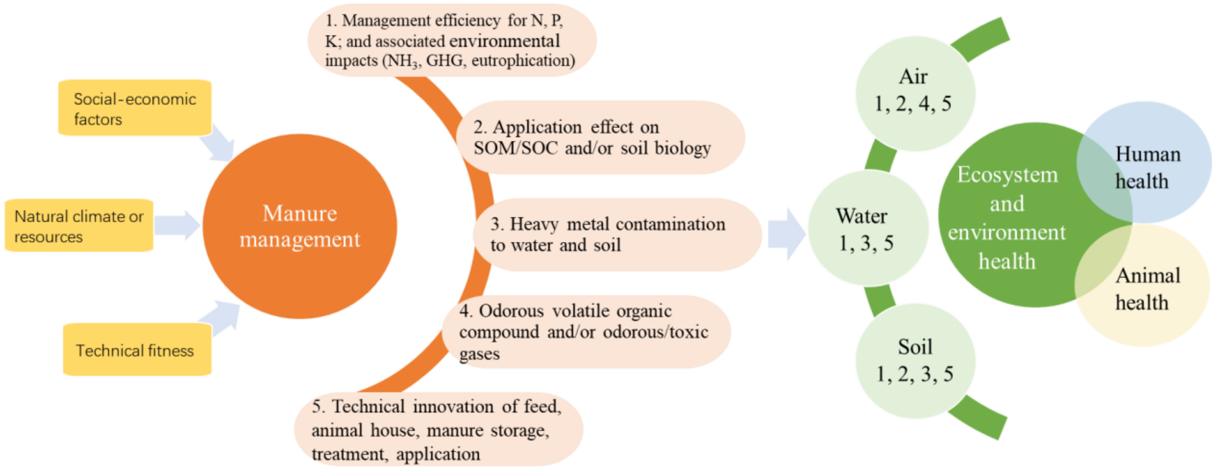

Figure 6.1. Synthesis and overview of important research topics related to manure management, including impacts on human and ecosystem health.

The use efficiency of manure N and P was defined (in this study) as the percentage of total manure N and P excreted that is applied to cropland. It is also referred to as manure N and P recovery rate (Hou et al., 2017) or manure N and P recycling rate (Bai et al., 2013 & 2016). Variations in manure N and P use efficiencies greatly contributed to the variations in farm N and P nutrient use efficiencies (Chapter 4). Manure use efficiency was estimated at 37% for N and 55% for P in China in 2010 (Bai et al., 2013 & 2016). For dairy farms in Hebei, I estimated that manure use efficiency was 50±22% for N and 89±22% for P (Chapter 4). My results indicate that less manure N is lost from dairy farms in China compared to USA (27-38% for N and 71-96% for P; Spears et al., 2003a & 2003b; Powell et al., 2006; Gourley et al., 2012). There are two possible reasons for the relatively high manure N use efficiency on intensive dairy farms in China and the relatively low manure N use efficiency in USA : i) the data for USA relate to 10 to 20 years ago; in the meantime manure management may have improved, ii) manure was frequently applied to on-farm cropland or exported to crop farms because of the limited manure storage capacity (<3 months for dairy farms, and <2 weeks for layer and broiler farms (Chapter 4), compared to 3-12 months in USA (Dutreuil et al., 2014; Aguirre-Villegas & Larson, 2017)). The practice of short-duration storage and frequent manure application tends to externalize N losses to cropland and crop farms, which was not accounted for in my definition of manure N use efficiency.

Manure N and P applications on cropland of dairy farms were on average 1364±1848 kg N and 281±437 kg P per ha per year (Chapter 4). The N application rates by far exceed the manure N application limit in EU (170 kg per ha per year) and the mean manure N application rate in Wisconsin dairy farms (Powell et al., 2005). Note that N and P withdrawals with harvested crops (86 to 158 kg N and 16 to 36 kg P per ha per year; Ma et al., 2010) were roughly one order of magnitude lower than the mean manure N and P application rates on the cropland of intensive dairy farms in Hebei. Dairy farms applied manure to on-farm cropland multiple times per year, but without supplemental synthetic fertilizer applications. As a result, the P content of the topsoil of cropland from dairy farms was relatively high compared to the P content of cropland from nearby crop farms (Chapter 5), but our soil sampling strategy may have missed notorious manure dumping fields.

I did not find clear relationships between livestock density, manure N and P applications and soil P contents at farm and regional levels. The lack of clear relationships between livestock density and soil P contents at farm and county levels is likely related to rapid recent changes in the structure of agriculture in Hebei (Bai et al., 2018), to the use of substantial synthetic P fertilizers (Zhang et al., 2016; Li et al., 2011), and possibly to sampling biases (Chapter 5). Most of the manure P that has been applied to cropland in excess to the P withdrawal with harvested crop will accumulate in the topsoil. However, if P leaches from the topsoil to the subsoil, the P contents of the topsoil will be lower than expected, and thereby obscure the expected relationship between livestock density and soil P content. Evidently, further field studies are needed to be able to get a better understanding of the spatial variations in soil P content, and of possible leaching of P from the topsoil to the subsoil.

To sum up, improved manure storages and increased manure recycling to cropland are important for reducing N and P losses from manure management, and for improving N and P use efficiency at farm and regional levels. The manure N and P recycling rates were relatively high in intensive dairy farms, which is related to the application of manure to on-farm cropland and the export of manure to crop farms. Manure N and P applications to on-farm cropland were very high, which will result in soil P accumulation (and high N leaching losses), but I found limited evidence for excessive soil P accumulation.

6.5 Overall main conclusions

Manure management requires a chain approach, from animal feeding up to manure application to cropland. Manure management on intensive livestock farms in China is perceived as a burden by livestock farms. Relief of this burden is expected to come in part from manure treatment, but the adoption of manure treatment techniques in practice was still low. Livestock farms externalize inefficiencies in manure management to the environment and to crop farms.

My research findings are based on interviews with farmers and on observations and measurements on the ground. The variations among livestock farms in manure management and manure treatment practices, and in N and P use efficiencies were very large. This underlines the importance of my central hypothesis formulated in the Chapter 1 that on-farm observations are needed for improving our understanding of manure management practices. The effects of improved manure management practices also greatly differed between farms. This indicates that blanket guidelines and governmental regulations for improving manure management will not be very effective. Instead, farm-specific approaches will be needed.

There are several barriers for using manure treatment techniques by livestock farms in practice, which so far have been neglected too much. Only a fraction of the manure treatment techniques were in operation, because of technical failures, high operation costs, lack of proper incentives, and lack of end-users for manure treatment products. This indicates that incentives should be redirected to increase manure utilization in cropland.

Overall, the N and P use efficiencies at farm level and the manure N and P use efficiencies at the dairy and poultry farms examined were higher than some previous studies have reported for livestock farms in China. This may suggest that the recent changes in livestock production systems, and the governmental policies and regulations on prohibiting manure discharge and on manure treatment have improved the nutrient use performance of livestock farms. However, there were still large variations between farms. The good performing farms that used precision livestock feeding, frequent manure cleaning, leak-tight manure storages, advanced treatment techniques, and had enough cropland or export manure (via contractors) to crop farms had an farm NUE of up to 87%. In contrast, the relatively poor performing farms had a farm NUE of only about 15%.

The expected relationships between livestock density and soil P contents at farm and regional levels were not found, likely because of confounding factors (rapid changes in farm structure, large use of synthetic P fertilizer, possible sampling biases and possible leaching of P from topsoil to the subsoil). Yet, intensive dairy farms applied excessive amounts of manure to on-farm cropland, and they exported manure only to nearby crop farms, also in counties with very high livestock density. My results point at the needs for (i) manure application limits for cropland on intensive livestock farms, (ii) improved manure storages and enlarged storage capacity, (iii) improved manure utilization in cropland, while replacing synthetic P fertilizers, and (iv) developing a 'manure market' with different manure treatment products and with the involvement of middlemen

6.6 Recommendations for future research

(1) In the model that I developed and used for quantifying nutrient flows in dairy farms, I used several parameters and coefficients which were derived from studies in other countries and from expert knowledge, because experimental studies on nutrient flows and losses in dairy farms in China are nearly not existing. This indicates the need for experimental studies in these farms in China, to verify and check the calculated N and P flows and losses.

(2) My research revealed the importance of developing a 'functional manure market' for improving manure management, manure redistribution and manure utilization in crop farms. The criteria, guidelines and business models for such 'functional manure market' need to be developed, together with the pertinent stakeholders.

(3) Chapter 5 indicates that the fate of the manure P applied to cropland is not sufficiently clear for deriving recommendations for improved manure P management and possibly for improved spatial planning and optimization of livestock farms. There is also need to examine the fate of other nutrients (e.g., N, K, Cu, Zn) in manure applied to cropland. Evidently, further research is needed here.

(4) My farm surveys were conducted in Hebei and Shandong provinces, which are livestock dense provinces with distinct cold and dry winters and hot and moist summers. Additional surveys are needed for livestock-dense provinces in the more humid/hot southern part of China, to better understand the drivers and barriers for improving manure management and treatment, and the variations between livestock farms in N and P flows and losses.

(5) Attempts to improving manure management and increasing nutrient use efficiency can be conducted at various spatial levels, i.e., field, farm, county, province, and national level. Attempts at county, province and national levels may lead to externalization of inefficiencies and losses to other counties, provinces and countries (Du et al., 2018). This suggests that coordinated efforts and attempts are needed at different spatial scales, which is an area for further research.

(6) In Chapter 2, I concluded that governmental incentives and subsidies for purchasing manure treatment techniques (and synthetic fertilizers) should be redirected to the users of manure and

manure treatment products in crop production systems. More research is needed to find the optimal set of incentives, guidance and regulations for cost-effective and environmental sound improvement of manure utilization in different crop production systems.

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Summary

Animal manure is a valuable resource of nutrients and organic matter to fertilize crops and amend soils. Animal manures contain about half or more of the nutrients and organic matter in the feed ingested by animals, depending on animal species, feed quality and management. However, manures are bulky and smelly. With the arrival of relatively cheap and easily applicable synthetic fertilizers on the market, manures have turned from a resource into a waste and pollutant to the environment, especially in industrial-sized and specialized livestock farms and in regions with high livestock density. Globally, some 130-140 Tg nitrogen (N) and 23-30 Tg phosphorus (P) are excreted in animal manure per year. These amounts are equal to or larger than the global synthetic fertilizer production. Animal manures (and fertilizers) contribute to ammonia (NH_3) and greenhouse gas (GHG) emissions into the air. Emissions of GHG contribute to climate change. Emissions of NH_3 contribute to eutrophication of natural ecosystems and to the formation of atmospheric fine particulate matter with diameter less than 2.5 μm (PM2.5), which threatens human health. Leakages of nutrients from manure storages and heavily manured cropland, and manure discharges contribute to both groundwater and surface water pollution; manure is a main source of surface-water eutrophication. Evidently, there is a global need to improve the utilization of manure nutrients, in part by replacing synthetic fertilizers, and to decrease GHG and NH_3 emissions and N and P losses from manures.

Livestock production in China has been transforming from traditional mixed backyard production systems to specialized industrial systems during the last few decades. It is expected that livestock production will increase further to meet the increasing animal-source food demand in China during the following decades. The newly emerged modern intensive livestock farms often have no or only a little cropland. The intensification of livestock production has led to spatial decoupling of livestock and crop production systems, making livestock manure recycling to cropland difficult. As a result, intensive livestock farms are struggling with manure management. However, not much is known about the situation in practice, and about the drivers of and barriers to improving manure management.

Manure management basically includes a chain of steps, from animal feeding, animal housing, manure collection, storage and/or treatment, to finally manure application to cropland. Farmers' adoption of improved technologies and practices differs greatly among countries and regions because of differences in systems, economic conditions, culture, knowledge infrastructure, climate, and policy regulations. Quantitative information on the variation of farmers' manure

management practices and on the drivers and barriers influencing the adoption of advanced manure management techniques in practice is required for improving manure management at farm level. However, there is a lack of empirical data, especially for intensive livestock farms in China. Understanding the drivers of and barriers to improving manure management and the relationship between livestock density, manure utilization, soil fertility, and external influencing factors will help to guide nutrient management and planning.

The overall objectives of my PhD thesis research were i) to increase the understanding of the drivers and barriers to improving manure management on intensive livestock farms in China, and ii) to explore options and impacts of improved manure management techniques and practices. My main hypothesis was that livestock farms greatly differed in manure management practices and that these variations can be quantified and understood through conducting farm visits, interviews and additional analyses. The research was part of the SURE+ project (Sustaining Resource Management For Adequate And Safe Food Provision), which was funded by the Royal Dutch Academy of Sciences (KNAW) and the Ministry of Science and Technology in China (MOST). In subproject 3 (Manure Management For Diminishing Environmental Pollution And Improving Soil Quality) five PhD students have been working on various aspects of the manure management chain, including specific emission mitigation measures and manure treatment technologies at different spatial scales. The research reported in my thesis focused on improving manure management at farm level with consideration of farmers' perceptions. My thesis has 4 research chapters, in addition to a general introduction (Chapter 1) and a general discussion (Chapter 6).

Chapter 2 focused on the drivers of and barriers to using manure treatment techniques on intensive dairy and poultry farms in Hebei and Shandong provinces, following the Theory of Planned Behavior. An initial semi-structured survey was conducted on 51 farms to gain basic insights into manure management practices and to identify relevant influencing factors. The identified outcomes, referents and controlling factors were quantitatively evaluated through a second structured survey on 338 intensive dairy, layer and broiler farms. Solid-liquid separation of manure slurry, anaerobic digestion and composting were the most common manure treatment techniques on these farms, but less than half of the techniques were actually used. Farmers perceived subjective norms from government agencies, perceived benefits to environment, and the financial support from government to invest in treatment techniques as the main drivers for investing in manure treatment techniques. However, the continuous operation of these techniques is associated with high operational costs in terms of both capital and labor, while the manure treatment products do not provide much income. Technical failures and the harsh conditions during winter were also barriers for operating manure treatment techniques. The barriers were larger than the incentives from the perceived good outcomes and subjective norms from social referents. Based on these findings, I recommended that governmental agencies redirect subsidies from investments to actual operations, and/or from the producers of manure treatment products to the users of manure treatment products. Further, there is a need for monitoring and verification in practice.

Low-protein feeding is one of the most cost-effective ways to reduce the excretion of N via urine and faeces, and thereby to reduce the N emissions from the whole manure management chain. Chapter 3 reports on the crude protein contents of animal diets and the influencing factors of feed management. To understand farmers' decision making in feed management, face-to-face interviews were conducted on 338 intensive dairy, layer and broiler farms. The variations among farms in crude protein content of animal diets were examined quantitively through analysis of whole-mixed feed samples, using near infra-red spectroscopy (NIRS). I found that livestock farmers had little knowledge and concerns about protein in feed and about the environmental impacts of protein overfeeding. Decisions about feed use were mainly based on feed brand, services provided by feed companies, and the price of the feed. Dairy and layer farmers mixed the feed ingredients simply following the instructions from feed companies. Broiler farms accepted the assigned feed from the contracting companies. The decision-making of farmers' feed management indicates that feed and contracting companies need to be actively involved in implementing any policy related to low-protein feeding. The feed analyses indicated that the average CP contents were close to the level internationally recommended for low protein feeding. This indicates that farmers' concerns about high feed prices (protein-rich feed is relatively expensive), helped to prevent protein overfeeding to animals. Indirectly, my results also indicate that several previous modelling studies may have overestimated NH_3 emissions from livestock farms because of the assumed protein overfeeding in the calculations. However, there are large variations among farms in the CP content of the diets, indicating that there are still large potentials on some farms to reduce the CP content, with benefits for farm income and the environment. This requires active involvement of feed companies and skilled advisors.

Chapter 4 presents variations in N and P flows, and N and P use efficiencies (NUE and PUE) of intensive dairy farms at herd, manure and farm levels. Also, effects of advanced management measures on improving nutrient use efficiencies were examined. To estimate variations in N and P flows and budgets, I developed a farm-level nutrient flow model based on a mass balance approach, and used the results from the farm survey and feed analyses of 141 intensive dairy farms. I found that the variations among dairy farms in manure management and in N and P use efficiencies were very large. The mean NUE and PUE at herd, manure management, and farm levels were relatively high compared to several previous studies, which used data from literature and statistics. Indirectly, this shows the value of farm surveys and on-farm observations and analysis for obtaining accurate and up-to-date results. I further explored the effects of mitigation technologies on each farm, using scenario analyses. Results showed that the mean changes of NUE and PUE were relatively small, but there were remarkably large differences among farms and measures. Improving current open-air manure storages to covered and leak-tight manure storages is the most effective single measure. If combined with solid-liquid separation and export of the solid fractions, NUE can be improved by 10-49 absolute percent points. The average NUE and PUE at farm level of the 141 farms may then reach values of 65±19% (mean±sd) and 87±23%, respectively. I also found extremely high manure application rates on dairy farms with cropland (1364±1848 kg N and 281±437 kg P per ha per year), because many farms had difficulties exporting manure to crop farms elsewhere. Evidently, such high application rates will significantly affect soil fertility and the environment.

In Chapter 5, I explored the relationship between livestock density and soil phosphorus contents at county and farm levels in Hebei. County-level relationship were examined on the basis of data from existing databases with livestock density and statistics on Olsen-P contents (note, there are 167 counties in Hebei). Mean livestock density at county level ranged from 0.4 to 16 livestock units per ha, and mean Olsen P from 9 to 41 mg per kg. Farm-level relationships were explored based on a farm survey among 80 livestock farms and 480 nearby crop farms, with soil sampling and analyses of soil total phosphorus (TP) and oxalate-extractable phosphorus (Pox) in the topsoil (0-15 cm) and subsoil (15-30 cm). I did not find clear relationships between livestock density and soil P contents at county level and at farm level. However, I discovered that livestock farms with cropland tended to have higher soil P content than crop farms. Livestock farms applied relatively large amounts of manure to on-farm cropland, independent of crop type. Meanwhile, 21% of the fields from livestock farms and 41% of the fields from crop farms had higher TP contents of the subsoil than of the topsoil, suggesting leaching and accumulation of P in the subsoil. My results indicate that livestock manure was not well distributed and utilized and that there is a need for manure application limits, especially on livestock farms.

In conclusion, my thesis provides a systematic analysis of the farm-level manure management of intensive dairy and poultry farms in Hebei and Shandong. The differences among these farms in manure management and manure treatment practices, and in N and P use efficiencies were very large, indicating that blanket guidelines and governmental regulations for improving manure management will not be very effective. Many intensive livestock farms were struggling with manure management. Adoption of manure treatment was relatively low and techniques were often not working, because of technical failures, high operation costs, lack of proper incentives, and lack of end-users for manure treatment products. Livestock farms with cropland applied large amounts of manure to on-farm cropland and the surplus amounts of manure to crop farms within 5 km distance. Yet, I did not find clear relationships between livestock density and soil P contents, likely because of confounding factors. My results point to the need for improved manure utilization in cropland, for developing a functioning 'manure market' with the involvement of middlemen, and for manure application limits for cropland on livestock farms. Further research is needed to find the optimal set of incentives, guidance and regulations for encouraging active involvement of middlemen and crop farms. Hopefully, my thesis will contribute to improving manure management at farm level and to improving the sustainability of agriculture in practice.

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About the author

Meixiu Tan was born on 9 May 1992 in Xuancheng, Anhui Province, P.R. China. In 2010 Meixiu started her bachelor in Applied Meteorology at China Agricultural University (CAU) after graduation from the Xuancheng second senior high school. She received a BSc degree with distinction (Cum Laude) in the College of Resources and Environmental Science (CAU) in 2014. During her BSc thesis study she analyzed the spatial and temporal variations of the optimal sowing dates of summer maize in Henan Province, using statistical and process-based models. For her master study at CAU, she was selected and funded by Chinese Scholarship Council to visit the Crop System Analysis Group in Wageningen University (WUR) for one year, as a joint master student. In 2017 she successfully completed her MSc study and received her MSc degree, with the thesis entitled "Modelling water use in wheat-maize intercropping system". She was supervised by Dr. Jing Wang from CAU and by Dr. Wopke van der Werf, Dr. Fang Gou, and Dr. Tjeerd-Jan Stomph from WUR. This master thesis has resulted in a paper that has been published in Field Crops Research, and has been presented at an international conference. After her MSc study she started her PhD research in the Soil Biology Group of WUR, under the supervision of Prof. Oene Oenema from WUR and Dr. Yong Hou from CAU. Her PhD thesis is about improving manure management in intensive livestock farms in China, to mitigate environmental pollution and improve soil fertility, with consideration of farmers' perceptions.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the 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)

Review of literature (4.5 ECTS)
- Project proposal: manure management for diminishing environmental pollution

Post-graduate courses (3 ECTS)
- Resilience of living systems, from fundamental concepts to interdisciplinary applications; WIAS / PE&RC (2018)
- Companion modelling; PE&RC (2020)

Deficiency, refresh, brush-up courses (6 ECTS)
- Rural households and livelihood strategies; Social Science Group (2018)

Laboratory training and working visits (0.6 ECTS)
- Farm survey of Chinese farmers; Chinese Academy of Science, Center for Agro-Resources Research (2018)

Invited review of (unpublished) journal manuscript (1 ECTS)
- Resources, Conservation & Recycling: nutrient imbalances from smallholder dairy farming systems in Indonesia: the relevance of manure management

Competence strengthening / skills courses (1.8 ECTS)
- Searching and organising literature for PhD; WGS (2019)
- Project and time management; WGS (2020)

Scientific integrity/ethics in science activities (0.8 ECTS)
- Ethics in Plant and Environmental Sciences; WGS (2018)
- Ethics for Social Science Research; SEC (2018)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)
- PE&RC First years weekend (2017)
- PE&RC Last years weekend (2021)

Discussion groups / local seminars or scientific meetings (6.2 ECTS)
- Discussion group (2018)
- SURE+ annual meeting (2020)
- Workshop on rural household survey (2018)
- SuReFood interdisciplinary workshop (2019, 2020)

International symposia, workshops and conferences (10.5 ECTS)
- International symposium Land-Water-Food Nexus: towards sustainable food production in China & other regions; Wageningen (2018)
- ISSPA conference; Wageningen (2019)

- SURE+ annual symposia; China (2019)
- ManuResource conference; Belgium (2019)
- iCropM conference; France (2020)
- International conference on sustainable resource management for adequate , safe and nutritious food provision; online (2021)

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