Greenhouse gas emissions on Chinese dairy farms and potential for reduction

Working Paper No. 384

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

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Abstract

A life cycle assessment method was used to calculate the greenhouse gas (GHG) emissions of a sample of 181 dairy farms. A database with survey data of these dairy farms was used to calculate and analyze the resulting GHG emission data. The results show that the annual average carbon footprint of milk from the sample farms is 1.95 kg CO_2-eq kg^{-1} fat and protein corrected milk (FPCM). There are great differences in GHG emission, ranging from 0.82 to 5.09 kg CO_2-eq kg^{-1} FPCM. Regions in south China have the highest carbon footprint, while those in North China have the lowest level. The largest emission source is feed production and processing (31.8%), followed by enteric fermentation (30.0%), manure management (20.8%), energy consumption (9.7%), transport (7.7%) and manure application (7.2%). This large range is caused by different farm conditions and farm management practices, such as herd size, milk yield, and manure management among others. Improving the local dairy production efficiency, manure management, and the integration of crop and dairy production systems are major factors to combine the growing Chinese demand for milk consumption with the global need to reduce GHG emissions. This should be guided through governmental policies, including closing the productivity and efficiency gaps in domestic dairy and feed production, innovations in manure management and the use of green energy. Policy guidelines for the reduction of GHG emissions should take into account differences between regions and farms.

Keywords

GHG emission; dairy farm; mitigation potential; carbon footprint; life cycle assessment.

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The project was executed by a consortium of three parties: the Institute of Environment and Sustainable Development in Agriculture (IEDA), that is part of the Chinese Academy of Agricultural Sciences (CAAS); the College of Animal Science and Technology that is part of the China Agricultural University (CAU) and by Wageningen Livestock Research that is part of Wageningen University and Research (WUR). Researchers from these institutes have collaborated on developing low-carbon dairy production in China. This report is the result of close collaboration between CAAS and CAU to design a questionnaire that was used to carry out dairy farm surveys in 2019 and 2020. The results of the surveys were used by CAAS to calculate greenhouse gas emissions from dairy farms. WUR supported in analyzing the data to come to recommendations on dairy farm management that will facilitate the reduction of greenhouse gasses emissions on dairy farms.

The whole project was led by Jelle Zijlstra from WUR and we like to thank him for the data analysis and lesson for our assessment. We like to thank Wei Wang from CAU for coordinating her part of the data collection. We also like to thank all other people involved in the data collection: colleagues from CAAS, CAU, dairy farmer and provincial livestock stations.

Content

1. Introduction

1.1. Background

Sustainable livestock development is one of the key issues for future animal protein production in China. Besides improved manure utilization and water resource efficiency, management of carbon emissions and carbon footprint (CF) is highlighted as an important research topic. In phase one of the “Piloting and scaling of low emission development in large scale dairy farms in China” project, a database for carbon footprint assessment of dairy cattle in China was developed with baseline information of 100 farms representing different production systems in different regions, such as large-scale, intensive farms, small-scale farms, and grazing farms in south, middle and north China. The database includes information on the number of animals, average milk production, feed intake and feed composition, manure management and more. The idea is to use this database to identify a spectrum of representative farms which is used to make farm assessments of carbon footprints and mitigation interventions.

1.2. Objective

The objective of phase two, described in this evaluation report, is to evaluate the carbon footprint results of the dairy sector using the results of survey farms obtained by farm data collection and by the use of the carbon footprint calculation model which was developed in phase 1. This evaluation should result in:

- A better quantitative insight in the greenhouse gas (GHG) emissions from large scale dairy farms.
- The variation in GHG emissions between farming systems and regions.
- An impression of potential options to reduce GHG emissions.

The main question the authors had at the start of this data evaluation process was: what are the lessons we can learn about GHG on large scale Chinese dairy farms from the evaluation of the data of the survey farms?

2. General introduction

2.1. Description of method to monitor and evaluate results

The method for monitoring and evaluation was based on a developed carbon footprint assessment model and established database based on questionnaires designed in 2019. The carbon footprint assessment of the Chinese dairy sector was developed in phase 1 in 2019. The dairy farm survey continued in 2019 and 2020. Then, options for reducing GHG emissions on dairy farm was used to evaluate the potential and the lessons that learned from the mitigation scenarios was discussed in this evaluation results.

2.2. Structure of the report

- The following contents are explained in this report:
- Farm survey included data collection (section 3.1) and basic information of the surveyed dairy farms (section 3.2).
- Calculation method of carbon footprint for dairy farm, Section 4.
- Evaluation results of carbon footprint of dairy farms, Section 5.
- Mitigation scenarios of Farm level N losses, including scenarios description in Section 6.1 and learns from mitigation scenarios in Section 6.2.
- Summaries from evaluation of the Chinese dairy farms in Section 7.

3. Farm survey

3.1. Data collection

The survey was undertaken in 2019 and 2020 by the Chinese Academy of Agricultural Sciences (CAAS) and the College of Animal Science and Technology that is part of the China Agricultural University (CAU) to collect individual farm data needed to calculate and analyze GHG emissions on dairy farms. A total of 220 questionnaires were sent out and 192 were returned, of which 181 proved usable after applying a data check, accounting for 82.3% of the total number of farms that were asked to participate in the data collection. The questionnaire is shown in Appendix 1.

The respondent farms include different production systems in different regions, such as large-scale intensive farms, small-scale farms, and grazing farms in 6 regions of China (North, Northeast, East, Central, Northwest and South of China). The farms were distributed over 16 provinces/cities representing all main dairy production regions in China (Table 1). The total milk yield in these 16 provinces/cities accounted for 86.8% of total yield in China in 2018.

Table 1. Surveyed dairy farms in China

Regions	Province	Number of survey farms	Farm size (number of cows per farm)		
			Maximum	Minimum	Mean
North China	Beijing	11	2400	217	934
	Tianjin	15	5052	400	1674
	Hebei	29	20159	325	1842
	Shanxi	11	2574	480	1193
	Inner Mongolia	17	5796	103	1051
Northeast China	Heilongjiang	22	5188	90	1618
	Liaoning	3	800	307	554
East China	Shandong	18	12218	420	1762
	Shanghai	2	4637	1611	3124
	Fujian	3	2020	1380	1767
Central China	Henan	13	8566	247	2248
Northwest China	Ningxia	6	9162	1144	3292
	Shaanxi	7	3045	91	1147
	Xinjiang	18	24289	319	2388
South China	Guangdong	2	2549	1944	2247
	Chongqing	4	1800	263	1057

The database with all the results of the survey farms includes information on the number of animals, average milk production, feed sources, feed intake and compositions, energy consumption, manure management, etc.

3.2. Survey results of dairy farm

The basic production information is shown in Figure 1. The farm size ranged from 90 to more than 20,000 heads per farm, and the milk yield ranged from 4.8 to 11.7 ton head^{-1} year^{-1}, with an average value of 8.5 tons head^{-1} year^{-1}. The average value of milk fat and protein was 3.3% and 3.9% respectively, ranging from 3.0% to 3.9% for fat content and from 3.2% to 4.8% for protein content. The proportion of mature cows in a herd structure was 54.6%, with a large range of 31.1% to 89.8%.

Concentrate to roughage ratio (CRR), feed crude protein (CP), feed conversion rate (FCR) and feed transport distance (TD) were included in feed information. The average value of CRR is 1.0. There is a large variability for feed C. The average CP was 16.0%, ranging from 6.3% to 56.9%. Previous study has shown the effects of protein levels from 13.5%, 15.0%, 16.5%, 17.9% and 19.4% on the performance and nitrogen emissions of dairy cows. When the crude protein level of the diet exceeded 16.5%, milk yield and milk protein composition did not continue to increase. There were no significant differences in feed conversion efficiency, but urine nitrogen increased linearly (Colmenero and Broderick, 2006). The FCR of surveyed farms ranged from 0.6 to 5.0, with an average value 1.4. The feed transport distance from feed crop planting areas to a dairy farm was 1.8 km/kg feed.

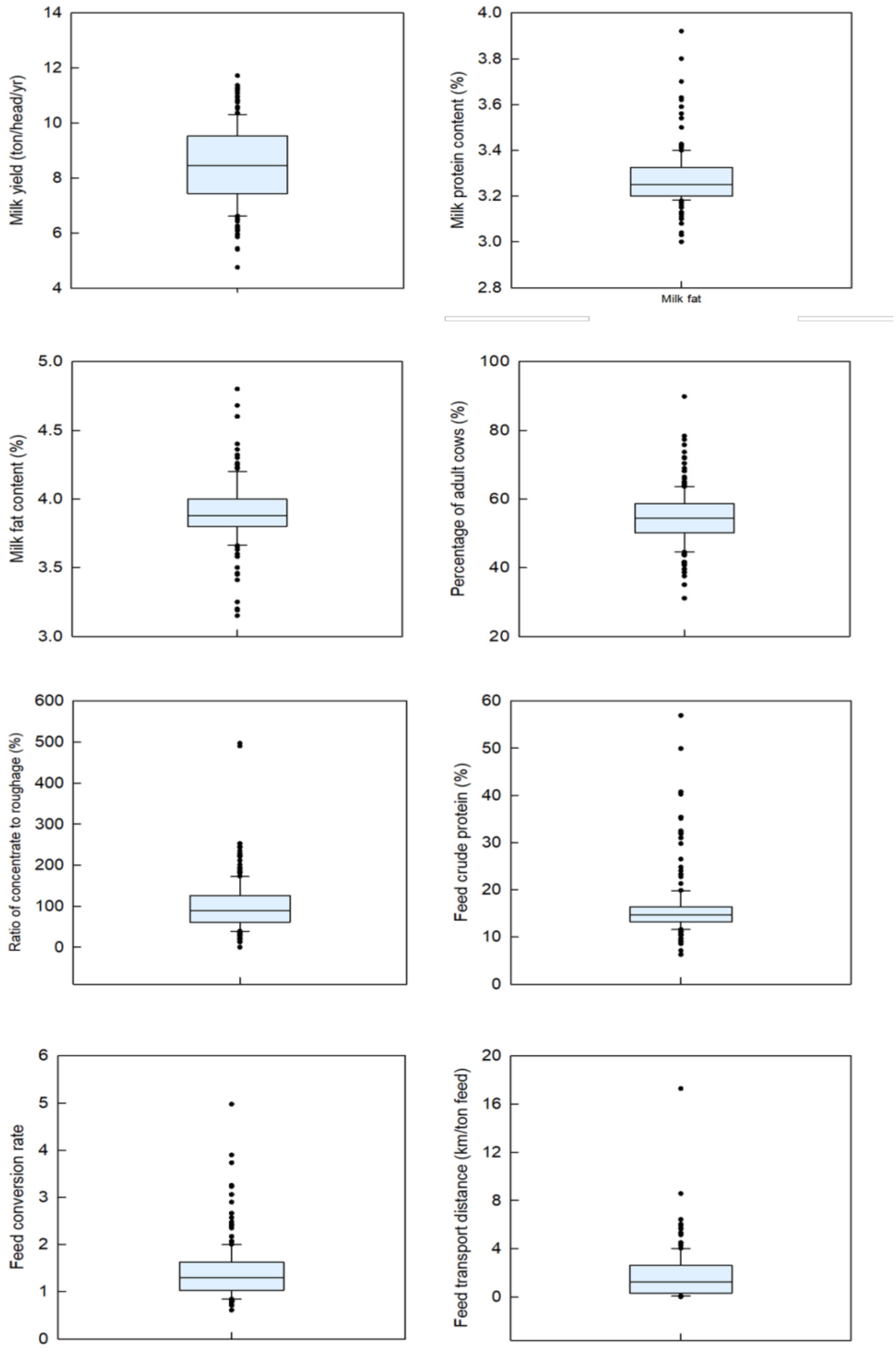

Figure 1. Basic information of surveyed dairy farm in China (The line in box represents the median value of the total data; the two short stripes above and below the box represent the upper and lower quartile, respectively; the black point represents the value out of upper and lower quartile)

4. Calculation of carbon footprint

A life-cycle assessment (LCA) method was used to estimate the carbon footprint of milk production (Dong, 2019). Three GHGs closely related to livestock production are included in the carbon footprint of milk production, namely CO_2, CH_4 and N_2O. Total GHG emissions were expressed in CO_2 equivalents (CO_2-eq) using the global warming conversion factors of 25 kg of CO_2e kg^{-1} for CH_4 and 298 kg of CO_2e kg^{-1} for N_2O (IPCC, 2007). The annual production cycle was selected as the evaluation period for the carbon footprint assessment.

4.1. System boundary, functional unit and allocation methods

The system boundary of this research covers production processes from "cradle" to "farm-gate", including

1. Fodder crop production and processing: direct and indirect emissions of N_2O in the process of N fertilizer manufacture and their subsequent application for feed production; fossil fuel CO_2 emissions from the manufacture of plastic sheeting and pesticides; application of urea during feed planting; and machinery use during feed planting, such as ploughing, seeding and harvesting;
2. CH_4 emissions from enteric fermentation and manure management;
3. Direct and indirect N_2O emissions from the manure management chain (housing, manure storage and treatment);
4. CO_2 emissions from energy generation and consumption on farm, including electricity, coal and gasoline (Ledgard et al., 2019).

The functional unit is 1 kg of fat and protein corrected milk (FPCM) - milk standardized to 4% fat and 3.3% protein - which was calculated according to IDF (2015).

$$M_{FPCM} = M_{RM} \times \left(0.337 + 0.116 \times M_{RM,F} + 0.06 \times M_{RM,P}\right) \qquad \text{(Eq. 1)}$$

Where, M_{FPCM} is annual milk production corrected for fat and protein content, t yr^{-1}; M_{RM} is annual raw milk yield, t yr^{-1}; $M_{RM,F}$ is fat content of raw milk, %; $M_{RM,P}$ is protein content of raw milk, %.

Emissions were allocated between milk and live-weight sold for meat co-products according to biophysical allocation and between feed co-products according to economic allocation based on IDF (2015) and the carbon footprint calculation model developed in phase 1.

4.2. Calculation method for the carbon footprint of milk production

The total emissions from an intensive dairy production system are the sum of GHG emissions from feed cultivation and processing after allocation, methane emissions from enteric fermentation, manure management and field application of manure, and GHG emissions from energy consumption on the dairy farm. The total system emissions are divided by the value of the standard annual total output of dairy farms. The calculation formula is as follows:

$$CF_{milk} = \frac{[G_{feed} \times AF_{feed} + \mathrm{G}_{enteric} + \mathrm{G}_{manure} + \mathrm{G}_{land} + \mathrm{G}_{energy}]}{M_{FPCM}} \times AF_p \quad \text{(Eq. 2)}$$

Where, CF_{milk} is the carbon footprint of milk production on the dairy farm, kg CO_2-eq/kg $FPCM^{-1}$; G_{feed} is GHG emissions from feed production, t CO_2-eq; AF_{feed} is allocation factors of main and by-products of feed; $G_{enteric}$ is GHG emissions from enteric fermentation, t CO_2-eq; G_{manure} is GHG emissions from manure management, t CO_2-eq; G_{land} is GHG emissions from land application of manure, t CO_2-eq; G_{energy} is GHG emissions from energy consumption, t CO_2-eq; AF_p is the allocation factor for greenhouse gas emissions from the whole system. The detail of calculation is shown in supplementary materials.

5. Evaluation of carbon footprint of dairy farms

5.1. Carbon footprint per kg milk

The annual average carbon footprint of China milk from the sample was 1.95 kg CO_2-eq kg^{-1} FPCM. It varies widely between farms, ranging from 0.82 to 5.09 kg CO_2-eq kg^{-1} FPCM (Figure 2).

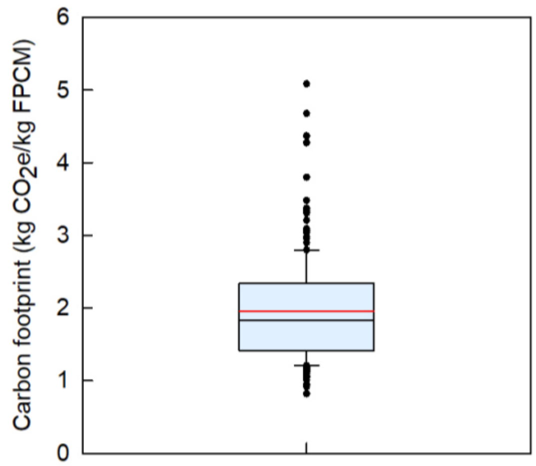

Figure 2. Carbon footprints of surveyed dairy farms in China (see Figure 1 for explanation of this type of figure)

The CO_2-eq emission sources on farms are presented in Figure 3. The largest source is feed production and processing with an average of 0.62 kg CO_2-eq kg^{-1} FPCM after mass allocation, accounting for 31.8% of the total CO_2e emission, followed by enteric fermentation (an average of 0.59 kg CO_2-eq kg^{-1} FPCM, accounting for 30.0% of the total CO_2e emission) (Figure 3a and 3c). The sum of the average GHG emissions from manure management, energy consumption, transport and manure application are 0.41 (accounted for 20.8%), 0.19, 0.15 and 0.14 kg CO_2-eq kg^{-1} FPCM respectively. The presence of substantial inter-farm variation across these contributing sources may be caused by large differences in management practices between different farms. This large variety indicates that there is great potential to reduce the CF of milk production in high emitting farms by changes in management.

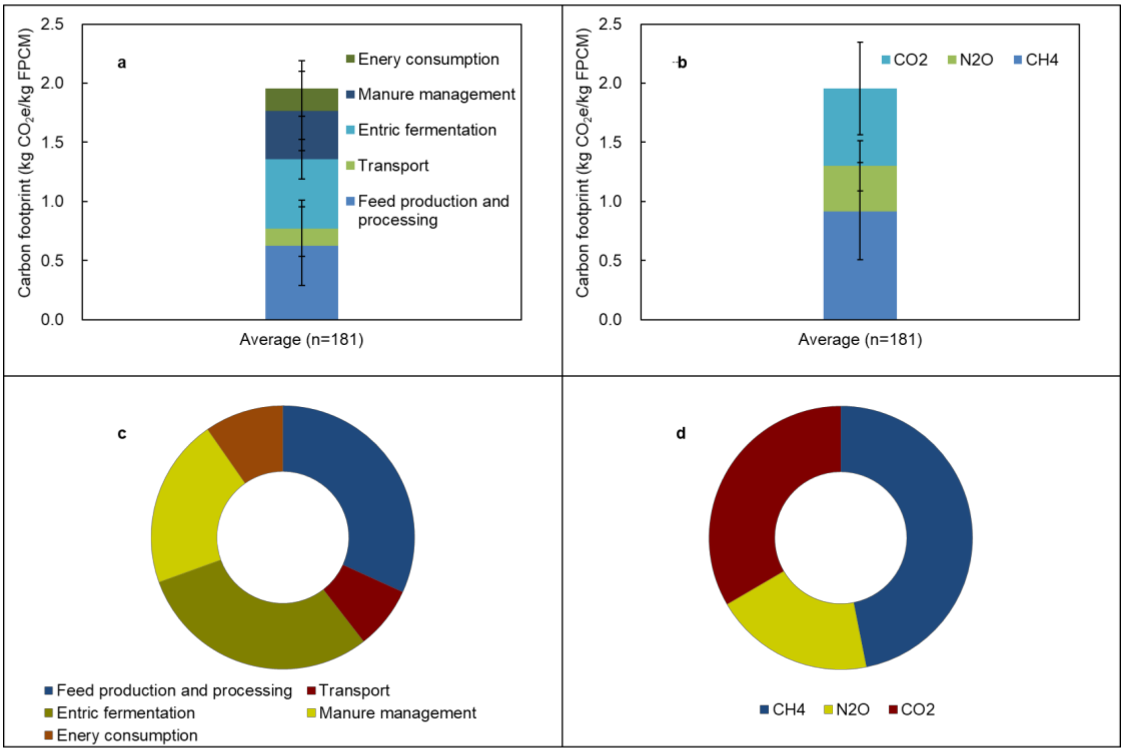

Figure 3. Carbon footprint and contributions of different emission sources on the farm (a, c) and the different greenhouse gases involved (b, d)

CH_4 emission was the largest emission gas source (0.92 kg CO_2-eq kg^{-1} FPCM), which accounted for 46.9% of the total CO_2-eq emissions, followed by CO_2 (33.4%) and N_2O (19.7%) (Figure 3b and 3d).

5.2. Impact of farm size on carbon footprint

The mean CF varied markedly among three farm size classes (Figure 4). The carbon footprint was negatively correlated with farm size. The average value of carbon footprint with mass allocation of small farms (< 500 head $farm^{-1}$) group was 2.1 kg CO_2-eq kg^{-1} FPCM which is 14.8% higher than the large farm group (> 2000 head $farm^{-1}$) which is 1.8 kg CO_2-eq kg^{-1} FPCM. The emission sources within the farms (enteric fermentation, feed production and process, and manure treatment) were quite similar for the different farm size groups.

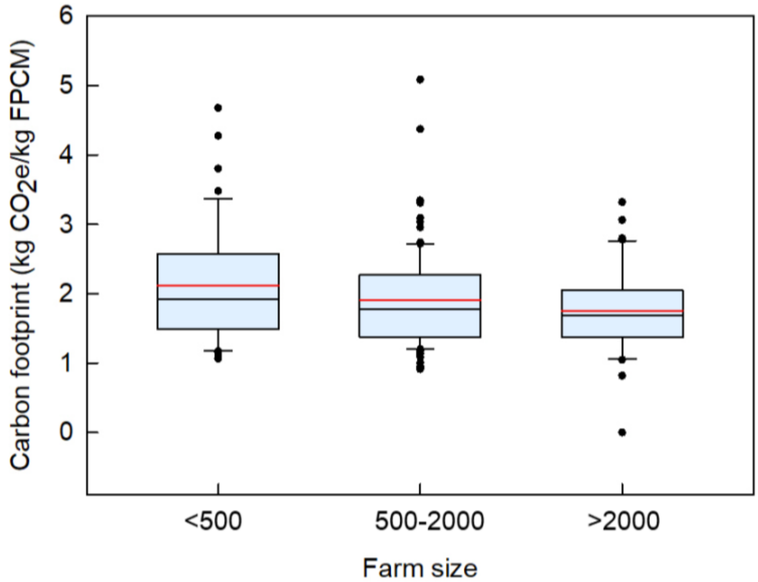

Figure 4. Comparison of milk carbon footprints of different farm sizes

5.3. Impact of cow productivity on carbon footprint (CF)

The mean CF varied markedly among three productivity classes (Figure 5). The carbon footprint of milk production was negatively correlated with productivity, and the average value of carbon footprint with a mass allocation of low productivity (< 7 tons head-1 yr-1) group was 2.5 kg CO2-eq kg-1 FPCM which is 57.4% higher than the high productivity group (> 10 ton head-1 yr-1) which is 1.6 kg CO2-eq kg-1 FPCM.

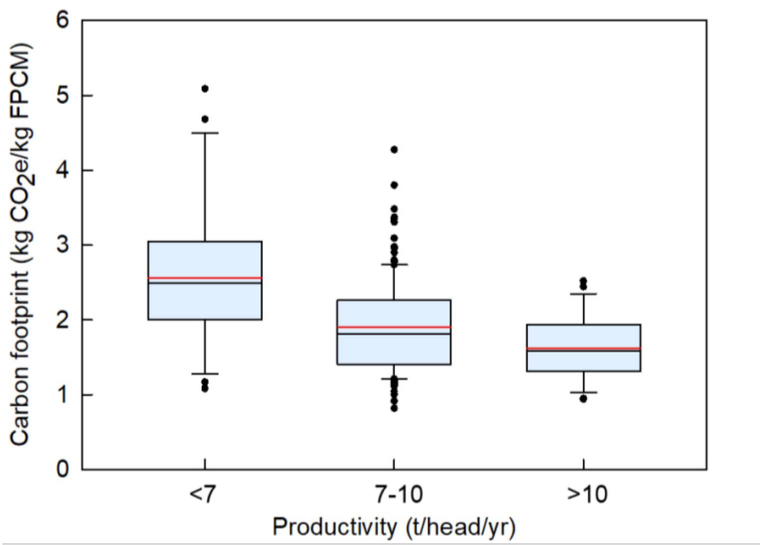

Figure 5. Comparison of milk carbon footprints of different productivity

5.4. Impact of region on carbon footprint

Regional differences in the average carbon footprint of dairy farms are shown in Figure 6. There is a big variation in the average carbon footprint across the six main dairy regions of China. South China had the highest carbon footprint (2.35 kg CO_2-eq kg^{-1} FPCM) which is 1.3 times higher than the region with the lowest value (North China Plain which is 1.76 kg CO_2-eq kg^{-1} FPCM). There are significant differences in carbon footprint between provinces in China. Provinces with the largest carbon footprint are Chongqing, 2.45 kg CO_2-eq kg^{-1} FPCM, followed by Xinjiang (2.37), Shaanxi (2.30), Henan (2.23), Shanxi (2.20), Guangdong (2.16), Shandong (2.05), Inner Mongolia (1.99), Heilongjiang (1.98), Fujiang (1.95), Liaoning (1.86), Hebei (1.70) and Ningxia (1.62). Beijing (1.47), Tianjin (1.51) and Shanghai (1.59) had the lowest carbon footprint which has enrichment in economic and a high level of technology, mainly caused by relative high investments in a high level of technology on the farms, leading to more efficient farms in converting feed into milk and to avoid emissions from manure. The difference between the provinces with the maximum and the minimum carbon footprint is quite large: the value for the maximum province (Chongqing) is 1.7 times higher than the value for the minimum province (Beijing).

The contributions of different sources within the farm for the different provinces/cities are shown in Figure 6. There are obviously differences between regions in the contribution of different sources. Feed production and processing is the major contributor to farm GHG in North China Plain, Central and Northwest China, while transport is the main contributor in East and South China. These results show that in about 50% of the provinces feed production and processing is the main contributor to GHG emission. In 31.3% of the provinces, enteric fermentation is the main contributor. The first contributor of the three provinces in South China (Guizhou, Fujian and Guangdong) is transport with 40.6%, 35.0% and 27.7% respectively. This is due to the large distance between the feed production region and the region where the dairy farm is located. Variation in the contribution of transport between provinces was very large, ranging from 0.1% to 40.6%. Due to these regional differences in emission sources, CH_4 is the main greenhouse gas in North China Plain, Northeast, Central and Northwest China, while the CO_2 is the main gas type in East and South China.

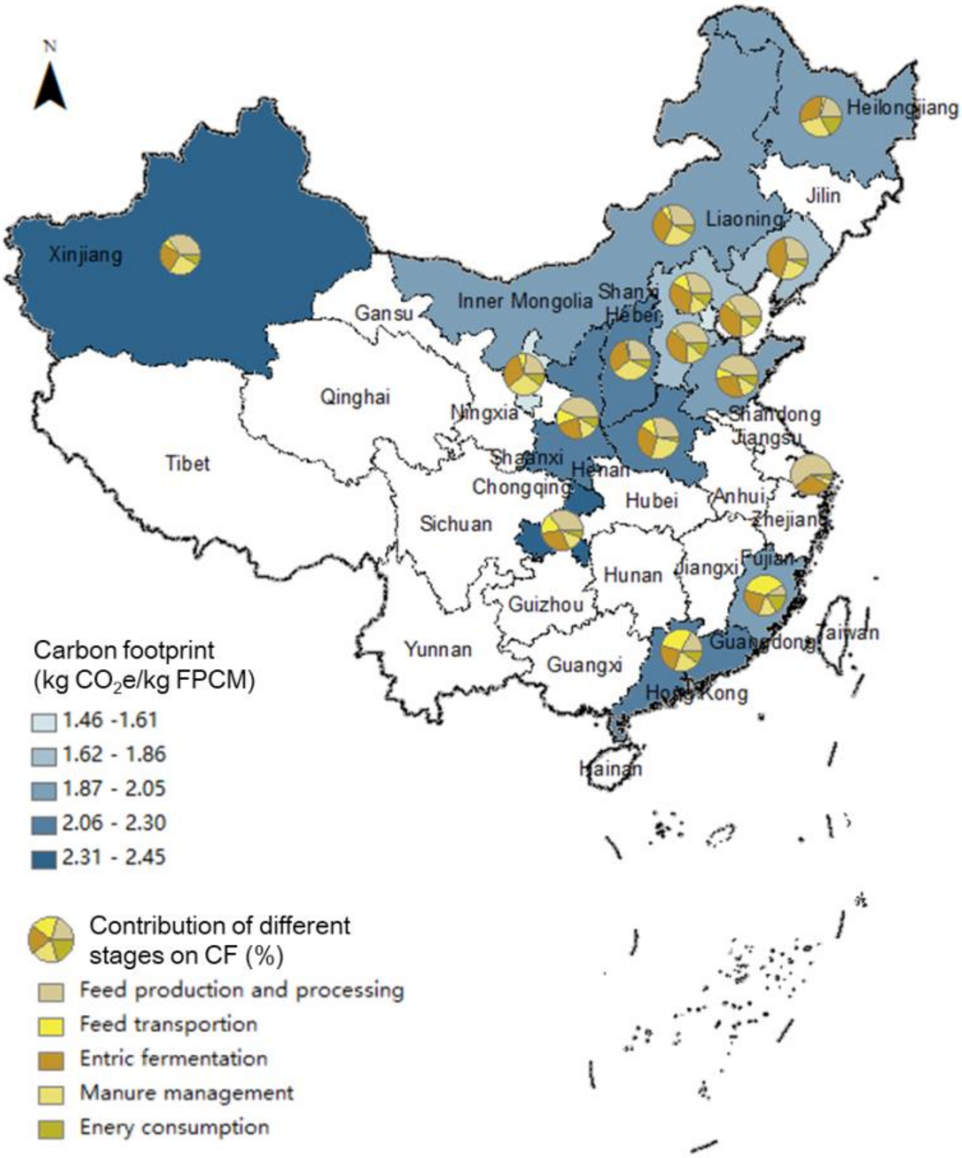

Figure 6. Comparing of carbon footprint in different regions and contribution of different stages

6. Mitigation potential

6.1. Indicators used to show mitigation potential

To explore the potential impact of mitigation options we defined groups of dairy farms based on scores for indicators that were available in the sample data. We defined three groups based on the scores of the indicators listed below: a low-25% group a middle-50% group and a high-25% group.

The comparison between the farm groups provides insight into the potential to reduce emissions. This comparison is made for these farm performance indicators:

1. **Herd size in number of dairy animals on the farm**
   This is an indicator of the scale of the farm. It includes adult cows, heifers and calves.

2. **Milk production per cow per year**
   This indicator is a result of the genetic level of the herd, animal healthcare and the quality of feeding and is considered to be an overall indicator for the herd performance and the skills of the farm staff to manage a dairy farm.

3. **The share of adult cows in the total number of cows**
   The total herd on a dairy farm is made up of adult cows and young stock. Young stock is needed to replace adult cows in the future. Young stock are not productive in terms of milk production, and this is why farmers usually aim at reducing the share of young stock and having a high share of adult cows in the herd. This will result in cows getting older and a reduced need for young stock to replace the culled cows.

4. **Concentrates/roughage ratio**
   This indicator reflects the ratio between concentrates and roughage in the diets of the herd.

5. **Nitrogen use efficiency**
   The nutrient use efficiency is defined as the ratio between nutrient output and nutrient input, which means product (meat and milk) nitrogen output divided by feed nitrogen intake on herd level. A high efficiency reflects low losses, which is generally positive for higher profitability and lower emissions to the environment.

6. **Distance between dairy farm and roughage crop producer**
   This indicator reflects the need for transport of feed. More feed transport corresponds

to higher emissions caused by higher use of fossil fuels needed for transport. A low value reflects that locally grown feed is used, and this will decrease the use of fossil fuels.

7. **Manure management indicator**

   The grouping method for manure management indicator was based on emission levels of each treatment option. There are 14 types of manure management: (1) pasture/range/paddock, (2) daily spread, (3) solid nature storage, (4) dry lot naturally on the playground, (5) composting - in-vessel, (6) composting - static pile, (7) composting - intensive windrow, (8) composting – passive windrow, (9) aerobic treatment, (10) deep bedding, (11) uncovered anaerobic lagoon, (12) anaerobic digester, (13) pit storage below animal confinements, and (14) slurry outside of barn. For one farm, there may be more than one manure treatment type applied, and each treatment process treats a certain percentage of the manure produced on the farm. If the manure treatment for a farm includes at least two high-emission manure treatments and the treated proportion is more than 30% (like natural storage of solid manure, natural air drying of the playground, unsealed compost, oxidation pond without cover), this type of farm belongs to the high emission manure management group. If the manure treatment for a farm includes at least two low-emission manure treatments and the treated proportion is more than 30% (daily spread, compost in vessel, anaerobic digester and liquid/ slurry stored in tank or below animal confinements with cover), this type of farm belongs to the low emission manure management group. A combination of other treatment options was categorized as the medium-emission group.

8. **Combined farm practices**

   The grouping method for the combined farm practices group is mainly based on the single grouping procedure which was described above under 7. Each farm is assigned to a high, medium or low emission group according to the grouping methods for the above scenario. A farm was here assigned to the high emission combined group if it was assigned to the high emission group in at least two single scenarios and to the medium emission group in two scenarios. In the same way, a farm was assigned to the low emission combined group if it was assigned to the low emission group in at least two single scenarios and to the medium emission group in two scenarios. The remaining farms were assigned to the medium-emission farm group.

6.2. Results of farm groups and mitigation potential

The results of the farm group comparisons are shown in Table 2 and explained in this paragraph. The results between farms groups are used to illustrate the potential of mitigation options to reduce GHG.

Table 2. Different performance of carbon footprint for different farm practices and mitigation potential

Farm feature incl. indicator	Group[c]	Group performance range	Average (kg CO_2eq/kg FPCM)	Mitigation potential (in %) compared to reference group:	
				Middle 50%	Top 25%
Herd size, head per farm	Bottom 25%	<500	2.10	9.5	14.3
	Middle 50%	500-2000	1.90	-	5.3
	Top 25%	>2000	1.80	-	-
Milk yield, ton/head/yr	Bottom 25%	< 7	2.52	24.2	36.5
	Middle 50%	7-10	1.91	-	16.2
	Top 25%	>10	1.60	-	-
Herd management (adult cow ratio), %	Bottom 25%	< 50%	2.30	18.8	23.5
	Middle 50%	50% - 60%	1.87	-	5.9
	Top 25%	> 60%	1.76	-	-
Concentrate roughage ratio (CRR)	Bottom 25%	< 0.6	2.05	4.4	13.5
	Middle 50%	0.6-1.5	1.96	-	9.5
	Top 25%	>1.5	1.77	-	-
Nutrient use efficiency (NUE), %	Bottom 25%	<25	2.13	10.1	15.3
	Middle 50%	25-40	1.91	-	5.9
	Top 25%	>40	1.80	-	-
Distance from feed crop to dairy farm, km	Bottom 25%	> 3	2.08	9.2	9.6
	Middle 50%	0.5-3	1.89	-	0.5
	Top 25%	< 0.5	1.88	-	-
Manure management [a]	Bottom 25%	High emission	2.12	1.1	26.4
	Middle 50%	Medium emission	2.10	-	25.6
	Top 25%	Low emission	1.56	-	-
Combined farm practices [b]	Bottom 25%	High emission	2.31	19.9	30.9
	Middle 50%	Medium emission	1.85	-	13.7
	Top 25%	Low emission	1.59	-	-

Notes: [a] the grouping method for manure management was expressed in section 6.1 item 7; [b] the grouping method for combined farm practices was expressed in section 6.1 item 8; [c] group names are based on GHG assessment: Top 25% means group with the lowest GHG emission; Bottom 25% means group with highest GHG emission.

The analysis of the results of the survey farms shown in Table 2 make us aware of differences between farms. These results will be helpful to design plans towards lowering greenhouse gases from large scale Chinese dairy farms.

6.2.1. General explanation of Table 2

The results in table 2 show the average group results for all the farm groups based on the grouping procedure described in 6.1. The general structure of this table is that is shows:

- Differences between the averages of the Top, Middle and Bottom groups for every indicator (Average column in table 2). These results reflect the variation between farms in the stratified sample. The whole population of Chinese dairy farms was divided into smaller groups (strata) based on region, farm size and farming system as main distinguishing categories. This means that the sample was not a representative sample for the whole Chinese dairy farm population, so the variation found in the sample may differ from the variation in the whole population of Chinese farms.

- The potential for mitigation if the worst performing Bottom 25%-group would improve their score towards the level of the Middle 50%-group or the best performing Top 25%-group (columns 5 and 6 in the table). This potential is also shown for the Middle 50%-group if it would improve its result to the level of the best performing Top 25%-group. E.g., the 9.5% decrease in GHG shown for the Bottom 25% farms for herd reflects the difference in GHG score for this group (2.10) and the Middle 50%-group (1.90) as percentage of the original 2.10. If the Bottom 25%-group would change all their management practices towards those of the Middle 50%-group, this would reduce the GHG emissions on farm level from 2.10 to 1.90, in other words minus 9.5 percent.

- Differences in mitigation potential between mitigation options that are connected to the eight indicators for which results are shown in table 2. For instance: the mitigation potential for milk yield per cow per year seems high (mitigation potentials ranging from 16.2 to 36.5) compared to that for decreasing the distance between the locations of the roughage grower and the dairy farm (ranging from 0.5 to 9.6). However, comparing all these percentages needs thorough considerations because the efforts, skills and investments to move from the score of one group to that of another group might differ strongly between indicators. Nevertheless, the comparison of these percentages is a good start to support decisions about future mitigation plans for the dairy sector. The first step in this process should be to explore which changes in farm management are needed to change from the score of one group to the score of another group. The second step is to assess the feasibility of these changes.

6.2.2. Explanation of results by indicator

Table 2 gave an overall overview of the mitigation potential of changes in farm management, based on the comparison of low, middle and high scoring farms groups for eight indicators. Below, we zoom in on the differences between the low 25% and high 25% farms groups shown in Table 3. This is done for all indicators that listed in Table 2.

1. **Herd size in number of dairy animals on the farm**

   Large herd size farms require high investments, both from the owner as well as from the government (in case of subsidies), in facilities and equipment for housing, feeding and manure management which lead often to lower GHG emissions. Table 3 shows that there are many differences in farm practices between small herd size and large herd size farms. The difference in GHG emission between the two groups is most likely caused by differences in milk yield, concentrates/roughage ratio, the distance between dairy farm and fodder crop producer and manure management practices. Literature has already shown (Gerber et al., 2011) that increasing the milk yield per cow will decrease GHG emission per kg FPCM. Increasing the concentrates/roughage ratio can reduce CH_4 emission from enteric fermentation which was the main resource of the whole GHG emission. Reducing the distance between dairy farms and roughage crop producers can decrease GHG emissions caused by energy consumption for feed transport.

Table 3. Comparison between Bottom 25% group and Top 25% group for herd size

Indicators	**Bottom 25% group[a]**	**Top 25% group[a]**
Herd size	<500	>2000
Milk yield per cow	8.0	9.3
Share of adult cows	55.7	54.7
Concentrates/roughage ratio	0.9	1.1
Nitrogen use efficiency	34.9	32.2
Distance between dairy farm and roughage crop producer	2.6	0.5
Manure management[b]	24	12
GHG emission	2.1	1.8

Notes: [a] group names are based on GHG assessment: Bottom 25% means group with highest GHG emission; Top 25% means group with the lowest emission; [b] the grouping method for manure management was expressed in section 6.1 item 7.

2. **Milk production per cow per year**

As mentioned before we know that milk yield per cow has a large impact on GHG emission intensity. Table 4 shows that herd size and milk yield per cow seems to be positively correlated in our sample. This relationship is often found when analyzing data from Chinese dairy farms. It is usually explained by the assumption that animal feeding, health and welfare are better taken care of on larger farms. Herd size seems to be positively correlated with the professional skills of the farm staff.

Table 4. Comparison between Bottom 25% group and Top 25% group for milk yield

Indicators	**Bottom 25% group[a]**	**Top 25% group[a]**
Milk yield per cow	<7	>10
Herd size	1312.2	3045.2
Share of adult cows	54.9	54.2
Concentrates/roughage ratio	1.2	1.1
Nitrogen use efficiency	35.1	34.4
Distance between dairy farm and roughage crop producer	1.3	1.2
Manure management[b]	8	14

GHG emission	2.5	1.6

Notes: [a] group names are based on GHG assessment: Bottom 25% means group with highest GHG emission; Top 25% means group with the lowest emission; [b] the grouping method for manure management was expressed in section 6.1 item 7.

3. **The share of adult cows in the total number of cows**

   Table 5 shows the results for the two extreme groups in the share of adult cows in the total number of cows. In the case of a high share of adult cows, the share of productive animals is higher, so the total emissions will be divided by a higher amount of milk produced, resulting in a lower emission per kg milk. This explains that the nitrogen use efficiency is higher in the high 25% group. The underlying differences in farm management between the two groups that may cause the differences in the share of adult cows most likely have to do with cow care: feeding, health, welfare and fertility. But these reasons cannot be confirmed by the data in table 5. The farms in the Bottom 25% group either keep too much young stock (planning issue) or they need all these young stock animals because the replacement rate of the animals is high. Table 5 shows a difference in the distance between dairy farms and fodder crop producers between the two groups. Whether this is an underlying reason for the differences in the share of adult cows is not clear. It may be a coincidence in the sample that the share of adult cows and the distance between dairy farm and crop producer seems to be related. It is hard to identify a cause-and-effect relationship between these two.

Table 5. Comparison between Bottom 25% group and Top 25% group for share of adult cows in total number of cows

Indicators	Bottom 25% group[a]	Top 25% group[a]
Share of adult cows	<50%	>60%
Herd size	1197.3	1095.6
Milk yield per cow	8.2	8.1
Concentrates/roughage ratio	0.9	1.0
Nitrogen use efficiency	40.3	31.5
Distance between dairy farm and roughage crop producer	2.0	1.4
Manure management[b]	26	26
GHG emission	2.3	1.8

Notes: [a] group names are based on GHG assessment: Bottom 25% means group with highest GHG emission; Top 25% means group with the lowest emission; [b] the grouping method for manure management was expressed in section 6.1 item 7.

4. **Concentrates/roughage ratio**

   Chinese feed experts consider a concentrates/roughage (CR) ratio of 1.5 as the optimal value. Table 6 shows that the GHG emission per kg FPCM is lowest for the Top 25% group with a CR above 1.5. Whether this is related to one of the other indicators in this table is not clear, because of a lack of knowledge about the relationships between all the indicators shown and the GHG emission. Possible reasons for the lower emission of the high CR group are the lower distance between dairy farm and crop producer and the somewhat higher milk production per cow and a higher share of adult cows.

Table 6. Comparison between Bottom 25% group and Top 25% group for concentrates/roughage ratio

Indicators	Bottom 25% group[a]	Top 25% group[a]
Concentrates/roughage ratio	<0.6	>1.5
Herd size	1649.9	2082.3
Milk yield per cow	8.5	8.7
Share of adult cows	0.5	0.6
Nitrogen use efficiency	44.8	24.2
Distance between dairy farm and roughage crop producer	2.1	1.2
Manure management[b]	20	16
GHG emission	2.1	1.8

Notes: [a] group names are based on GHG assessment: Bottom 25% means group with highest GHG emission; Top 25% means group with the lowest emission; [b] the grouping method for manure management was expressed in section 6.1 item 7.

5. **Nitrogen use efficiency**

Nitrogen use efficiency is an indicator of the use of resources. More efficient use of resources is expected to contribute to lower GHG intensity (Table 7). Then the next question is what are the differences in farm conditions between the Top and Bottom groups in Table 7 that cause the difference in nitrogen use efficiency? The indicators that show a higher milk production, which is most likely related to the better management on the larger herd size farm, may be one of the reasons. Apart from that, it may be expected that the choice of the feed ingredients and precision feeding (based on the needs of the animals) are better finetuned on the farm in the Top 25% group. The large difference in concentrates/roughage ratio between the two groups could indicate that the farms in the Bottom 25% group are overfeeding with concentrates with a relative high protein content.

Table 7. Comparison between Bottom 25% group and Top 25% group for nitrogen use efficiency

Indicators	Bottom 25% group[a]	Top 25% group[a]
Nitrogen use efficiency	20%	54.5%
Herd size	1540.4	1955.4
Milk yield per cow	8.4	8.7
Share of adult cows	0.6	0.5
Concentrates/roughage ratio	1.3	0.6
Distance between dairy farm and roughage crop producer	1.3	2.3
Manure management[b]	24	26
GHG emission	2.1	1.8

Notes: [a] group names are based on GHG assessment: Bottom 25% means group with highest GHG emission; Top 25% means group with the lowest emission; [b] the grouping method for manure management was expressed in section 6.1 item 7.

6. **Distance between dairy farm and roughage crop producer**

   The longer the distance between a dairy farm and the fodder crop producer, the more fossil fuels are needed for transport of feed. That is the basic explanation for the difference in GHG intensity between the two groups shown in Table 8. Table 8 shows that many practices differ between the short transport distance dairy farm and the long transport distance dairy farm. The GHG emission for different distances between the dairy farm and the roughage crop producer are affected mostly by herd size, concentrates/roughage ratio and manure management. The large herd size of the high group was related to high milk yield and the large share of adult cows that will also contribute to the high milk yield per cow. This will cause a low GHG emission per kg milk. The concentrates feed resource in China is generally closer than roughage resource since the main roughage (such as alfalfa) is mostly imported from abroad. So, the high concentrates/roughage ratio of the high 25% group will lead to a shorter distance between feed supplier and dairy farmer which causes the low GHG emission.

Table 8. Comparison between Bottom 25% group and Top 25% group for distance between dairy farm and roughage crop producer

Indicators	Bottom 25% group[a]	Top 25% group[a]
Distance between dairy farm and roughage crop producer	3	0.5
Herd size	560.0	2951.3
Milk yield per cow	8.2	8.2
Share of adult cows	0.5	0.6
Concentrates/roughage ratio	0.8	1.1
Nitrogen use efficiency	38.9	31.4
Manure management[b]	30	18
GHG emission	2.1	1.9

Notes: [a] group names are based on GHG assessment: Bottom 25% means group with highest GHG emission; Top 25% means group with the lowest emission; [b] the grouping method for manure management was expressed in section 6.1 item 7.

7. **Manure management indicator**

   The differences in the manure management scores for the two groups shown in Table 9 are caused by the difference in applied practices that were described in paragraph 6.1. These differences also have an impact on the resulting GHG emissions. Apart from these manure management differences, Table 9 shows there are small differences in milk yield, NUE and distance between dairy farm and roughage crop producers.

Table 9. Comparison between Bottom 25% group and Top 25% group for herd size

Indicators	**Bottom 25% group[a]**	**Top 25% group[a]**
Manure management[b]	A farm includes at least two high-emission manure treatments and the treated proportion is more than 30%	A farm includes at least two low-emission manure treatments and the treated proportion is more than 30%
Herd size	1681.0	1381.8
Milk yield per cow	8.3	8.6
Share of adult cows	55.4	55.7
Concentrates/roughage ratio	1.00	0.97
Nitrogen use efficiency	33.0	36.4
Distance between dairy farm and roughage crop producer	1.2	2.3
GHG emission	2.1	1.6

Notes: [a] group names are based on GHG assessment: Bottom 25% means group with highest GHG emission; Top 25% means group with the lowest emission; [b] the grouping method for manure management was expressed in section 6.1 item 7.

6.3. Lessons from mitigation potentials

The differences in farm management between groups of farms based on differences in farm management and applied practices that were presented in 6.2 show the potential to reduce greenhouse gas emissions on Chinese dairy farms. Larger farms perform better for GHG per kg FPCM. They pay more attention to the whole production system, including herd and milking management, calf/heifer management, feed/crop management, environmental risk, milk marketing, and employee/labor-management (Lai et al., 2019; Solano et al., 2006), while small farms lack strong emphasis on herd, feed, manure or energy management areas (Yang et al., 2019). Our findings are strongly supported by other studies where significant potential to reduce GHG is expected in farms and regions with low productivity. Improving productivity through improved herd health, reproductive performance and feed management will result in fewer animals that are needed to produce the same amount of milk combined with using less feed (Thomassen et al., 2009; Bellarby et al., 2013; Herrero et al., 2016).

Our analysis and results show the way to reduce greenhouse gas emissions from Chinese dairy farms. Individual farms can use the results in table 2 to first find out how their GHG emissions differ from the score of best-in-class farms. These differences will be closely related to differences in management practices on the farm. Each farm can compare its own farm practices with peer farms with relatively low GHG emissions to find out what needs to be optimized in management to reduce GHG emissions. The next step is to choose adjustments in farm management practices that match with the needs of the farm and contribute to lower GHG emissions. All farm features presented in Table 2 can be considered: herd management, feed management, manure management, etc.

7. Summary and discussion

7.1. Summary of evaluation

The largest emission source is feed production and processing (31.8%), followed by enteric fermentation (30.0%), manure management (20.8%), energy consumption (9.7%), transport (7.7%) and manure application (7.2%). The carbon footprint is negatively correlated with herd size and milk production per cow per year. There is a big variation in the average carbon footprint across the six main dairy regions of China. South China has the highest carbon footprint, while North China realizes the lowest level. Also, there are differences between regions in the contribution of different emission sources. Feed production and processing is the major contributor to farm GHG in the North China plains and Central and Northwest of China due to the high agricultural material inputs to produce feed. Transport is the main contributor in east and south of China due to the long feed transport distances.

The combination of meeting China's need for milk consumption and the global need to reduce GHG emissions will be a great challenge. The current mean value of the carbon footprint of Chinese milk production is 1.95 kg CO_2-eq kg^{-1} FPCM. But the differences between farms are big: ranging from 0.82 to 5.09 kg CO_2-eq kg^{-1} FPCM on farm level. These data show many Chinese farms with a generally high GHG emission level compared to the level of dairy farms in more developed regions around the world. However, the variety in carbon footprint also demonstrates that there are already low-emission farms in China with CO2-eq levels that are comparable to the world's top-level farms; but at the same time there are some Chinese farms that produce more than fivefold of this top level. This large variety indicates that there is great potential to reduce the carbon footprint of milk production in high emitting farms by applying changes in farm management.

7.2. Lessons learned about GHG in the Chinese dairy sector

Improved technologies in animal management and manure management will be a major factor in supplying the growing milk consumption without increasing GHG emissions. Improving the local dairy production efficiency, manure management, and grassland management, and combining this with the integration of crop and dairy production systems are the big challenges with a lot of potential to reduce GHG. Closing the productivity and efficiency gaps in domestic dairy and feed production, accompanied by dairy production system adjustment, greater utilization of grassland resources along with feed ration improvement and strict milk quality control systems appears to be the most dairy sector promising strategy. This should be guided through governmental policies, mainly focusing on innovations in manure management, feed production and crop-livestock system integration, while also disseminating the experiences from Chinese top dairy farms with excellent herd management to other farms.

The increase in farm productivity and farm-scale combined with the application of matching mitigation options in different regions require policy guidelines should take into account these differences between regions and farms. At the same time changes in feed resources (exploit the feed potential of local agricultural by-products) and feed quality (concentrate and roughage ratio), and manure management (increasing low emission manure handling practices) are needed to achieve significant reduction in greenhouse gases.

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Appendix 1. Survey questionnaire

Investigation Questionnaire on Carbon Footprint Evaluation of Dairy production			
Name of Filler ： Phone number： Name of checker ： Phone number： Date of Form-filling： (Day) (Month) (Year)			
A01 Name of Farm		A04 Legal Representative	
A02 Address of Farm		A05 Person to Contact	
A03 Geographical Coordinates	Longitude: degrees minutes seconds	A06 Contact Phone	
	Latitude: degrees minutes seconds	A07 Annual average temperature	

B In-farm —— Basic Information of Animal Production			
Items	[a] **Number (head/yr)**	[b] **Average Weigh (t kg/head)**	[c] **Weight Gain (kg/ day)**
B01 Total Number of Dairy		——	——
B02 Calves (0-6 months)			
B03 Bred Cattle (7month-first match)			
B04 Backup Cattle (First match-delivery)			
B05 Lactating Cows			
B06 Dry Cows			
B07 Bull Calf			——
B08 Eliminated Cows			——

Information of Milk Production					
B09 Total Milk Yield (ton/yr)		B10 Milk Yield (kg/head/day)		B11 Yield (t/head)	
B12 Lactation Days (day)		B13 Content of Milk Protein (%)		B14 Content of Milk Fat (%)	

C In-farm —— Information of Feed Intake				
C01Whether it is TMR?		① Yes ② No		
Feed Category	**Feed Types**	**[a] Intake (t/yr)**	**[c] Source of Feed (Country - province - city)**	**[d] Transportation Distance (km)**
	C0201 Whole-plant of Corn Silage			
	C0202 Whole-plant of Corn Yellow Silage			
	C0203 Herbage Silage			
	C0204 Wheat Silage			
	C0205 Alfalfa Silage			
	C0206 Imported Alfalfa			
	C0207 Domestic Alfalfa			
C02 Fodder	C0208 Leymus Chinensis			
	C0209 Oat Grass			
	C0210 Ryegrass			
	C0211 Corn Straw			
	C0212 Rice Straw			
	C0213 Wheat Straw			
	C0214 Peanut Seedling			
	C0215 Melon Seedlings			
	C0216 Bagasse			
	C0217 Cottonseed			

	C0218 Other Fodder			
C03 Concentrated Feed	C0301 Corn Grain			
	C0302 Wheat Grain			
	C0303 Soybean			
	C0304 Bran			
	C0305 Soybean Meal			
	C0306 Cottonseed Meal			
	C0307 Sugarbeet Meal			
	C0308 Full Price Concentrated Feed			
	C0309 Premixed Concentrate			
	C0310 Other Concentrates			

D In-farm —— Energy Use

Energy Type	D01 Electric (kwh/yr)	D02 Coal (t/yr)	D03 Diesel (L/yr)	D04 Gasoline (L/yr)	D05 Water (L/yr)

E In-farm —— Manure Management

E01 Feces (t/yr)		E02 Urine (t/yr)		E03 Sewage t/yr	
E04 Have Bedding or Not	① Yes ② No	E05 Have Playground or Not?	① Yes ② No	E06 Padding Material	①Sand ② Sawdust and rice husk ③ Rubber ④Dry manure ⑤ Cement bed
E07 Floor Types	① Solid floor ② Half leakage ③ Full leakage ④ Other ( )				
E08 Manure Collection Pattern	① Gan Qing Fen ② Scraper Dry Cleaning ③ Forklift Dry Cleaning ④ Water Flushing ⑤ Dung Absorbing Truck ⑥ Other ( )				

Management Technique (Note: Fill in E09-E10 with Gan Qingfen and solid-liquid	**Unit**	**E09 Percent of Solid Manure**	**E10 Percent of Liquid Waste**	**E11 Percent of Slurry**

separation treatment； Other treatment fill in E11)				
01 Grass land	%			
02 Daily spread	%			
03 Solid storage	%			
04 Dry lot (open confinement area without significant vegetative cover)	%			
05 Composting (in-vessel)	%			
06 Composting (natural aeration windrow)	%			
07 Composting（static pile）	%			
08 Composting（forced aeration windrow）	%			
09 Cattle deep bedding	%			
10 Aerobic treatment	%			
11 Anaerobic lagoon	%			
12 Anaerobic digester	%			
13 Liquid/slurry stored in tanks or earthen ponds outside animal housing	%			
14 Pit storage below animal confinements	%			

E24 Utilization Ratio of Urine and Sewage	①Slurry Land use__% ② Biogas slurry returning__% ③ Liquid Organic Fertilizer Production in-farm__% ④Recycling in-farm__% ⑤ Delegation processing__% ⑥Standard Discharge__% ⑦ Discharge__% ⑧ Fish pond culture__% ⑨Other ( )
E25 Utilization Ratio of Manure	①Farmyard Manure__% ②Composting in-farm__% ③ Biogas Residue Returning__% ④Reuse as bedding__% ⑤ Cultivation Substrate__% ⑥ As Fuel__% ⑦ Delegation processing__% ⑧ Fish pond culture__% ⑨Discharge out-farm ⑩Other ( )
E26 Dead Animal Treatment	① Chemical treatment ② Incineration ③ Biodegradation ④ Deep Burial ⑤ Composting ⑥ Centralized Processing ⑦ Other ( )

G On-farm----Cost-benefit analysis

G01 Costs	**Unit**	**a**	**G02 Incomes**	**Unit**	**b**	**G03 Benefit**	**Unit**	**c**
G0101 Total investment	10 thousand RMB		G0201 Raw milk price	RMB /kg		G0301 Annual net profit	10 thousand RMB /yr	
G0102 Annual operating cost	10 thousand RMB /yr		G0202 Bull price	RMB/head		G0302 Net profit per head	RMB/head	
G0103 Total cost per head	RMB/head		G0203 Elimination of cow prices	RMB/head				
G0104 Material and service costs	RMB/head		G0204 Sold price of manure	RMB/ton				
G0105 Feed and processing costs	RMB/head		G0205 Income from biogas project	10 thousand RMB /yr				
G0106 Medical quarantine costs	RMB/head		G0206 Income from composting	10 thousand RMB /yr				
G0107 Death loss costs	RMB/head		G0207 Cropping income	10 thousand RMB /yr				

G0108 Technical service costs	RMB/head		G0208 Subsidies	10 thousand RMB /yr		
G0109 Water costs	RMB/head					
G0110 Fuel and power costs (gasoline, diesel, coal, electricity, etc.)	RMB/head					
G0111 Other costs	RMB/head					
G0112 Depreciation of fixed assets	RMB/head					
G0113 Insurance costs	RMB/head					
G0114 Labor costs	RMB/head					
G0115 Land costs	RMB/head					

C04 Annex: Feed formula						
Feed Category	**Feed Types**	**a Calves**	**b Bred Cattle**	**c Backup Cattle**	**d Lactating Cows**	**e Dry Cows**
C041 Fodder (kg/head/day)	C04101 Whole-plant of Corn Silage					
	C04102 Whole-plant of Corn Yellow Silage					
	C04103 Herbage Silage					
	C04104 Wheat Silage					
	C04105 Alfalfa Silage					
	C04106 Imported Alfalfa					
	C04107 Domestic Alfalfa					
	C04108 Leymus Chinensis					
	C04109 Oat Grass					
	C04110 Ryegrass					
	C04111 Maize Straw					

	C04112 Rice Straw					
	C04113 Wheat Straw					
	C04114 Peanut Seedling					
	C04115 Melon Seedlings					
	C04116 Bagasse					
	C04117 Cottonseed					
	C04118 Other Fodder					
C042 Concentrated Feed (kg/head/day)	C04201 Corn Grain					
	C04202 Wheat Grain					
	C04203Soybean					
	C04204 Bran					
	C04205 Soybean Meal					
	C04206 Cottonseed Meal					
	C04207 Sugar beet Meal					
	C04208 Full Price Concentrated Feed					
	C04209 Premixed Concentrate					
	C04210 Other Concentrates					

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