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REVIEW

Phosphorus status, use and recycling in a Chinese peri-urban region with intensive animal husbandry and cropping systems

Results from case study in a Sino-German applied research collaboration project

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Abstract The Sino-German research collaboration project, “Recycling of organic residues from agricultural and municipal origin in China” (2008–2012), comprising different interdisciplinary research groups, and also German small and medium-sized enterprises, aimed at developing integrated strategies and solutions for the recycling of organic residues in China. In an intensive crop-livestock agricultural region in the Shunyi District of Beijing, five typical cropping systems were investigated. The research was conducted in the form of analyses of phosphorus (P) in soil, plants, animal feed, animal products, manures, mineral and organic fertilizers and the derivation of the corresponding nutrient balances and P flows. The mean annual P balance surplus was 492 $kg \cdot ha^{-1} \cdot yr^{-1}$ P for the vegetable production system, significantly higher ($P < 0.05$) than that for orchards (130 $kg \cdot ha^{-1} \cdot yr^{-1}$ P) and cereal crops (83 $kg \cdot ha^{-1} \cdot yr^{-1}$ P). Plant-available P (Olsen-P) concentrations of topsoils (0–20 cm) had good correlations with the amounts of P applied (from mineral and organic sources). Compared to results from the Second Chinese National Soil Survey of 1981, mean concentrations of available P in soils of 19 plots investigated in Shunyi District increased 10-fold (from 7.3 to 60 $mg \cdot kg^{-1}$) from 1981 to 2009. On average, the critical limit for Olsen-P concentrations (> 30 $mg \cdot kg^{-1}$) that can lead to increased risk of P loss was exceeded in all five cropping systems. With feed additives, the “natural background value” (Chinese Environmental Quality Standard for Soils) of copper and zinc in topsoils was exceeded at several sites. Screening for several substances in the veterinary antibiotic classes of sulfonamides, tetracyclines, and fluoroquinolones revealed widespread topsoil contamination. Calculated livestock densities were 10.6 livestock units per ha arable land in 2007. Animal husbandry is increasingly conducted in large operations, making traditional ways of reuse difficult to apply. Comparing three management systems for treatment of organic residues from a pig farm via aerobic (composting) or anaerobic (biogas) treatment in a life cycle assessment, the resulting cropland demand for a

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sustainable land application of biogas effluent varied between 139 and 288 ha·yr^{-1}, well above the cropland area owned by the farm (10 ha). The mismatch problems in the above context between business-as-usual and improving performance are framed and discussed as (1) the mismatch between centralized animal husbandry and smallholder farming, (2) the mismatch between livestock density and cropland, (3) nutrient (including P) recycling and increasing organic matter content versus energy production, (4) subsidies for compost production and biogas, as well as (5) advances in the regulatory framework in China.

Keywords cropping systems, life cycle assessment, North China Plain, balances and nutrient flows, transdisciplinary approach

1 Introduction

The agricultural use of manure as fertilizer has been an important component of agriculture from its very beginnings. Agriculture in China has traditions of recycling organic materials dating back over several thousand years[1]. Since the early-mid 1980s, however, there has been a steep decline in recycling of crop residues, growing of green manures, compost preparation and use of complex rotation techniques. Large and unbalanced amounts of mineral fertilizers (mainly nitrogen (N)) are being applied, while straw is frequently burnt on the field after harvest[2]. In particular, since the introduction of industrial-scale animal production, traditional ways of reuse have become difficult to apply. Large amounts of manure are produced at one location, and the application over both space and time may become difficult. Thus, from the perspective of an animal production operation, manure is of low value. New technologies such as anaerobic digestion, improved composting, nutrient removal and other forms of processing may offer new options for the economic and ecological use of manure. Currently, China produces nearly half (48.9% in 2009) of the world's pigs[3]. In 2011, about 30% of animal husbandry in China was conducted in large-scale operations, raising a thousand or more pigs per year. There is an increasing tendency toward these large-scale consolidated operations, many of which are wholly industrialized and use a CAFO (confined animal feeding operation) model of production[4]. According to the first Chinese national pollution census in 2010, manure from industrial livestock facilities (mostly pigs and chicken) was the number one source of water pollution in the country[4]. The objectives of this report are to summarize the project results relating to different aspects of the phosphorus (P) cycle, to offer recommendations from the scientific and technological point of view, to discuss policy options in the field of animal husbandry and manure management in China, and to relate these to recent advances in the regulatory framework in China.

2 Materials and methods

The Sino-German research collaboration project, "Recycling of organic residues from agricultural and municipal origin in China", had a duration from September 2008 to March 2012. The project approach considered planning, technical improvement regarding animal production techniques, feed optimization, manure storage and treatment for minimizing emissions, as well as hygienization (sanitation), designation of organic fertilizers for specific usage, carrying capacity of cropland, economic factors, administrative issues and environmental regulations[5]. This interdisciplinary project was organized in nine subprojects which covered most components of the agricultural nutrient and pollutant cycles. This paper summarizes mainly the P-related aspects.

Data were gathered via farmer household surveys at village and district (corresponding to county in the Beijing, China) scale as well as from agricultural and statistical yearbooks on a provincial and district scale. A pig farm and village in Shunyi District of Beijing served as a pilot farm and village for the project. To investigate plant-available P concentrations in the topsoils for the five main cropping systems, 26 selected plots in the Shunyi and Huairou Districts of Beijing, classified as Eutric Cambisols with a predominantly silty loam soil texture, were monitored (Fig. 1) over a three-year period (2009–2011)[6]. These included plots from the "ecological feeding gardens" of a pilot pig farm (Section 3.6). Mineral and organic P fertilizer application rates were gathered via farmers interviews and plant-available P (Olsen-P) concentrations in he topsoil (0–20 cm) at the same sites were determined. The P status of the soils was investigated in detail by Xue et al.[7]. The soil surface P balances (total inputs minus removal of crop products by harvest) and P surplus for three of the main cropping systems in Shunyi District were calculated in three villages in the eastern part of the District, with cereals (summer maize-winter wheat), orchards, and open field vegetables as the predominant cropping systems[8]. A total of 68 smallholder households, with an arable land area ranging from 0.2 to 1.5 ha per farm, were monitored over a full year (2008–2009). Figures on animal manure generation in the different districts and the whole of Beijing, as well as the corresponding amounts of P were gathered[9].

In a parallel study of pollutants in the same field plots[10], the veterinary antibiotics classes sulfonamides, tetracyclines and fluoroquinolones were investigated. While tetracycline and fluoroquinolone antibiotics were only detected in topsoils of the study area, sulfonamides exhibited a relatively high mobility in the soil profile. On 25% of the investigated field sites sulfamethazine was detected down to the maximum sampling depth of 200 cm[10].

A pig farm in Shunyi District served as a pilot pig

Fig. 1 The five main cropping systems in Shunyi District of Beijing (© Lisa Heimann, 2009–2011). (a, b) Winter wheat-summer maize double-crop rotation; (c, d) Chinese cabbage-glutinous maize double-crop rotation; (e) orchards; (f) field vegetables; (g) poplar plantations.

farm for the collaborative research project. Pig manure handling, storage, treatment and use were examined in detail. Crude protein and P contents in feed and manure, and the main nutrients in feed and wastewater, as well as in manure were analyzed[11–13]. P and N flows and balances for the pilot farm (different sectors) and its surrounding cropland were derived and calculated by several scientists[14], using different approaches. Only the P flows and balances are mentioned here.

In a life cycle inventory, the fluxes of feed, water, wastewater, waste air, nutrients and energy in pig production (centralized pig houses only) on the pilot pig farm were collected for a life cycle assessment (LCA) performed at the Thünen Institute, German Federal Research Institute for Rural Areas, Forestry and Fisheries, Braunschweig and China Agricultural University[14,15]. Annual input and output of the pig farm was calculated on the basis of livestock units (LU, 1 LU is about 500 kg live weight). Fattening pigs (25–110 kg), breeding pigs (0–30 kg) and sows (150 kg) corresponded to 0.13, 0.04 and 0.30 LU, respectively (German Agricultural Society DLG standards). The system boundary for the LCA was cradle-to-gate, and the annual production of the pig farm was the functional unit. Only the P flows are described here.

3 Results

3.1 Shunyi District, Beijing, China

Shunyi District of Beijing, China (40°00′–40°18′ N, 116° 28′–116°58′ E) has a total area of 102100 ha[16]. The population of the district in 2017 was 1592000 (vs. 732000 in 2009), comprising 1128000 permanent and 464000 temporary residents, giving a population density (permanent and temporary residents) of 1106 persons per km^2 (compared to 718 in 2009) (ibid.). The urbanization rate in 2017 reached 55.3% (2009: 47.2%)[17]. The overall district achieved a GDP of 1715 billion CNY in 2017, with a growth of 9% over the previous year[17]. The average GDP per capita exceeded 152000 CNY (approximately 21525 USD) in the Shunyi District in 2017 (ibid.) (compared to 8030 USD in 2009).

The cultivated land area in Shunyi District amounted to 32003 ha in 2014 showing no decline compared to 31031 ha in 2009. Prior to 2009, it had been declining at a rate of 1926 $ha \cdot yr^{-1}$[17]. The agricultural land use types include mainly cereals, orchards and vegetables, occupying about 62%, 15% and 13% of the total cultivated land area, respectively. Summer maize and winter wheat are cultivated as the main cereal crops and mostly in the traditional double-crop rotation[16]. Orchards mainly include pears, peaches and apples, while a variety of vegetables under annual double or triple cropping are grown in Shunyi District. Smallholder farming is still the predominant agricultural production pattern, despite the rapidly increasing intensification of agriculture, due to the district location within Beijing (ibid.).

The total value of agricultural output in 2017 reached 4.83 billion CNY[17]. Shunyi District was designated as a meat production base by the Beijing Municipal Government in the late 1980s. In 2004, there were 188 pig farms in Shunyi District, representing 34% of the total pig production in Beijing[18], and 42 large pig raising plants each had a production capacity above 20000 pigs per year in Shunyi in 2004. Shunyi District represented 43% of total pig production in Beijing in 2011 and is the predominant district in animal husbandry[11]. The annual output of meat of the District in 2017 dropped to 70 kt (compared to 109 kt in 2007), with 760000 pigs, 85000 sheep and 18774 head of cattle sold annually[17]. The corresponding figures for 2007 were 839000 pigs, 222000 sheep and 25000 head of cattle (ibid.). The gross output value of animal husbandry in 2007 reached 2.31 billion CNY[14]. This very intensive animal production in combination with decreasing cultivated land area leads to very high livestock densities, amounting to 10.6 $LU \cdot ha^{-1}$ arable land in 2007 (calculated from Beijing Statistical Yearbook[17]). Farmland in these peri-urban areas of Beijing is therefore oversupplied with nutrients.

3.2 Plant-available P in the topsoil in cropping systems of Shunyi District

Generally, a good relation could be seen between the amounts of P applied (from mineral and organic sources) and the plant-available P concentrations in soil (Table 1). In particular the plots with Chinese cabbage, open field vegetables and orchards receiving high amounts of farmyard manure (FYM) showed very high ($>$50 $mg \cdot kg^{-1}$) Olsen-P concentrations. Most soils under winter wheat-summer maize and poplar plantations had medium (10–30 $mg \cdot kg^{-1}$ Olsen-P) concentrations. Differences in fertilization practice between cropping systems were similar to those observed in the three villages investigated in the eastern part of Shunyi District (Table 2).

A critical level of 10–20 $mg \cdot kg^{-1}$ Olsen-P has been established for optimum crop growth and yields for most cereal crops in China, and of 20–60 $mg \cdot kg^{-1}$ P for vegetables in North China[19]. Soils with Olsen-P concentrations $>$30 $mg \cdot kg^{-1}$[20] or 60 $mg \cdot kg^{-1}$[21] can lead to increased risk of P loss[22]. Table 1 shows that on average, the critical limit of 30 $mg \cdot kg^{-1}$ Olsen-P was exceeded in all cropping systems. The higher threshold value of 60 $mg \cdot kg^{-1}$ Olsen-P was exceeded on plots of the three cropping systems receiving FYM, while only the winter wheat-summer maize double-crop rotation with

Table 1 Annual mineral and organic P fertilizer application rates (mean±SD) (in pure nutrients) for the five main cropping systems (2008–2009 season) and plant-available P (Olsen-P) concentrations (mean±SD) in topsoils (0–20 cm) sampled in Shunyi and Huairou Districts of Beijing in March 2009[6,14]

P	Winter wheat-summer maize (n = 9)	Chinese cabbage-spring maize (n = 6)	Field vegetables (n = 4)	Orchards (n = 4)	Poplars (n = 3)
P inputs/($kg \cdot ha^{-1} \cdot yr^{-1}$)					
Mineral	64±73	0±0	4±8	0±0	0±0
Organic*	18±32	525±822	510±445	389±411	96±167
Total	82±64	525±822	514±444	389±411	96±167
Olsen-P/($mg \cdot kg^{-1}$)	42±32	106±51	130±68	67±43	30±0

Note: *Three of the vegetable plots received FYM and one plot received biogas effluent.

Table 2 Soil surface P balance calculation for three main cropping systems based on a survey in Shunyi District (2008–2009)

P balance items	Cropping systems		
	Cereals (n = 21)	Orchards (n = 23)	Vegetables (n = 21)
Inputs			
Mineral fertilizer	111.3 (28.5–271.1)	89.8 (0–350.4)	59.6 (0–98.2)
Farmyard manure	3.9 (0–35.6)	59.1 (0–304.5)	617.7 (177.1–1298.6)
Incorporated residues	13.1	2.6	0
Atmospheric P deposition	0.25	0.25	0.25
Total	128.6 (44.0–286.9)	151.8 (2.8–479.8)	677.6 (226.4–1362.7)
Outputs			
Crop product	45.9 (29.1–59.4)	22.3 (7.4–39.6)	185.7 (66.0–351.9)
P balance			
Inputs minus outputs	82.7 (–1.4–294.0)	129.5 (–10.7–464.8)	491.8 (111.3–1198.8)
Scaled to Shunyi District			
Sown area in 2009 (/ha)	21262	1221	4847
Total P surplus /($t \cdot yr^{-1}$)	1758	158	2383

Note: Inputs, outputs and balance are mean values with range (in brackets) as $kg \cdot ha^{-1} \cdot yr^{-1}$ P from Hou et al.[8]. Scaled figures for Shunyi District from Yong Hou (Hebei Agricultural University, 2009, personal communication) with sown area from Beijing Statistical Yearbook[17].

predominantly mineral P, and poplar plantations with less or no P fertilization, were below[6]. According to Xue et al.[22], P loss through surface runoff is of greater concern in these light soils receiving manure, while the potential for P leaching will increase after higher manure application over a longer duration, as in vegetable plots.

By comparison, results from the Second Chinese National Soil Survey of 1981 when cereal cropping was predominant showed Olsen-P concentrations of only 7.3 ± 2.8 $mg \cdot kg^{-1}$ on corresponding cereal plots in the same locations[6]. From 1981 to 2009 mean concentrations of available P in soils of the 19 plots investigated in Shunyi District increased almost 10-fold (ibid.). It is very likely that this increase was mainly due to high FYM inputs[6]. Compared to applying P only as mineral fertilizer, the application of FYM accelerated the increase in soil Olsen-P almost three times[19].

3.3 Soil P balances and P surplus in Shunyi District

Table 2 shows the P balance calculation for the three cropping systems. The mean annual P balance surplus was 492 $kg \cdot ha^{-1} \cdot yr^{-1}$ P for the vegetable production system, significantly higher ($P < 0.05$) than for orchards (129.5 $kg \cdot ha^{-1} \cdot yr^{-1}$ P) and cereal crops (82.7 $kg \cdot ha^{-1} \cdot yr^{-1}$ P). These high P balance surpluses cause the soils to be heavily oversupplied with nutrients.

Although the ranges are quite wide, the following differences can be seen. Fertilization of all three cropping systems, and to vegetables in particular, was far in excess of crop demand. There was an oversupply of mineral fertilizers for all main crops. P input to vegetables was mainly derived from organic fertilizers, orchards received less, and cereals almost no organic P (Table 2). The winter wheat-summer maize double-crop rotation is fertilized almost exclusively with mineral fertilizers since it generates the least income for small-scale farmers in this peri-urban area with high off-farm labor and income opportunities. In contrast, FYM requires higher labor for transport and handling, and is therefore only applied to the open-field vegetables and orchards from which higher economic benefit is achieved. However, the nutrient value of FYM is not properly taken into account since farmers also apply additional mineral P fertilizer. From the perspective of farmers there is a lack of knowledge on the nutrient concentrations of FYM. Based on these values, scaling to the level of the Shunyi District (Table 2), the annual P surplus on cropland reached several thousand tons (Yong Hou, Hebei Agricultural University, 2009, personal communication).

3.4 Animal manure and P in Beijing

The most recent available figures on animal manure generation in the different districts and the whole of Beijing, as well as the corresponding amounts of P, are listed in Table 3 for 2011[9]. The corresponding amount of animal manure in the Beijing in 2008 was 7.62 Mt (fresh matter) (Guoxue Li, China Agricultural University, 2012, personal communication), indicating a further rise from 2008 to 2011.

3.5 Soil pollutants

The feed additives Cu, Zn, Cr and As were found in topsoil (0–20 cm) with concentrations ranging from 12 to

Table 3 Animal manure generation and manure P generation distributed in the different districts of Beijing in 2011 (adapted from Jia et al.[9], with permission from Elsevier)

District	Manure (fresh weight)/kt					P (dry weight)/t				
	Cattle	Pig	Sheep and goat	Poultry	Total	Cattle	Pig	Sheep and goat	Poultry	Total
Shunyi	574	983	141	194	1892	808	2567	215	743	4333
Daxing	601	569	182	362	1714	827	1485	277	1302	3891
Fangshan	236	396	79	288	999	327	1034	120	1071	2552
Pinggu	93	361	96	171	721	135	943	146	783	2007
Miyun	405	218	68	271	962	556	569	104	1130	2359
Tongzhou	424	304	89	188	1005	586	793	136	664	2179
Yanqing	406	104	17	202	729	558	272	26	911	1767
Huairou	203	98	16	111	428	278	255	24	418	975
Changping	193	103	19	55	370	264	269	30	263	826
Mentougou	6	7	7	22	42	9	18	11	85	123
Haidian	46	27	1	5	79	63	69	2	21	155
Chaoyang	53	0	0	0	53	72	0	0	0	72
Fengtai	17	11	1	6	35	24	29	2	29	84
Shijingshan	0	0	0	0	0	0	0	0	0	0
Total	3257	3181	716	1875	9029	4507	8303	1093	7420	21323

65 $mg \cdot kg^{-1}$, 56 to 130 $mg \cdot kg^{-1}$, 22 to 36 $mg \cdot kg^{-1}$, and 4 to 10 $mg \cdot kg^{-1}$, respectively[10]. For Cu and Zn, the "natural background value" for Cu (35 $mg \cdot kg^{-1}$) and Zn (100 $mg \cdot kg^{-1}$), based on the Chinese Environmental Quality Standard for soils (GB15618-1995; described by Huang and Jin[23]) was exceeded at several sites. The agricultural fields exhibiting the highest Cu and Zn concentrations were all directly or indirectly (by irrigating with river water contaminated with animal husbandry wastes) fertilized with pig manure, compost or biogas effluent[10]; this gave further evidence that pig husbandry strongly contributed to increased heavy metal contamination of soil. Measurements in a lysimeter experiment confirmed that the use of Cu as a growth promoter and subsequent high loads of manure application on soil, both being typical for the intensive agriculture in peri-urban Beijing, can lead to a distinct accumulation of Cu in the soil[24].

3.6 Pilot pig farm and pilot village

The pilot animal production plant was located in Zhaoquanying Town, Shunyi District (about 40°07′ N, 116°38′ E). The whole pilot village consisted of 450 households with a population of 1500. The total land area was 440 ha, of which 73% or 320 ha was arable land. On 200 ha formerly dedicated to cereals, new and different crops such as flowers, alfalfa, tree nurseries, orchards and vegetables were grown. Figure 2 shows an aerial view of the farm.

Pig production was conducted on a dual scale:

(1) Large-scale: the centralized pig raising farm was set up in 1995 and had an annual stock of 12000 breeding boars and 20000 fattening pigs (porkers). The facility had an area of 10 ha and consisted of 56 houses with an average capacity of 200–300 pigs[12,13]. Breeding boars were sold with a weight of 50 kg at about 5 months, while fattening pigs were slaughtered at about 100 kg. Also, 1800 basal sows were raised for piglets.

(2) Household-scale: pork production was also conducted on a household scale, known as "ecological feeding gardens", consisting of 160 small pig holders covering an area of 25.33 ha[25]. Every household raised between 30 and 50 pigs (maximum 300) and sold an average of 140 pigs per year with a weight of either 20–30 kg (piglets) or 80–100 kg (fattening pigs)[25]. Each household had 0.2–0.33 ha of land, where Chinese cabbage and glutinous maize were grown in a double-crop rotation.

Pigs were kept and fed in four growth stages: gestating sows (pregnant sow), farrowing sows (sows between giving birth and weaning the piglets), weaner pigs (between 3 and 6 and 10 weeks old, 25–30 kg live weight), and fattening pigs (for pork production, above 10 weeks old, slaughtered at 90–110 kg live weight)[11]. Imported pig breeds were used; the main ones were Large White, Landrace, Duroc, Pietrain. There was no differentiation between breeding and fattening pigs during the growing phases[23].

Fig. 2 Aerial view of the pilot pig farm with centralized pig houses (top right), biogas plant (center right) and composting facility (bottom left) (the "ecological feeding gardens" are not shown) (GeoEye1 © 2019 DigitalGlobe Inc., a Maxar Company, reproduced with permission from the Maxar Company)..

3.7 Pig manure handling, storage, treatment and use

In contrast to most European stable systems, the pigs were mainly housed on solid floors, not on slatted floors. The so-called "*gan qing fen*" technique ("cleaning manure dryly"[26]) is used as manure system. Solid manures are collected manually twice per day using shovels or scrapers and the floor is flushed with 6–9 L water per pig per day (up to 25 L in small units) (Fig. 3)[26,27]. Due to water shortage in North China, the *gan qing fen* system is obligatory for the pig fattening farms in the Beijing. Two main fractions are generated through this manure collection system: (1) solids (manure), consisting of feces and some urine, with high N, P and potassium (K) contents, and (2) liquids (piggery wastewater), consisting of urine, water and some particles of feces.

The dry matter content of the feces from the *gan qing fen* system is in the range of 271–280 $g \cdot kg^{-1}$. Generally, most of the P, calcium and magnesium are in the feces, while most of the N and K is in the urine[27]. The main matter (nutrient and pollutant) flows on the pilot pig farm are shown in Fig. 4.

The solid fraction was first stored on a platform near the stables and used in one of three ways. (1) About 75% was used in the biogas plant of the pilot pig farm, this proportion being higher during winter and lower during summer. A certain amount of poultry manure from a nearby farm was used as supplement to the biogas plant to increase the biogas yield during winter[15]. (2) A lesser proportion (> 20%) was used by the composting facility

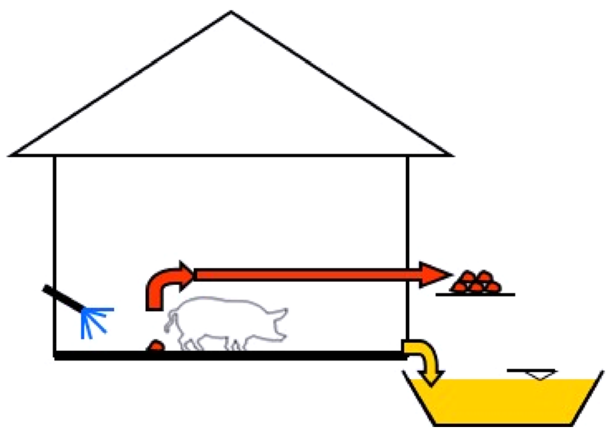

Fig. 3 "*gan qing fen*" stable system for pig production in China as used on the pilot pig farm[27] (with permission from Journal of Agricultural Science and Technology A & B).

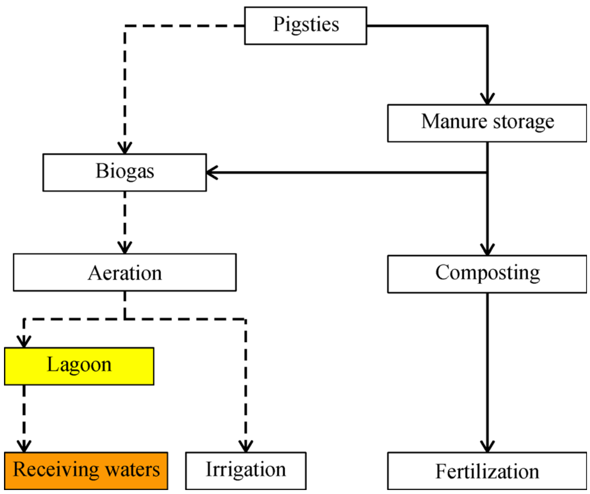

Fig. 4 Flow diagram for manure use on the pilot pig farm (dashed lines for liquids and solid lines for solids).

for organic compost production. (3) A small proportion (< 5%) was used directly as organic fertilizer for crops and vegetables on small farm plots nearby.

The liquids have been treated since 2001 following environmental regulations by Beijing. The pilot pig farm was equipped with a medium-scale mesophilic biogas plant with a volume of 1000 m^3 (working volume of 800 m^3) in four digesters operating at low organic loading rates (< 1.5 $kg \cdot m^{-3} \cdot d^{-1}$ organic dry matter (oDM)) and low temperatures (28°C)[28], followed by an "aeration pond", but no further wastewater treatment step. At these low organic loading rates and temperatures the biogas plant on the pilot pig farm was able to degrade organic matter efficiently, as was described by Guo et al.[28]. However, this low organic loading rate is not common for highly productive and economically operated biogas plants. Usually organic loading rates are > 3 $kg \cdot m^{-3} \cdot d^{-1}$ oDM[14]. The biogas plant effluent is in part retreated anaerobically a second time, with the aim of further reducing the chemical oxygen demand. However, anaerobic treatment does not reduce N and P contents.

The biogas produced from all four digesters (about 200 m^3 biogas per day) was collected and fed into a micro gas grid for cooking and heating for the farmers in the "ecological feeding gardens". The feeding operation of the plant was driven by the gas demand for heating. Therefore, in the summer the input from the solid fraction into the biogas plant was reduced, as the biogas demand was lower than in winter, and the surplus pig manure was composted[28]. No combined heat and power generation was undertaken.

The liquid effluent of the biogas plant was then stored in the open aeration pond before partly being used for irrigation of nearby cropland and orchards. A large part, however, flowed into a nearby lagoon (with no impermeable liner). Excess wastewater was frequently discharged via an open sluice into a mostly dry riverbed, causing great pollution risk to the environment[11]. Based on anecdotal reports, 90% of Beijing livestock farms used to discharge their biogas effluent directly to the environment because of the expensive treatment costs (ibid.).

The solid components removed by the *gan qing fen* manure collection system were used for composting in an indoor composting facility, with addition of sawdust and zeolit (as absorbing mineral). However, the composting facility was working suboptimally during the project period (2008–2012), seldom attaining the temperature required for sanitation (55°C), and the resulting product smelled strongly of ammonia[14].

3.8 P contents in feed and manure

The pig feed used at the pilot pig farm consisted of a mixture of commercial feedstuffs and the formulation varied according to the pig growing stage[12]. Pig diets consisted of corn (maize), wheat, soybean meal, fish powder (65% protein, imported from Peru) compound premix and lysine (ibid.). Crude protein and P contents in feed samples from the pilot pig farm for sows and pigs taken at the different growth stages are shown in Table 4.

The main nutrient concentrations (dry matter basis) in the solids (pig feces) for the four pig production stages are shown in Table 5. The P concentrations (fresh matter basis) in the solids and liquids for the four production stages are shown in Table 6.

3.9 P flows and balances in a pilot pig farm

The P flows and balances were analyzed both for the centralized pig houses and for the "ecological feeding gardens" of the pilot pig farm in Shunyi District by Hou[25]. Feed purchased from outside of the pilot village was the main source of P inputs of the pilot farm. In the centralized pig houses with only 9.5 ha of cropland, the total P input via feed was 26.551 t in 2009, amounting to 2795 $kg \cdot ha^{-1} \cdot yr^{-1}$ P (98.6% of total input)[25]. Irrigation with biogas plant effluent was restricted and no manure was applied. Therefore, 99.4% of the total P inputs on this small area of cropland were derived from synthetic P fertilizer in 2009 (Fig. 5).

In the "ecological feeding gardens" with a total of 25.3 ha of cropland in 2009, the total input via feed was 54.967 t in 2009, amounting to 2173 $kg \cdot ha^{-1} \cdot yr^{-1}$ (99.7% of total input). Of this total, 920 $kg \cdot ha^{-1} \cdot yr^{-1}$ P from manure (55.6% of the excreted P) was applied (mainly to the Chinese cabbage crop in autumn), resulting in recycled P from organic sources covering 99.4% of total P input in this system. This led to an extremely high calculated P surplus of 837 $kg \cdot ha^{-1}$ P for these small farmers' household plots[25], largely caused by an imbalance between animal stocking density and available cropland (Fig. 6).

Table 4 Crude protein contents (%) and P contents (%) per kg feed (90% dry matter) of feed sampled on the pilot pig farm for sows and pigs at different growth stages (mean±SD; n = 76) (adapted from Mendoza Huaitalla et al.[11])

Content in feed samples	Pregnant sow (gestation)	Lactating sow (farrowing)	Suckling piglet (farrowing)	Weaning piglet	Fattening pig
Crude protein/%	15.64±0.87	18.51±1.39	20.70	19.61±0.94	17.35±2.38
Total P/%	0.73±0.03	0.68±0.04	0.60	0.65±0.07	0.52±0.08

Table 5 Main nutrient concentrations in different pig manures (dry matter basis, about 28% dry matter; pig feces collected from the concrete floor of pig barns) sampled on the pilot pig farm (mean±SD; n = 140) (data from Mendoza Huaitalla et al.[12])

Nutrient ($g \cdot kg^{-1}$ dry matter)	Gestation	Farrowing	Weaning	Fattening	Mean
Total N	27.08±2.61	29.87±8.47	41.33±10.89	41.48±3.60	35.06
NH_4^+-N	5.38±1.84	4.68±2.44	7.95±1.97	7.88±2.57	16.71
Total P	29.60±4.78	30.53±7.92	19.51±1.89	15.32±1.59	23.74
Total K	11.05±1.19	11.40±2.76	17.33±4.14	12.45±1.50	13.06

Table 6 P concentrations (fresh matter basis or as sampled) in different pig manures (pig feces collected from the concrete floor of pig barns) (mean±SD; n = 20), and piggery wastewater (collected from the gutter channels and external collective ditch) sampled on the pilot pig farm (n = 76) (data from Mendoza Huaitalla et al.[12])

Total P (fresh matter)	Gestation	Farrowing (sow)	Weaning	Fattening	Mean
Solid (pig manure)/($g \cdot kg^{-1}$)	8.59±1.10	9.27±2.74	5.36±0.73	3.89±0.30	
Liquid (wastewater)/($g \cdot L^{-1}$)	0.15	0.02	0.07	0.11	0.13 (n = 76)

3.10 Life cycle assessment

In the LCA[14,15], the existing (i.e., in 2011) manure management system with 75% (1680 t) of the solid fraction (pig feces) used in the biogas plant and 25% (560 t) in the composting facility, both without and with land application of biogas effluent (Option 1), was compared to two alternative management systems, Options 2 and 3. In Option 2, all of the feces (2240 t) are used in an improved composting facility (with additions of corn stalks and triple superphosphate). In Option 3, 100% of the feces are fed to the biogas plant. In 2011, the farm had a stock of 1037 LU and produced 1956 LU annually. The annual (2011) P input and output of the centralized pig houses, the biogas plant and the composting facility for Options 1–3 are given in Table 7. If all feces were used for composting (Option 2), it would be possible to export 87% of P, 29% of N, 34% of K and 75% of Mg via the compost[15].

The existing (i.e., in 2011) waste management system (without proper land application of biogas effluent) had the highest pollution of the environment, with an eutrophication potential (EP) of 91.7 t PO_4 equivalent. The existing system, but with land application (Option 1) would have an EP of 56.0 t PO_4 equivalent, while Options 2 and 3 would have an EP of 34.1 and 68.0 t PO_4 equivalent, respectively)[14,15].

A typical winter wheat-summer maize double-crop

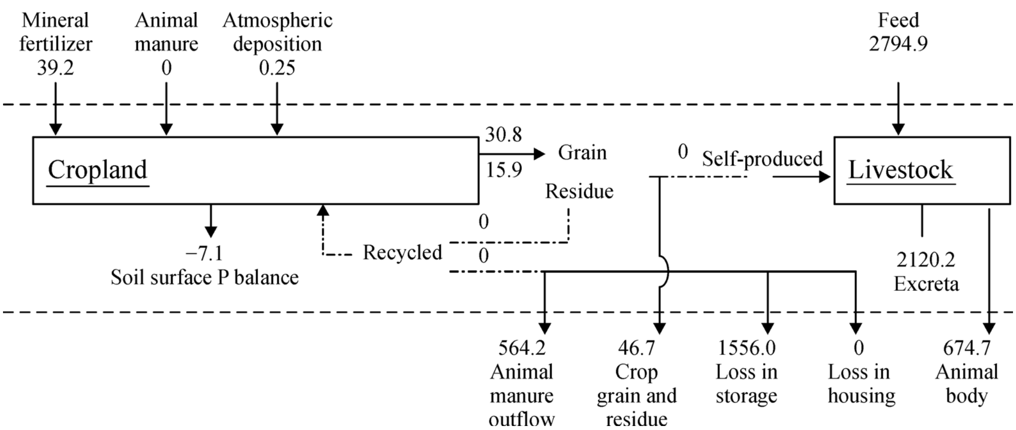

Fig. 5 P flow in the centralized pig houses of the pilot pig farm in 2009 ($kg \cdot ha^{-1} \cdot yr^{-1}$ P) (translated from Hou[25]).

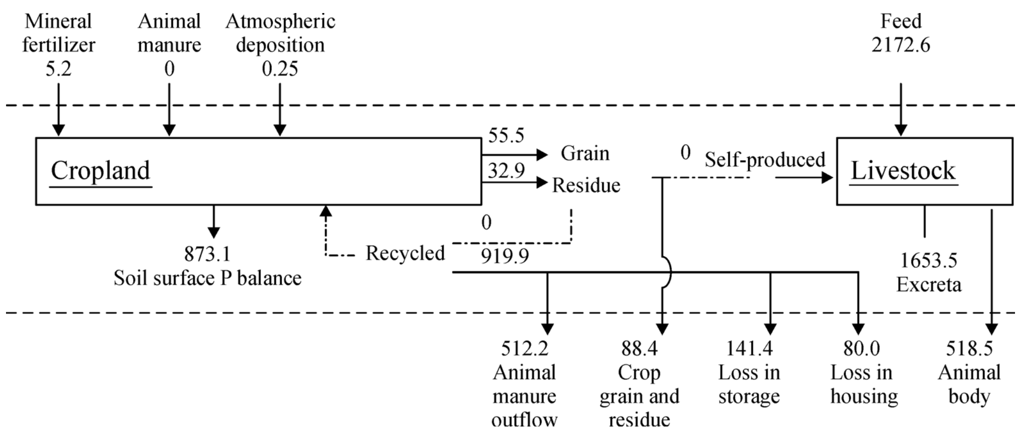

Fig. 6 P flow in the "ecological feeding gardens" of the pilot pig farm in 2009 ($kg \cdot ha^{-1} \cdot yr^{-1}$ P) (translated from Hou[25]).

rotation in Shunyi District has an approximate nutrient demand per ha and year of 338 kg N, 56 kg P, 263 kg K and 50 kg Mg[6,15] in a balanced system (optimum plant-available nutrient concentrations in soil). The resulting cropland demand for a sustainable land application of biogas effluent for the existing system (Option 1) would then be 238 $ha \cdot yr^{-1}$ (limited by P demand of crops). For Option 2, it would be 139 $ha \cdot yr^{-1}$ (limited by N demand) and for Option 3, the land area demand would be 288 $ha \cdot yr^{-1}$ (limited by P demand)[14,15]. However, as long as the cropland is oversupplied with nutrients (Section 3.3), the land area necessary for a sustainable utilization of the wastewater nutrients would be 476, 168 and 576 $ha \cdot yr^{-1}$ for Options 1–3, respectively. These nutrient recommendations are based on one half of the annual crop requirement during 1–5 years (Frank Schuchardt, Thünen Institute, and Lisa Heimann, Technische Universität Braunschweig, 2012, personal communication). The centralized pig houses only own about 10 ha.

Finally, the use of biogas for combined heat and power generation resulted in a smaller global warming potential

Table 7 Annual P input and output (in LU and t P) of the centralized pig houses, biogas plant and composting facility of the pilot pig farm (life cycle inventory, 2011) under the existing manure management system, as well as for two alternative options (data from Heck[14])

Pig houses		Biogas plant		Composting facility	
Input	Output	Input	Output	Input	Output
Option 1 (existing manure management system)					
Feed: 23.64 t	Pigs to market: 1956 LU	Pig feces: 9.89 t	Liquid effluent: 13.32 t	Pig feces: 3.30 t	Compost: 3.99 t
	Dead pigs: 49 LU	Poultry manure: 1.16 t	Biogas sludge: 0.68 t	Biogas sludge: 0.68 t	
	Pig feces: 13.19 t	Wastewater: 2.95 t		Sawdust: 0.02 t	
	Wastewater: 2.95 t				
Sum: 23.64 t		14.0 t	14.0 t	4.00 t	3.99 t
Option 2					
Feed: 23.64 t	Pigs to market: 1956 LU	Pig feces: 0 t	Liquid effluent: 2.95 t	Pig feces: 13.19 t	Compost: 19.57 t
	Dead pigs: 49 LU	Poultry manure: 0 t	Biogas sludge: 0 t	Corn stalks: 0.61 t	
	Pig feces: 13.19 t	Wastewater: 2.95 t		T-Superphosphate: 5.76 t	
	Wastewater: 2.95 t				
Sum: 23.64 t		2.95 t	2.95 t	19.56 t	19.57 t
Option 3					
Feed: 23.64 t	Pigs to market: 1956 LU	Pig feces: 13.19 t	Liquid effluent: 16.14 t	Pig feces: 0 t	Compost: 0 t
	Dead pigs: 49 LU	Poultry manure: 0 t	Biogas sludge: 0 t	Biogas sludge: 0 t	
	Pig feces: 13.19 t	Wastewater: 2.95 t		Sawdust: 0 t	
	Wastewater: 2.95 t				
Sum: 23.64 t		16.14 t	16.14 t	0.0 t	0.0 t

and abiotic resource depletion potential (ADP-fossil) in the LCA and is therefore recommended over the existing external use for heating and cooking in the “ecological feeding gardens”.

4 Discussion

4.1 Mismatch between centralized animal husbandry and smallholder farming

One recurring phenomenon is the interrupted nutrient cycles due to the different scale of the centralized industrial-scale animal production operations and the surrounding smallholder farmers. There are historical reasons for this. When the “Household Responsibility System” was introduced in the early 1980s, the cropland was reallocated to farmer households. Several of the former People’s Communes, however, opted for remaining collective and chose to specialize on certain economic activities, such as pig breeding (Keyi Mei, Beijing Municipal Government, 2009, personal communication). As an example, the pilot pig farm in Shunyi District was built by the village committee of the pilot village in 1994 and gradually became a major pig producer mainly supplying the Beijing markets[14]. This has led to a mismatch in scale, with landless intensive animal production plants on one side, and a large number of small-scale crop farmers on the other, frequently having only a fraction of a hectare. This causes infrastructural and logistical problems for manure storage, purchase, transport and distribution between the producers and the potential cropland users. Economic and social obstacles also worked against smallholders being interested in receiving manure from large pig farms. In the late 1990s, land-use rights were extended to 30 years[14]. Due to the proximity of Beijing, activities that primarily use commercial organic and inorganic fertilizers such as greenhouse vegetable farming, quality fruit production, flowers, tree nurseries and recreation that have little need for unprocessed manures from large animal farms have increasingly been encouraged by the Beijing Municipal Government since the 2000s (ibid.).

4.2 Mismatch between livestock density and cropland

As the above results show, FYM from a livestock density of 11 $LU \cdot ha^{-1}$ is too high by far to apply all animal excreta on arable land in the Shunyi District of Beijing. Thus, the farmland in the peri-urban region of Beijing is heavily oversupplied with nutrients. In contrast, arable soils in the North China Plain (NCP) are low in soil organic matter (SOM) and total N (N_{tot}) and show (mainly on cereal plots receiving no organic fertilizers) low (<10 $mg \cdot kg^{-1}$) to medium (10–30 $mg \cdot kg^{-1}$) Olsen-P concentrations. The tradition of applying “soil manure” (soil used as bedding material for animals which is thereby enriched with nutrients over several months, and is later applied as basal fertilizer to winter crops in autumn) to cereal land has been largely abandoned by farmers in recent years and straw is frequently burnt in the field. Due to the very high mineralization and nitrification capacity of the soils in North China[29,30], a regular input of organic fertilizers is essential. Also, due to the high livestock densities and the structural problems described in Section 4.1, surplus nutrients from organic sources have to be exported out of the peri-urban region of Beijing. If composted FYM were sold to the more outlying areas of surrounding Hebei Province, this could solve problems in North China by (1) reducing the nutrient load in the peri-urban areas, (2) lead to a better and faster increase in SOM in the poorer agricultural areas of the NCP and (3) save mineral P fertilizer by providing P from organic sources.

4.3 P recycling and organic matter buildup vs. energy production

The biogas plant on the pilot pig farm was built primarily for pollution reduction, not energy generation. The economic value of recycling manure nutrients was only a minor consideration. In China, the question whether to promote the *gan qing fen* manure collection system or to expand energy production from biogas can only be decided on a case by case basis[5]. The *gan qing fen* system is necessary if nutrients (including P) are to be exported from a region (most nutrients other than K are in the solids), i.e., to make compost from the solids of animal excreta. If energy production is the main aim, then high carbon (chemical oxygen demand) content in the liquids is preferred, which in turn results in more nutrients in the liquids (slurry)[5]. Different options exist, according to the size of the animal operations:

Small-scale farming: solids may be sold to the neighboring farmers.

Medium-sized livestock farm: some solids may be sold, and some used for crops. In those Chinese cities where subsidies for FYM are in place, selling is preferred.

Large-scale animal operations: use of industrial-scale biogas plants, similar to those in Germany, is preferred. These operations follow strict enterprise policies and prefer the digestion of manure in biogas plants. Another possibility is to combine the two, adding some solids to the biogas plant, thereby achieving higher biogas plant efficiency, and at the same time an increase in nutrients in the biogas effluent. This may, however, only be used in a nearby area due to much higher transport costs of liquids. Nutrients from the biogas plant can also be used after treatment of the digestate by composting or drying with excess heat. The drying and pelletizing of the digestate may be another option to transport nutrients over longer distances, though questions of energy use and related emissions need to be considered[5]).

Taking the biogas plant of the pilot pig farm as an example, there was no wastewater treatment step at the time of the project. Therefore, it would not be advisable to anaerobically digest all the manure, due to the limited farmland at the pilot farm. In situations such as these, the *gan qing fen* method as it is currently conducted is particularly suitable[5]. A wastewater treatment plant was under construction on the pilot pig farm in 2017.

Finally, incineration of surplus manure cannot be viewed as beneficial due to carbon loss and CO_2 emissions. Besides the nutritional aspects, the replenishment of SOM in the outlying areas via compost in order to build up soil fertility is very important.

4.4 Subsidies for compost production and biogas plants

If nutrients are to be exported from a region, this must be done in the form of transportable and marketable fertilizers. Therefore, for example, it is necessary to compost the solids of animal excreta. Compost creates a buildup of stable SOM in form of humic substances and this occurs more rapidly compared to straw alone, in particular in a region with subhumid climate as in the NCP. Nevertheless, composting is a controversial issue in China, especially in view of the government subsidies for compost production which are now in place in several Chinese provinces[5]. In the Beijing, the subsidized compost was priced at 600 $CNY \cdot t^{-1}$ in 2011–2013[15] (market price for compost without subsidy was 350 $CNY \cdot t^{-1}$). Since subsidies were put in place, the composting facility of the pilot pig farm has been expanded and its economic importance has increased. This organic fertilizer is now being sold to specialized farming operations in Beijing and beyond. An important counter argument put by many experts against subsidies is the increasing costs of the manure treatment[5].

Besides composting, a range of other innovative technologies for manure processing are being investigated worldwide, including pyrolysis of manure and biochars. For nutrient separation and removal, successful experiments with P-removal through struvite ($MgNH_4PO_4$) precipitation, and ammonium-N removal via ammonia stripping from the biogas effluent have been reported[14]. The struvite technology is becoming operational in China.

However, the Chinese government should support the economic manure treatment sites if it has the political will to improve the existing situation. As an example, in order to be able to apply the results from the LCA (Section 3.10), government subsidies for compost production must continue. However, it is assumed that the market price for quality fertilizer products is likely to increase. Hence, good composting procedures or high-end biogas plants may become economically viable without subsidies in the future[5].

The revised Chinese Organic Fertilizer Standard NY525-2011[31] stipulates a moisture content of $\leqslant 30\%$, an oDM content of $\geqslant 45\%$ and a total nutrient concentration ($N + P_2O_5 + K_2O$) of $\geqslant 5\%$ (dry matter basis). Since December 2011, it has been applied by the Chinese Ministry of Agriculture to all companies (Guoxue Li, China Agricultural University, 2012, personal communication). Compared to the previous standard NY525-2002 stipulating a "free water" content of $\leqslant 20\%$, this new standard not only gives energy savings by avoiding an extra drying step, but also reduces composting costs[5].

4.5 Advances in the regulatory framework in China

Since early 2015, a policy to achieve zero growth in chemical fertilizer and pesticide use by the year 2020 has been implemented nationwide in China (e.g., Jin & Zhou[32]). This has since led to strong efforts by provincial governments to reduce mineral fertilizer use. As a result, per ha application rates of mineral N and P fertilizers have been declining in many provinces since 2016. Calculations based on data from the National Bureau of Statistics of China[33] on fertilizer consumption (total nutrients basis, $N + P_2O_5 + K_2O$) and sown area for the years 2015–2017 resulted in a decline of per ha application rates by 2.4% as a national average and by a range between 0.1% and 5.8% for three provinces in the NCP in 2017 compared to 2015. Other concomitant policies aim to promote the replacement of mineral fertilizers by fertilizers derived from organic sources.

Other policies also aim at relocating large-scale animal husbandry operations away from the major cities. Plants in the outer districts of Beijing were closed or moved to neighboring Hebei Province, and many pig farms near Shanghai were closed by the government in recent years.

In 2013, the Ministry of Agriculture of China (since 2018: Ministry of Agriculture and Rural Affairs) issued "Regulations on Prevention and Control of Pollution from Large-scale Breeding of Livestock and Poultry"[34]. On May 31, 2017, the General Office of the State Council released the "1st Specific Guideline for the Utilization of Livestock and Poultry Wastes"[35]. Specifically, five administration systems and one mechanism are to be established. These comprise (1) environmental impact assessment of animal husbandry, (2) pollution inspection of animal husbandry, (3) territorial management responsibility, (4) major responsibility of large-scale farms, and (5) performance evaluation. The mechanism aims at recoupling the cycle between plant production and animal husbandry.

In 2018, the Ministry of Agriculture of China published "Technical guidelines for assessment of land carrying capacity to livestock and poultry wastes"[36]. This guideline is to fill the gap in calculating the carrying capacity of the land according to farm scales. As to management of pollution, the construction of facilities to collect, store, and utilize manure by third parties, as well as the improvement of operation and equipment for water-saving animal husbandry operations and construction of facilities for manure utilization by scaled farms is to be supported, all based on the method of awards rather than subsidies. To promote the utilization of organic wastes from animal husbandry, the production of organic fertilizers using livestock and poultry wastes is to be encouraged and chemical fertilizers are to be replaced with organic ones. By 2018, the utilization rate of livestock and poultry wastes in China had reached 64% (Zhenhai Yang, National Animal Husbandry Service, 2018, personal communication).

Moreover, the geographical distribution of animal husbandry over China is currently being rearranged, with swine production being moved toward North and West China and poultry production toward East and South China. The aim is to bring pig production closer to the main feed (maize) producing regions and to reduce transportation costs (Zhenhai Yang, National Animal Husbandry Service, 2018, personal communication). Regarding feed, two new group Standards have been drafted by The China Feed Industry Association, determining (among others) the upper limit of raw protein and total P content and promoting new techniques to produce low-protein feed (ibid.). Regarding feed additives, the "Safety specification of feed additives" has been revised, aiming at lowering the upper limit of Cu and Zn in feed and reducing more than 8000 t of Cu and 16500 t of Zn per year (ibid.).

5 Conclusions

The Sino-German project "Recycling of organic residues from agricultural and municipal origin in China" (2008–2012) was a successful example for an interdisciplinary approach involving different German and Chinese research groups from various disciplines, all aiming at jointly investigating the status quo in a single case study (pilot pig farm) and making recommendations not only for the case study but for the wider region (NCP) and other newly industrializing countries in Asia. Though only the P-related research was the focus of this paper, the project offered very relevant results in other related fields as well. The project may therefore also serve as an example for other international and interdisciplinary approaches dealing with agriculture and the environment.

Briefly, in view of the changes having occurred in China in recent decades, there is a need for recoupling the interrupted nutrient cycles between animal and plant production both at farm and field scales as well as on an altered, regional scale. There is also a strong requirement for further technology development and spatial planning to obtain even nutrient balances, including the nutrients in manures.

Organic and mineral P fertilization should be based strictly on crop requirements and soil P status, aiming at optimum available P concentrations in soil. In those cropping systems receiving high manure amounts, mineral P fertilization may even be omitted for several years[6]. While P input by FYM is mostly sufficient in the study region (peri-urban areas of Beijing), excess manure should be processed and transported to areas of the North China Plain with soils low in soil organic matter (ibid.) and low available P in soil.

The livestock density in the peri-urban area of Beijing should be reduced from 11 $LU \cdot ha^{-1}$ (in 2009) to 3–4 in the medium term and 2–3 $LU \cdot ha^{-1}$ in the long-term, taking into consideration the harvests of two main crops per year in the wheat–maize and Chinese cabbage–glutinous maize double-cropping systems, which are able to take up nutrients during most of the year[6].

Agriculture-derived pollution has become the focus of national attention in China in recent years, and great progress has been made regarding the regulatory framework for management of animal wastes and manure use. However, it remains to be seen how the standards and regulations will be implemented and enforced at the local level, where conflicting interests frequently persist.

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