Journal of Environmental Management 228 (2018) 232–238

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Nutrient use efficiencies, losses, and abatement strategies for peri-urban dairy production systems

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ARTICLE INFO

Keywords:
Manure management
Nitrogen
Phosphorus
NUFER model
Nutrient cycling
Dairy farms

ABSTRACT

Manure management is an important aspect of urban livestock production that has a profound impact on metropolitan living. Data were collected from 28 dairy farms in peri-urban Beijing and analysed to determine farm nitrogen and phosphorus flows and costs associated with various manure management options to reduce nutrient losses. Dairy production in peri-urban Beijing was characterized by its use of high protein diets (16.3–17.0% crude protein), high reliance on imported feeds (92–98%), and low manure recycling (3.0–10.8%). Farms of 900–2000 cattle showed lower use efficiencies than farms of < 900 cattle. Costs of manure handling ranged from 0.1 to 1.0 Yuan kg^{-1} milk. Among various manure treatment options, biogas digesters with aerobic lagoons had the lowest N losses and costs, justifying their investments. In conclusion, peri-urban dairy production systems were contrasting with traditional systems and within their own systems in nutrient use efficiency and losses, which was mainly decided by their farm size. To improve the nutrient use efficiencies and reduce losses, farmers and managers of peri-urban dairy production system should have a full awareness of different feed intake and manure management.

1. Introduction

Urban and peri-urban agriculture continues to grow in the world as local demands for milk, meat, and eggs increase (Satterthwaite et al., 2010; Rosegrant and Cline, 2003). In developing countries, animal husbandry evolves rapidly in response to increasing demands for protein products, whereas in developed countries, the demand is stagnant. While improving in production efficiency and sustainability (Thornton, 2010), peri-urban livestock production has been rapidly industrialized, raising environmental concerns about manure, odours, fine particle matters ($PM_{2.5}$), and risks of zoonosis spread (Menzi et al., 2010; Basset-Mens et al., 2007; Steinfeld et al., 2006; Herrero and Thornton, 2013). Nutrient management has become a strategic endeavour for peri-urban animal production in the Netherlands and China.

Concentrated urban animal production entails massive importation of forages and grains (Abdulkadir et al., 2012), interrupting natural nutrient recycling and potentially causing losses of nutrients to the environment. Ma et al. (2012) showed that it was a few metropolitan areas that accounted for most of the release of nitrogen (N) and phosphorus (P) in China. Dairy production was prioritized by the Beijing Seed Industry Development Plan (2010–2015) among 16 top animal and crop industries for receiving supports for nutrient management (BMCRA, 2010). While the environmental impact of dairy production has been extensively evaluated in the United States and in Europe (Sonneveld et al., 2008, 2012), evaluations in China have been limited to model predictions for the nation or regions (Wang et al., 2016; Bai et al., 2014; Na and Dong, 2009; Liu, 2007) and did not include private farms. Little information on nutrient losses and management costs is available for peri-urban dairy production at the farm level in China.

Rapid population growth in Beijing has resulted in an increased demand for milk products and expanded local dairy production (Fig. S1). From 1978 to 2013, the number of dairy in Beijing increased from 16.9 to 138.0 thousand (MOA, 2015). In the meantime, arable land shrank from 0.43 to 0.22 Mha (Fig. S1), resulting in increased animal densities or in the decoupling of dairy farming from the available land. Urbanization was accompanied by intensification of dairy operations as well as increasing numbers of animals, indicated by an increased

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https://doi.org/10.1016/j.jenvman.2018.09.016
Received 30 November 2017; Received in revised form 29 August 2018; Accepted 4 September 2018
0301-4797/

proportion of large sized farms and decreased proportions of traditional medium and small sized farms (MOA, 2015; BMBS, 2015). Production intensification has been associated with imbalanced nutrient inputs and outputs (Giller, 2002) that could have profound environmental impacts (Steinfeld et al., 2006; Tilman et al., 2002). The environmental impact of peri-urban dairy farms needs to be quantitatively evaluated.

This study was undertaken to assess the environmental impact of dairy production in peri-urban Beijing and the cost of manure treatment options for alleviating externalities. Specific objectives were to 1) quantify N and P input-output balances of dairy farms of different sizes, 2) provide an analysis of current manure treatment systems and associated nutrient emissions, costs, and benefits, and 3) explore options for improving the environmental impact of dairy production in peri-urban regions.

2. Material and methods

Beijing, the capital city of China, is one of the ten largest metropolitan cities in the world. The metropolitan is situated in the eastern coast of the Eurasian continent, at the northern tip of North China Plain, surrounded by mountains in the west and the north. The municipality extends on 1.6 million ha of land and consists of 14 administrative districts. In a 2012 census, the city had a population of 20.7 million, 60% of which resided in the urban city, 30% in peri-urban districts, and 10% in rural communities. The peri-urban districts account for 60% of the arable land of the municipality (MOA, 2014), raising a large population of dairy cows (i.e. Yanqing, Haidian, Daxing, Changping and Tongzhou).

2.1. Collection of data

Empirical data were collected from a survey conducted during 2012–2013. Managers of 28 dairy farms in the municipality of Beijing were contacted. These farms were selected randomly from the Livestock Environmental Emission Registry, representing 12% of the farms in Beijing. Farms were classified into small (200–899 head of cattle), medium (900–1999 head of cattle), and industrial (≥2000 head of cattle) sizes (Table 1). Since farms with < 200 cattle were rare in the area and considered economically nonviable, they were excluded from the selection. All selected farmers completed a questionnaire (Table S1). Holsteins were the predominant cattle breed, and herds included calves, heifers, lactating cows, and dry cows. Most farms used artificial insemination. However, farms of different sizes differed in production, feeding, and manure management (Table 1).

Table 1
Main characteristics of dairy farms of different sizes in Beijing in 2013.

Farm characteristics	Farm size (number of animals per farm)		
	200–899	900–1999	≥2000
Total number of farms in Beijing	161	46	9
Number of farms surveyed	18	8	2
Type of farms surveyed (%)			
Privately owned	48	50	14
State-owned	0	0	28
Cooperative	52	22	29
Contracted	0	28	29
Labour (full-time employee per farm)	26	30	41
FCR (kg feed DM (kg milk)$^{-1}$)	1.0	0.9	0.9
Dietary crude protein (%)	16.5	16.3	17.0
Lactation length (days)	334	331	327
Milk yield (kg (head yr)$^{-1}$)	6667	7688	8390
Mortality (% per year)	9.1	7.6	6.4
Feed purchase ratio (%)	92	96	98
Manure recycling ratio (%)	10.8	6.5	3.0

Note: FCR is feed conversion ratio.

Dairy production data (number of cattle, milk yield, and acreage) for peri-urban Beijing were derived from statistical yearbooks (MOA, 2014). Data and parameters used for estimating N and P balances (N and P content of feeds and milk, and emission factors and N and P losses from housing, manure storage, and treatment) were derived from literature (Bai et al., 2014) and by modelling using a static mass flow model (NUFER; Bai et al., 2014; Ma et al., 2010) that calculates N and P flows, balances, and use efficiencies involved in the whole food production–consumption chain (Ma et al., 2010).

2.2. Calculation module

Analysis of data involved calculation of nutrient balances, use efficiency, and costs and benefits of manure managements for the 28 dairy farms.

2.2.1. Nutrient input and output

Nutrient input from feed sources was calculated from the number of animals, animal feed dry matter (DM) requirements, and the nutrient composition of feeds (Bai et al., 2014) using Equations (1) and (2). Data on the number of animals of different age and production stage, feeding days, feed intake, and feed composition were obtained from the survey. Total N and P intakes were calculated from the content of these nutrients in feeds and feed consumption (Ma et al., 2010).

$$I_{feed} = \sum Day_{feed_i} \times A_{feed_i} \times Com_{feed_{ij}} \quad (1)$$

$$N(P)I_{feed} = I_{feed} \times N(P)C_{feed} \quad (2)$$

where I_{feed} is feed intake in a year (kg); Day_{feed_i} is feeding days in different stages of a cow in a year; A_{feed_i} is feed intake per day; $Com_{feed_{ij}}$ is the proportion of feed j in stage i of a cow; $N(P)I_{feed}$ is intake of N or P (kg head^{-1}); $N(P)C_{feed}$ is the N or P content (%) of the diet.

The output of N and P in dairy products was estimated using Equations (3) and (4):

$$N(P)O_{milk} = O_{milk} \times N(P)C_{milk} \quad (3)$$

where $N(P)O_{milk}$ (kg) is output of N or P in milk; O_{milk} is milk yield per cow; $N(P)C_{milk}$ is milk N or P content (%).

$$N(P)O_{animal\ body\ weight} = O_{animal\ body\ weight} \times N(P)C_{animal\ body\ weight} \quad (4)$$

where $N(P)O_{animal\ body\ weight}$ is the amount of N or P retained in the body of the animal; $O_{animal\ body\ weight}$ is weight gain of the animal; $N(P)C_{animal\ body\ weight}$ is the N or P content (%) of live weight gain.

2.2.2. Nutrient input-output balance

N and P surpluses (NS, PS) were estimated from input-output balances using Equation (5).

$$N(P)S = (N(P)I_{feed} + N(P)I_{calves}) - (N(P)O_{animals} + N(P)O_{manure}) \quad (5)$$

where $N(P)I_{feed}$, $N(P)I_{calves}$ are inputs of N or P in feed and in the bodies of calves imported by the farm, respectively; $N(P)O_{animals}$, $N(P)O_{manure}$ are outputs of N or P in sales of animal products (sum of $N(P)O_{milk}$ and $N(P)O_{animal\ body\ weight}$) and manure, respectively.

2.2.3. Nutrient use efficiencies

Nutrient use efficiency was calculated by dividing nutrient output by nutrient input for N and P (NUE and PUE) using Equations (6) and (7) for the animal $N(P)UE_{animal}$ and the herd $N(P)UE_{herd}$.

$$N(P)UE_{animal} = N(P)O_{milk} / N(P)I_{feed_{animal}} \quad (6)$$

$$N(P)UE_{herd} = N(P)O_{mm} / N(P)I_{feed_{herd}} \quad (7)$$

where $N(P)UE_{animal}$ is N or P use efficiency at the animal level, and $N(P)UE_{herd}$ is N or P use efficiency at the herd level. $N(P)O_{mm}$ is N or P retention in milk and meat. $N(P)I_{feed_{animal}}$ is feed N or P input for