Guide to mitigation options to reduce greenhouse gas emissions in Chinese dairy sector

Working Paper No. 382

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

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Abstract

Livestock emissions from dairy farms contribute to global warming. To mitigate this impact, dairy farms can consider and implement mitigation options. The objective of this report is to give an overview of mitigation options that can be applied on large scale Chinese dairy farms to reduce the emission of the greenhouse gases methane, nitrous oxide and carbon dioxide. This report is expected to support researchers, farm advisors, policy advisors, farm managers and dairy chain stakeholders to become informed about the characteristics of mitigation options and their potential to contribute to the reduction of greenhouse gas emissions from dairy farms.

The report contains descriptions of 27 mitigation options divided into seven main domains in the reduction of greenhouse gases on dairy farms. The first group of options is about herd management and deals with animal health, idle cows, raising young stock, age at first calving, transition period and genetic selection. The second group is about crop production and contains options about fertilization and crop yields. The third domain is feeding and feed management that describes options on precision feeding, adjusted diets, feed additives and providing water. Domain number four is about stable characteristics: cooling against heat stress, manure collection and open-air playgrounds for cattle. The fifth group is about manure management containing mitigation options on manure storage, cover lagoon, acidification, anaerobic digestion, composting and manure application. Group six focuses on energy management: saving energy and the production of renewable energy. The seventh and last domain is carbon sequestration in soils.

For each of the mitigation options we have strived to provide information about these aspects: technical principles, technical considerations relevant to implementation, advantages and disadvantages, mitigation potential and references. All this collected information is presented in a separate paragraph for each mitigation option. These paragraphs can be seen as factsheets that can be read independently from each other.

Key words

Agriculture; greenhouse gases; dairy farm; mitigation options; sustainable agriculture

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Contents

Editor’s preface

This report is a result of the project “Piloting and scaling of low emission development in large scale dairy farms in China”. This project was funded by the CGIAR research program on Climate Change, Agriculture and Food Security (CCAFS). It was executed by the Institute of Environment and Sustainable Development in Agriculture (IEDA), that is part of the Chinese Academy of Agricultural Sciences (CAAS), by the College of Animal Science and Technology that is part of the China Agricultural University (CAU) and by Wageningen University and Research (WUR). In this project researchers from these institutes have collaborated on developing tools and best practices on farms to reduce greenhouse gas emissions from the large-scale dairy sector in China. This report is one of the results of the collaboration between the three participating institutes. It is the result of a three-years period during which we gradually collected more detailed information about mitigation options to reduce greenhouse gas emissions on Chinese dairy farms. The shared expertise of all the three institutes created wonderful opportunities to collect research results on many mitigation options and to describe the results in a way that is tailor made for Chinese dairy farms.

Abbreviations

ADF	Acid detergent fiber
BW	Body weight
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CP	Crude protein
DCD	Dicyandiamide (nitrification inhibitor)
DDGS	Dried distiller's grain with soluble
DE	Digestible energy
DM	Dry matter
DMI	Dry matter intake
ECM	Energy corrected milk
FPCM	Fat and protein-corrected milk
GE	Gross energy
GHG	Greenhouse gas (in this document, GHG refers to CO_2, CH_4 and N_2O)
GWP	Global warming potential
LCA	Life cycle assessment
ME	Metabolizable energy
Mt	Million tons
N	Nitrogen
NDF	Neutral detergent fiber
NEB	Negative energy balance

NFC	Non-fiber carbohydrates
NH_3	Ammonia
N_2O	Nitrous oxide
OM	Organic matter
P	Phosphorus
SOC	Soil organic carbon
SOM	Soil organic matter
TMR	Total mixed ration
VFA	Volatile fatty acids
VOC	Volatile organic compounds
Y_m	CH_4 energy emitted as percent of GE ingested

Introduction mitigation options and readers guide

Objectives and context

Livestock emissions contribute to global warming. To mitigate this impact from the Chinese dairy sector we have collected and selected options that can be applied on farm level to reduce the emission of greenhouse gases (GHG). The relevant GHG on farm level are carbon dioxide CO_2, methane (CH_4), and nitrous oxide (N_2O). The objective of this report is first of all to create more awareness amongst researchers, consultants and other stakeholders within the dairy sector about ways to reduce GHG. This report contains 27 of these options that can be applied by farm managers to reduce GHG emissions on the dairy farm. The second objective is to list qualitative as well as quantitative information about these mitigation options to support the actors in understanding the feasibility of the different mitigation options as well as the expected reduction in GHG they may deliver. This information is available for most of the mitigation options, but not for all. The users can use this information to apply mitigation options in a more tailored way.

For all mitigation options we have strived to provide information about these aspects:

- Technical principles
- Technical considerations relevant to implementation
- Advantages and disadvantages
- Mitigation potential
- References

Not all aspects could be filled for all the mitigation options. This is why this information is sometimes lacking.

Reader’s guide

This report is in fact a collection of fact sheets about mitigation options containing for every option the information of the aspects mentioned above. The mitigation options are group in seven main categories that reflect the main domains in managing GHG on dairy farms:

1. Herd management

2. Crop production

3. Feeding and feed management
4. Stable
5. Manure management
6. Energy management
7. Carbon sequestration

The above numbers are also the chapter numbers in this report. Within every chapter you will find multiple mitigation options. Chapter 7 only has one. All mitigation options that are presented in separate paragraphs within the seven chapters can be read as a stand-alone fact sheet about that option.

1. Herd management

Increasing herd and animal efficiency can be achieved by improving herd and animal health management, extending the productive life of animals, and improving reproduction rates to reduce the number of animals kept for herd maintenance rather than production. Reducing the prevalence of common diseases and parasites would generally reduce emissions intensity as healthier animals are more productive, and thus produce lower emissions per unit of output. However, the mitigation potential from health interventions remains poorly quantified, largely due to limited disease statistics and barriers to the adoption of existing disease control mechanisms.

1.1. Improve health management

Marion de Vries and Sha Wei

1.1.1 Technical principles

Livestock health is an important aspect of animal welfare, food safety, human health, and production efficiency. Healthy animals are more productive and hence more efficient in using the offered feed and other inputs and care to generate the desired products. Unhealthy animals tend to have a lower milk yield, growth, fertility and longevity, resulting in higher emissions per unit of animal product. The most common dairy health issues include clinical and subclinical mastitis, foot lesions, ketosis, calf diarrhea, and calf pneumonia. Improving animal health can thus reduce emissions per unit of animal product, while also improving productivity, with important positive consequences for food security, farmer income, animal welfare, food safety and public health.

1.1.2 Technical considerations relevant to implementation

The impact of health improvements on GHG emissions and economic performance depends on the farm-specific prevalence of diseases, pathogen type, farm management, and prices (e.g., milk and feed).

1.1.3 Advantages and disadvantages

Diseases in dairy cows can result in lower milk production and poorer reproductive performance and longevity. It also leads to increased GHG emissions, poorer animal welfare, and reduced income of farmers due to reduced milk yields, more discarded milk, treatment costs, a prolonged calving interval, and removal (culling or dying) of cows. Particularly the reduction in milk yield has high impact on economic performance, whereas cow removal and discarded milk have a high impact on GHG emissions (Mostert, 2018).

1.1.4 Mitigation potential

The magnitude of impact varies per type of health disorder (ADAS, 2015). For some diseases, increases in GHG emission intensity of cows have been quantified:
Subclinical ketosis: 21 kg CO_2eq/t FPCM (2.3%) per case (Mostert et al., 2018a)

- Subclinical mastitis: 3.7% per case (Gülzari et al., 2018)
- Clinical mastitis: 58 kg CO_2eq/t FPCM (6.2%) per case (Mostert et al., 2019)
- Digital dermatitis: 4 kg CO_2eq/t FPCM (0.4%) per case (Mostert et al., 2018b),
- White line disease: 39 kg CO_2eq/ t FPCM (4.3%) per case (Mostert et al., 2018b),
- Sole ulcer: increase 33 kg CO_2eq/ t FPCM (3.6%) per case (Mostert et al., 2018b),
- Heat stress abatement did not have significant impact on GHG EI in a study in Austria (Herzog and Winckler, 2021), but more impact is expected in case of higher average temperatures and when in reproductive performance and culling rate are included in analysis.

At population level, impact depends on the country-specific prevalence of diseases. For example, combined effects of ketosis, mastitis, and foot lesions were estimated to increase GHG emissions of the Dutch herd population by 0.37 Mton CO_2eq/ year (i.e., about 3.4% of total sector emissions; Mostert, 2018). A higher impact will be reached when other diseases are included as well, but to our knowledge quantitative effects have not yet been investigated (e.g., displaced abomasum, metritis, subacute ruminal acidosis).

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1.2. Remove idle cows

Wei Wang, Marion de Vries and Jelle Zijlstra

1.2.1 Technical principles

Idle cows refer to low-productive or unproductive animals in a herd. Removing idle animals is a direct and simple approach because it can reduce the emission intensity (Ei) through reducing the number of animals in a herd while maintaining the performance (kg of milk produced) of the whole herd.

1.2.2. Technical considerations relevant to implementation

Rearing idle cows in a herd means extra feed purchases and increased density of the animal housing. Therefore, identifying the low-productive animals should consider 1) the genetic potential of an animal (in case of young stock); 2) the real production of the animal in former lactations, 3) the expected future production. Therefore, keep good records on each cow's production would be useful when making decisions. General guidelines for culling can be helpful to reduce the number of low productive cows in the herd and to increase profitability.

1.2.3 Advantages and disadvantages

A relative high share of non-productive or low productive animals in the herd is often observed on smallholder farms where cows also are kept for other reasons as just milk or beef production. E.g., cows can be kept for savings.

1.2.4 Mitigation potential

Since this report is focusing on large scale dairy farms in China with relative high milk production per cow levels, the issue of idle cows is not very common. For this reason, we do not elaborate this topic. The impact of removing idle cows has overlap with some other mitigation options: improve health management, improve longevity and mitigation options related to feeding.

1.3. Increase longevity

Jelle Zijlstra

1.3.1 Technical principles

Longevity here stands for the productive lifespan of dairy cows. Longer living dairy cows will reduce the culling rate of the herd and result in lower GHG emissions because of less young animals that have to replace culled cows. A substantial amount of GHG emissions is produced during the period between birth and first calving. The GHG emissions for this period are allocated to the produced milk. By keeping dairy cows for a longer period in herd, less calves have to be grown and subsequently the GHG emissions will reduce. Next to that: a dairy herd with a higher average age will have a higher average milk production because of a lower share of first-calf dairy cows. The group of first-calf dairy cows usually has a lower milk production than older cows. The higher milk production per cow will in general reduce the emission per kg milk.

A higher longevity of the dairy herd can be achieved in many ways. These are the main factors that determine the longevity performance of a dairy farm:

- **Animal health and welfare**
  Improvement of the health status will result in less cows with diseases. Mastitis, leg and claw problems and fertility are important reasons for culling cows on dairy farms. More emphasize on prevention of diseases, early warning and successful medication are ways to improve animal health and welfare. Housing of animals with due consideration of animal welfare conditions will usually pay off in longevity. Soft bedding, enough eating space and dry floors are some of the requirements to offer welfare to the animals.
- **Feeding**
  Balanced rations and high-quality feed are important underlying factors to achieve healthy cows.
- **Rearing young stock**
  Successful young stock rearing requires quality feed and attention to health and welfare. This will result in a high growth rate of the young stock resulting in a dairy cow with a higher potential for a high life span and high lifetime production.

- **Breeding for longevity**

  In more and more countries breeding values for longevity are available and offer an extra opportunity to improve this indicator.

1.3.2 Technical considerations relevant to implementation

Improving longevity works best if a combination of the above-mentioned measures is taken. A farm assessment for the factors mentioned above can show the most limiting factors to improve longevity.

1.3.3 Advantages and disadvantages

A higher longevity will lead to higher revenues form milk sales because of the higher average age of the cows. The costs of rearing young stock will be reduced. The overall profitability will be improved.

Less young stock rearing on a dairy farm because of a higher longevity will result in more young calves available for meat production and less meat coming from cull cows. When ultimately this would lead to less meat production from animals originating from dairy farms, it could lead to an increase in meat production from other animal meat producing sectors when the demand for meat will be unchanged. Therefore, benefits of extended lifespan of dairy cattle may be limited when culled cows play an important role in beef production.

All the knowledge to increase is internationally available. It may require extra skills from dairy farm workers and managers to adopt management practices in favor of a longer cow life. Improvement of animal welfare may require investments in housing: optimal cubicle size, implement soft bedding in cubicles, more m^2 per animal, better ventilation, more feeding space per cow, etc.

1.3.4 Mitigation potential

Productivity and economic benefits will likely remain the main drivers for improved animal health. However, making the link between animal health status and GHG emissions intensity more explicit could help re-direct and coordinate resources from agriculture, development, food security and climate change perspectives.

Based on literature evaluated by De Vries et. al. 2018. the reduction on Dutch farms is estimated to be:

- 10-20 g CO_2-eq per kg FPCM for every extra year life span of cows
- 1.4 % reduction on farm level (based on average emission in The Netherlands of 1100 g CO_2-eq per kg FPCM)

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1.4. Optimize young stock management

Wei Wang and Marion de Vries

1.4.1 Technical principles

Healthy heifers are the fundament of productive dairy cattle. Good management and feeding of heifers can ensure optimal growth prior to first calving and help reducing calving difficulties and stillbirths.

1.4.2 Technical considerations relevant to implementation

Key factors to good young stock management include aspects of animal health, housing, feed ration meeting nutritional needs in different growth stages, and mating management. To reduce the calf mortality rate, the following measures can be taken:

- Feeding pregnant cows according to their feed needs.
- Feeding minerals to dry cows during the last eight weeks of pregnancy.
- Vaccination against scours.
- Implement hygiene plan.
- Feeding colostrum as fast as possible after birth.

1.4.3 Advantages and disadvantages

A well-managed young stock rearing system results in improved animal performance, minimal disease and mortality, optimum growth rates to achieve target live weights (important for milk production and fertility, and to minimize calving difficulties), and lower costs of inputs (e.g., feed, animal health costs, etc.). Proper development of the heifers reduces age at first calving and increases productivity and longevity of the mature cow. In addition, a lower survival rate of heifers implies reduced beef output (Zehetmeijer et al., 2014. and less opportunity for genetic improvement in the herd: when a heifer dies, there are fewer opportunities to replace unprofitable cows in the herd (Moran, 2009).

1.4.4 Mitigation potential

To our knowledge integral and direct effects of improved young stock management on GHG emissions of dairy production have not been investigated. Soberon et al. 2012. found that an increase in preweaning growth of young calves was significantly correlated with milk production in the first lactation. Every 100 gram of extra preweaning daily growth delivered between 85 and 111 kg of extra milk in the first lactation. Knowing that extra milk per cow per year results in reduction of the emission intensity, it will be clear that better young stock care will contribute to a decrease in GHG emission. Meanwhile, a low survival rate of heifers is expected to have a significant effect on increase of GHG emissions because of rearing emissions and omitted beef and milk output. In beef cattle systems, reducing calf mortality have shown to reduce emission intensity by 3% (Samsonstuen et al., 2020), but obviously these systems (thus mitigation potential) differ from dairy production systems.

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1.5. Decrease age at first calving

Wei Wang

1.5.1 Technical principles

Reducing age at first calving can save the energy required during the young stock period then reduces the unproductive period of a cow and therefore contributes to the mitigation of GHG.

1.5.2 Technical considerations relevant to implementation

Young stock should have a certain weight before they are recommended to be inseminated. In the Netherlands the recommendation is to inseminate at a live weight of heifers of about 360 kg. The objective is to reach this weight at an age of 14 months, so that is also the time to start with insemination. This will lead to an average age at first calving of about 24 months. In case of a reduced growth rate of the young stock the stage of 360 kg will be reached at a higher age of the heifer, and this will in turn lead to a higher age at first calving. So, aiming at a lower age at first calving starts with better feeding practices that will improve the growth rate of young stock. Clear goals for growth rate as well as the target weight at first insemination are basics of young stock management. Once started with inseminating heat detection and the number of inseminations needed to get heifers pregnant are the next determining factor for age at first calving.

1.5.3 Advantages and disadvantages

Reduction of the age at first calving requires good quality feed and skilled farm staff to work with feeding schemes that are aiming at live weight targets at a certain age of the heifers. Weighing cows (or alternative: measuring height that is correlated to weight) is a precondition to monitor growth rate and to make sure that insemination is started at right weight.

Reducing the age at first calving is in general considered as an option that contributes to profitability. The main reasons for this are more productive days during the cow’s life span.

1.5.4 Mitigation potential

According to research from Dal-Orsoletta. 2019, decreasing the age at first calving to two-year old could mitigate GHG emissions by 8-10%.

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Dall-Orsoletta, A.C., et al. 2019. A quantitative description of the effect of breed, first calving age and feeding strategy on dairy systems enteric methane emission. *Livestock Science*, 224: p. 87-95.

1.6. Optimize transition period

Wei Wang

1.6.1 Technical principles

Transition period from gestation to lactation is one of the most challenging periods in dairy cattle management. Poor status at transition period could lead to high incidences of metabolic and infectious diseases such as ketosis, milk fever, displaced abomasum, etc., and results in high culling rate, mortality and loss of production in this reproductive cycle or even the lifetime production.

1.6.2 Technical considerations relevant to implementation

Good management in transition period can decrease the morbidity and involuntary culling rate. This requires the best quality of feed and extra careful attention to the metabolic status of cows. To improve the health of transition cow, the following points should be considered:

- Make sure the body condition score should between 3 to 3.25 (scale 1-5).
- Check the urine pH to confirm the calcium status of cows at calving and evaluate the necessity of supplementing anionic salts in the transition diet or providing low calcium diet, to avoid milk fever.
- Minimize heat stress.
- Supplementing yeast or rumen protected choline to enhance the rumen fermentation.
- Provide good quality and sufficient amount of roughage.
- Keep certain amount of DMI before and right after calving.
- Keep a clean and dry environment during calving.

1.6.3 Advantages and disadvantages

The transition period is extremely important in ensuring future health, milk production, and reproductive success of the dairy cow. Maintaining proper rations and management practices before calving are critical to how well the cow performs in the early lactation period and even the whole lifetime.

1.6.4 Mitigation potential

If ketosis occurred during the transition period, the GHG emission intensity of cows can be increased by 21 kg CO_2-eq per kg FPCM (2.3%) per case (Mostert et al., 2018a). Therefore, a well-managed transition period can help avoid this potential emission. Besides this, optimizing the transition period implies a systematic improvement of the health and longevity of cows, the potential on GHG emission should be substantial.

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1.7. Genetics: direct selection on low enteric CH_4

Michael Aldridge

1.7.1 Technical principles

Direct selection for lower methane production is still in the development stage. The small amount of direct selection at the moment is under experimental conditions and until recently has been based on high and low samples. Direct selection for traits facilitates the greatest potential in genetic gain. However, before this can be achieved there are still some gaps that need to be filled including the genetic relationship with other important traits, a cheap and easy method of large-scale recording, and enough animals have to be phenotyped.

1.7.2 Technical principles

For direct selection to be effective you need to record the trait of interest, or you need a good indicator of the trait. There is still debate in the literature about which will be the most effective trait to reduce methane production. Here the assumption is methane production as g CH_4 / cow / day would be most effective.

There are a number of methods that can be used to measure methane production. However, they are not suitable for animal breeding purposes which requires large numbers of animals to be phenotyped. The most accurate measurements would be with respiration chambers, but they are expensive, require a large amount of labor, are stressful for the cows, and have a very low throughput. For similar reasons, other methods that have been suggested for breeding are still limited, including: SF_6 (a halter and harness are attached to a cow which measures methane with sulphur hexafluoride tracers) and systems like GreenFeed (using infrared sensors and environmental measurements; the manufacturer C-Lock Inc., USA, recommends only a maximum of 25 cows should be measured by one unit, and to record for a minimum of 7 days). There are currently no products that record methane production that allow for large scale recording and are cost effective. Perhaps as the technology matures this will change but in the meantime researchers and industry have been exploring infrared spectroscopy or ‘sniffers’.

Sniffers allow for large scale and continuous recording, but the disadvantage is they do not record the air flux which limits the measurements to methane concentration (ppm). The correlation between methane production and methane concentration is high (between 0.51 and 0.96) and is currently the best candidate as an indicator trait for direct selection. It is now a matter of recording methane concentration on enough cows, to estimate the required parameter estimates of heritability, repeatability, genetic and phenotypic correlations, which can then be used to estimate breeding values and be incorporated in a selection index. Current estimates indicate a low to moderate heritability (0.12 to 0.45) and unfavorable correlations with production traits and methane intensity. This does not mean we can’t select for higher productivity and lower methane production. It just means the progress will be slower.

1.7.3 Technical considerations relevant to implementation

Mentioned several times now is the need to record methane on enough individual cows. It is common practice that before a trait can be included in a selection index, the reliability of prediction should be above 0.40. Using the literature means of the currently available parameter estimates it is predicted that measurements on approximately 20,000 cows would be required. This also assumes that all cows are genotyped (de Haas et al. accepted 2021). Assuming an average herd size of 150 cows, this target could be achieved in two years with 100 farms. While this would provide confidence in including the trait in a selection index, the measurements could be used by individuals to benchmark and rank their animals sooner resulting in some progress.

Selection for lower methane production will only have an economic impact if there is a large, desired gain or a high carbon price. Also of note, is that with higher carbon prices the weight placed on methane in a selection index will be greater and the rate of genetic gain will increase.

Selection should not be made only on methane production due to the unfavorable correlation with other traits. Therefore, if too much weight is placed on reducing methane, other traits such as milk production will decrease in genetic gain.

1.7.4 Advantage and disadvantage

The largest issue currently faced with direct selection, is that it is still an early adoption trait. That means the technology required for measuring individual methane is still expensive and still needs large scale investment to be able to record on enough cows. That means there is still no dairy population in the world that has enough phenotypic records and genotyped animals that would allow breeding values to be estimated with a high enough accuracy. Recent literature has shown that methane production is heritable and the required genetic and phenotypic correlations with other production traits are starting to be estimated. However, before methane can be included in a selection index the correlation matrix needs to be completed.

1.7.5 Mitigation potential

One of the benefits with genetic selection is that the methane reduction made is cumulative and permanent. Direct selection can be used to maintain the current production of methane per cow, which means the undesired increase in methane production from the indirect selection would be offset, while still improving methane intensity and methane yield. To achieve the highest rates of genetic gain and to actually reduce methane production, an economic value from a carbon price or desired gain needs to be included.

Selection indexes are specific to their production systems and the potential methane mitigation from direct selection is highly dependent on the economic values used. With no economic value placed on methane, genetic gain for methane production will continue to increase (González-Recio et al. 2020). It is possible to fix the current methane production and have no change, while still increasing milk production and thereby improving methane intensity by between 17% to 19% by 2050. With strong active selection for a reduction of 5.79 g/day each year, milk production could still be increased, and selection intensity improved by 21 to 24% by 2050. The theoretical maximum that methane could be reduced each year (based on the Dutch dairy population) is 12.75 g/day, but this would result in lowering milk production per cow per day (de Haas et al. accepted 2021).

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1.8. Genetics: indirect selection by selection on milk production and feed efficiency

Michael Aldridge

It is highly likely that dairy farms in China and around the world are already mitigating methane with indirect selection on this trait and that farmers are unaware of this way to reduce methane emission. Indirect selection can reduce methane in one out of two ways, (1) using traits that can reduce methane intensity, methane yield, or residual methane production, or (2) using traits that are easier to measure as an indicator of total methane production (g or L CH_4 / day). In this paragraph, only way 1 will be considered. Way 2 is easier to explain in the context of direct selection (described previously in paragraph 1.7).

1.8.1 Technical principles

Selection for traits that increase production efficiency will reduce the amount of methane produced per kg of milk (g CH_4 / kg milk, methane intensity) or per kg of feed intake (g CH_4 / kg DMI, methane yield). The two most obvious traits that increase efficiency are milk production and feed efficiency, and others can include health and fertility traits.

The easiest trait for breeding that would reduce methane emissions selection is milk yield. It is a relatively easy trait to measure and is highly economically important. The main reason for methane mitigation with increasing milk production is because fewer cows are required to produce the same amount of milk. If the herd size is maintained or increased, total methane production will still increase but the methane intensity of the milk will decrease.

Selecting for improved feed efficiency also mitigates methane. By selecting for improved feed efficiency, the same amount of milk can be produced with less feed thereby decreasing the methane yield (g CH_4 / kg DMI).

Selecting for health and fertility traits are beneficial because they also improve the efficiency of the dairy. They help to achieve the maximum milk production and feed efficiency and thereby help to reduce methane intensity and methane yield but to a lesser degree than milk yield or feed efficiency.

1.8.2 Technical considerations relevant to implementation

An important point to consider about improving animal breeding is that selection is almost never made for only one single trait. The reason for this is that milk production and feed efficiency traits tend to have unfavorable genetic correlations with other important traits. This was observed with the historically heavy selection on milk yield which resulted in a reduction in fertility and health traits. Recent selection experiments on sheep in New Zealand have shown that the rumen of animals selected exclusively for lower methane have smaller rumens, it is not yet clear if this will cause other issues or if there could be other unintended consequences (Bain et al., 2013). It is for this reason that breeders use selection indexes and breeding goals with multiple objectives, therefore the traits mentioned should be included as part of a breeding objective that is not designed only for methane mitigation.

To make selection decisions accurate estimated breeding values are required. The models used require pedigree and/or genomic information, and a suitable number of animals need to be phenotyped. It is standard practice, and it is relatively easy to collect the required milk production information. Feed efficiency traits though are not as simple and harder to implement. The feed traits require the feed provided and the remaining feed to be weighed for each individual animal, which requires a significant amount of time and infrastructure investment.

1.8.3 Advantage and disadvantage

The traits mentioned for indirect selection are not targeted at their methane mitigation potential. Indeed, they are used because they are very important economic traits. They increase net income by providing more milk, lower feed costs, fewer replacement cows, fewer treatment costs and reduce dry periods.

Indirect selection for components of methane intensity and methane yield will help limit the amount of methane produced per unit of production. Methane intensity, methane yield, milk production, and feed efficiency are unfavorably positively genetically correlated with methane production. So, the amount of methane produced per kg of milk or feed is decreased, but individual cows will produce more methane (unless methane production is selected for directly).

1.8.4 Mitigation potential

Results from selection indexes are specific to the production system, the defined breeding goal, and the economic value or weight given to traits. To achieve the highest rates of gain an economic value or desired gain should be added to methane production. Recently researchers have been using the current indexes to determine what effect indirect selection has had on methane production. Without intervention methane production is expected to increase each year by approximately 0.32% or 1.5g CH_4/cow/day, while methane intensity is expected to decrease by 0.43%. Maintaining current selection indexes until 2050 would decrease methane intensity by approximately 13% (Zhang et al. 2019; de Haas et al. accepted 2021).

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2. Crop production

Crop production (sometimes also called fodder production) includes the crop planting and processing processes on the farm. The emissions from crop planting and processing include CO_2 emissions from the production of N, P, and K fertilizers, direct and indirect N_2O emissions from the application of N fertilizer during planting; CO_2 emissions from the decomposition of urea in N fertilizer, CO_2 emissions from the production of agricultural film and pesticides, CO_2 emissions from diesel oil and power consumption for mechanical planting and irrigation, and CO_2 emissions from the transportation of agricultural materials such as feeds and fertilizers. Among the emission sources, the direct and indirect N_2O emission sourcing from the land application of N fertilizer and the CO_2 emission sourcing from fertilizer production were the two most important contributors of GHG emissions for the feed production process, occupying 49.5% and 17.9% of the total emissions, respectively, based on a LCA case in an intensive Chinese dairy farm in Shandong Province (Huang, 2015). Therefore, the GHG mitigation in feed production process should be targeted at reducing the N_2O emission from N fertilization and reducing the amount of the fertilizer can also contribute much to the GHG mitigation.

2.1. Optimize fertilization efficiency

Yue Wang and Sha Wei

2.1.1 Technical principles

It's a quite severe issue that fertilizer was highly overused in China. The degree of overfertilization of rice, wheat and maize in China (the three main crops in China) were respectively 43.5%, 34.6% and 32.8% (Kong et al., 2018). The high overuse not only leads to a substantial waste of the resources, but also causes high N_2O emission. It's reported that when nitrogen application exceeds the optimal application rates of maize and wheat, cumulative and unit yield N_2O emissions increase exponentially (Song et al., 2018). Meanwhile, excessive nitrogen fertilization also causes other severe environment issues, including NH_3 emission, which induced lake eutrophication, soil acidification, and air pollution. Optimization of the fertilization efficiency and reducing the excessive use of chemical fertilizer is therefore a priority in feed production. Soil testing and formula fertilization technology was proposed to solve the problem. The core of soil testing and formula fertilization technology is to adjust and solve the contradiction between crop fertilizer demand and soil fertilizer supply. The fertilization should match with the fertilizer demand of the crop taking into account the soil fertilizer supply performance, fertilizer effect, the given application of organic fertilizer. It should also dictate the right application quantity, right application period and right application method of nitrogen, phosphorus, potassium fertilizer, and addition of necessary mineral and trace elements based on soil test and fertilizer field experiment. At the same time, the nutrition elements needed by crops should be supplemented in a targeted way, which means the crops should supplement what elements they lack and how much they need to supplement, so as to realize the balanced supply of various nutrients and meet the needs of crops. The purpose is to increase the fertilizer utilization rate and the reduce fertilizer consumption, combined with the appropriate application way. Meanwhile, for reducing the fertilizer consumption, planting catch crops like clover can also reduce the use of synthetic fertilizers.

2.1.2 Technical considerations relevant to implementation

The soil testing and formula fertilization technology including the following processes:

- **Soil testing**

  Select the sampling area based on the whole crop planting region and collect enough soil samples; analyze the organic matter, total nitrogen, hydrolyzed nitrogen, available phosphorus, slow-acting potassium, quick-acting potassium, and medium and trace elements of the sampled soil, and thus providing basic data for formulating the appropriate fertilizer and field fertilizer experiments.
- **Fertilizer formulation**

  Design field fertilizer plot experiments with different fertilizer dosages, and different ratios of topdressing and base fertilizers, thus, to find out basic parameters such as soil fertility, soil nutrient correction coefficient, crop fertilizer requirement and fertilizer utilization rate. The next step is to propose the suitable fertilizer formulas such as nitrogen, phosphorus, potassium and mineral and trace elements, and also recommend the best fertilization time and fertilization method. Usually, deep application is a good practice for fertilization.
- **Fertilizer production**

There are mainly two modes for producing the needed formulated fertilizer: one is that farmers buy various basic fertilizers according to the formula and apply them together; the other is that the formula fertilizer is processed by fertilizer companies according to the formula, and the farmers directly buy and use it.

- **Demonstration promotion**

  Establish a soil testing and formula fertilization demonstration base to show the effect of this technology, and guide farmers to use the soil testing and formula fertilization technology.

2.1.3 Advantages and disadvantages

Using the soil testing and formula fertilization technology can avoid the excessive use of fertilizers, thus reducing the cost for the farmers and also reducing the waste of the natural resources such as phosphorus. The application of fertilizer based on the crop needs will help reduce the waste of fertilizer, and thus reduce the fertilization induced environmental issues, such as reducing the NH_3 emission, and the N leaching and runoff.

The disadvantage is that the process is quite complex, and quite labor intensive and requires specific equipment. For (the most common) small farms in China, it’s not attractive in doing so much extra work for using this technology. It should first be popularized with the support of local government.

2.1.4 Mitigation potential

Based on an assessment of Professor Zhang Fusuo in China Agriculture University, the fertilizer utilization rate can be increased by 5-10% and the yield increase rate can reach 10-20% by using soil testing and formulated fertilization. Zhang also showed that by maintaining current crop yields and balancing fertilizer input with crop uptake, China could reduce nitrogen fertilizer input by 10 million tons. The reduction in fertilizer input could reduce carbon dioxide (CO_2) emissions by 77 to 128.5 million tons.

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2.2. Reduce N_2O emission from fertilization

Yue Wang

2.2.1 Technical principles

N_2O emission is the most important contributor to the GHG emissions during feed production in the field. The rapid development of new fertilizers and inhibitors provides some options for mitigating N_2O emission from fertilization. The new fertilizers and inhibitors include slow and controlled release fertilizers, nitrification inhibitors and urease inhibitors.

Slow and controlled release fertilizer refers to fertilizers with a slow nutrient release rate and a long release period by controlling the water solubility of conventional fertilizer. It realizes one-time fertilization to meet the needs of the whole growth period of crops, thus avoiding the N surplus which causes the excessive N_2O emission and improves the fertilizer utilization efficiency.

Nitrification inhibitors are chemicals that inhibit the bioconversion process of ammonium nitrogen to nitrate nitrogen, thus reducing the nitrogen loss in the form of nitrate and reduce the N_2O formation during the nitrification process.

Urease inhibitors refer to a class of chemical agents that can inhibit urease activity in the soil and delay urea hydrolysis. It can reduce the NH_3 emission directly, thus contributing to the reduction of indirect N_2O emission.

Meanwhile, mechanical and deep application of fertilizers can reduce the nitrogen remained in the topsoil, thus reducing the N_2O emissions. Indirect N_2O emissions can also be reduced as the NH_3 emission was substantially reduced by using mechanical and deep application of fertilizers.

2.2.2 Technical considerations relevant to implementation

- **Slow and controlled release fertilizer:**
    - Choose the right type of slow and controlled release fertilizer which can meet the nutrient demand of specific crop.
    - Slow and controlled release fertilizer must be used as base fertilizer or during the early topdressing period, that is, when the crop is sown or in the seedling

  growth period after sowing. For corn, it can be applied at the time of sowing or before six leaves of a seedling.
  - It is suggested that the applied amount of slow and controlled release fertilizer per unit area of crops should be 80% of the amount applied in previous years and should be increased or decreased appropriately according to different target yields and soil conditions.
  - Application of controlled release fertilizer should be applied into the soil depth of about 10 cm.

- **Nitrification inhibitors**

  The effect of nitrification inhibitors varies greatly with different application conditions. It can increase the yield on most of the irrigated grain crops (Liu et al., 2016). However, the nitrification inhibitor was not recommended for leguminous crops as it may be harmful to the agrobacterium tumefaciens, thus decrease the yield (Pi, 2010).
- **Urease inhibitors**

  Some types of urease inhibitors and their decomposition products may be toxic to some type of soil microorganisms or crops, such as hydroquinone was found to be carcinogenic (McGregor, 2007). Therefore, farmers should pay attention to the used crops and the according ecological conditions, thus avoiding the side effects.
- Different types of mitigation measures can be combined to achieve a better integrated mitigation effect.

2.2.3 Advantages and disadvantages

Applying slow and controlled release fertilizer can improve the utilization rate of chemical fertilizer and reduce the amount of chemical fertilizer. Meanwhile, it can reduce the number of fertilization times, resulting in saving labor. However, this type of fertilizer was not suitable for dry land and sandy land. In the absence of water, nutrients cannot be released effectively, which may result in crop failure due to the inability to absorb available nutrients. In addition, the plastic wrapping agent may cause secondary pollution.

Nitrification inhibitors are beneficial to reduce nitrogen leaching loss and greenhouse gas (nitrogen oxide) emissions, and they have positive effects on improving fertilizer efficiency under certain conditions. However, nitrification inhibitors have not been widely used due to their costs and environmental impact. It is necessary to find some nitrification inhibitors with good inhibition effect without polluting the environment.

Urease inhibitors may not be a reliable option for direct N_2O mitigation. Urease inhibitors can reduce the NH_3 emission, thus contributing to the reduction of indirect N_2O emission. However, some type of urease inhibitor was found to be toxic to the environment.

Mechanical and deep application of fertilizers can reduce the NH_3 emission and N leaching and runoff, however, the specific fertilizer machinery was needed for applying this technology.

2.2.4 Mitigation potential

Guo et al. (2016) reported that compared with the farmer's common practice, application of controlled released urea can reduce GHG emission by 37.2%, while the grain yield can increase by 9.6%. Studies have shown that compared with conventional urea application, adding nitrification inhibitors can effectively reduce N_2O emissions in wheat-maize rotation system by 35% to 38% (Liu et al., 2013). Xu et al. (2015) found that deep fertilizer application can reduce N_2O emission by 21% to 29% in wheat crop. It's reported one kind of urease inhibitor, r N-(n-butyl) thiophosphoric triamide (NBPT) reduced total NH_3 loss by 28–88% over the entire study duration of two years, and by 82 to 96% during periods of peak loss from surface applications of unamended granular urea (Rawluk et al., 2001). Based on IPCC (2006) guideline, 1% of NH_3-N would be transferred to N_2O-N, therefore, the huge reduction of NH_3-N loss means that to a certain extent indirect N_2O emission can be avoided. However, some literatures reported the urease inhibitors may not be a reliable option for direct N_2O mitigation (Abalos et al., 2016; Volpi et al., 2017).

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2.3. Reduce synthetic fertilizer by planting catch crops

Yue Wang

2.3.1 Technical principles

After the main crop is harvested, and before the planting of the following main crop, the idle land can be used to plant the catch crops. In south China, the idle land in winter can be used to plant wheat, barley, rape, beans, peas, potatoes, winter green manure crops, vegetables, etc. In north China, the idle land in summer can be used to plant buckwheat, millet, soybean, summer corn, etc.

Planting the green manure crops is a good option. Legume crops such as clover, Vicia villosa Roth variety is the widely used type of green manure. It can absorb and fix nitrogen, thus contains a variety of nutrients and a large amount of organic matter in the stem. After growing for a certain period during the idle periods, it can be cut off and directly returned to soil, thus being a natural fertilizer, which can improve soil structure, promote soil ripening, and enhance soil fertility.

2.3.2 Technical considerations relevant to implementation

- The sowing amount of catch crop should be increased appropriately, which can be two or several times of the conventional sowing amount. Increasing the density appropriately can increase the absorption area and improve the yield of straw.
- The purpose of planting catch crops is not to harvest grain, therefore, the growth period should be shortened in order to not affect the optimal time of planting of the next crop.

2.3.3 Advantages and disadvantages

- The catch crop can absorb and utilize the remained nitrogen and phosphorus in the soil, thus reducing the leaching of nitrogen and phosphorus.
- After being returned to the soil, the catch crop would decompose quickly and thus become a natural fertilizer, which can help improve soil structure, promote soil ripening, and enhance soil fertility. The amount of applied synthetic fertilizer can be reduced and thus reducing the cost of farmers.

2.3.4 Mitigation potential

On the basis of burying Vicia villosa Roth (15 000 kg /hm^2) to the soil, the maize yield can be increased by 19.92% ($p<0.05$) when the synthetic fertilizer was reduced by 15%; when the synthetic fertilizer was reduced by 30-45%, the maize yield was not reduced. It was found that on the basis of burying Vicia villosa Roth (15 000 kg /hm^2) to the soil, reducing the amount of fertilizer 15% can help achieve the highest income of farmer, by increasing by 11.5% compared with the 100% fertilizer group.

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2.4. Increased crop yields

Sha Wei and Yue Wang

2.4.1 Technical principles

Technical measures of production management, fertilizer and irrigation are important measures to increase crop yields. Developed countries such as the United States have achieved 77 % of their maize yield potential (Van Wart et al., 2013), while developing countries and regions such as Asia and much of Africa have achieved only 41% of their maize yield potential (Meng et al., 2013; Sanjani et al., 2012; Verdoodt et al., 2003). The main reason for this difference is production management techniques. Studies on a global scale have shown that increases in crop yields can eliminate yield gaps by increasing N by 30%, P_2O_5 by 27%, K_2O by 54% and irrigated area by 25% respectively, in areas where nutrient and water conditions are limited (Mueller et al., 2012).

2.4.2 Technical considerations relevant to implementation

The breed of the fodder crop, better management of irrigation, fertilization, sunshine, and also the improvement of mechanized planting, should all be improved to achieve an increased crop yield.

2.4.3 Advantages and disadvantages

Increased crop yields not only benefit to the GHG mitigation from feed production for dairy, but also contribute a lot to ensuring food security, and realizing the target of Zero Hunger.

2.4.4 Mitigation potential

The present GHG emissions of whole maize, wheat and rice production chain were 4052 kg CO_2/ha (0.48 kg CO_2/kg), 5455 kg CO_2/ha (0.75 kg CO_2/kg) and 11881 kg CO_2/ha (1.6 kg CO_2/kg) (Zhang et al., 2017). Increased crop yields will reduce the GHG emission from fodder crop production based on keeping fodder crop consumption of dairy farms on a constant level.

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3. Feeding and feed management

Feeding costs are the most important contributors to the total cost of milk production and it is also the most determining factor for the enteric methane (CH_4) emission of the dairy herd. The enteric methane emission is the largest contributor to the total direct emissions of GHG of a dairy farm. The inputs of purchased forages and concentrates feed are responsible for a large part of the indirect (off-farm) fossil energy use and GHG emissions. Therefore, improvements in feeding management can make important contributions to the reduction of the direct and indirect GHG emissions of a dairy farm and in many cases at the same time will improve profitability. The main cornerstones of improved feeding management to reduce greenhouse gas emissions are precision feeding through balanced rations, formulation of cattle diets with a focus on low enteric methane emissions and the use of feed ingredients and additives that modify rumen fermentation by suppressing methanogenic microbial populations or act as a sink for hydrogen in order to inhibit ruminal methanogenesis.

3.1. Precision feeding to match cow requirements

Ronald Zom and Wei Wang

Optimizing dairy cattle rations to reduce greenhouse gas emissions can be achieved through precision feeding and manipulation of the rumen fermentation through dietary carbohydrates and fats and the use of feed additives.

Feeding above or below the net energy and protein requirements is unbeneficial. Overfeeding is unnecessary input of purchased concentrate feeds resulting in increased feeding costs and off-farm greenhouse gas emissions. Underfeeding prevents the animal to express its genetic potential for growth and milk production. A severe negative energy balance (NEB) or obesity (fat cow syndrome) resulting from under- or overfeeding, increases the risks of metabolic disorders, reduced fertility and impaired immune response (Roche et al. 2009). Feeding excess of dietary protein results in an increase of the excretion of urinary nitrogen mainly as urea. During storage of the liquid manure (feces with urine), urea is converted to ammonia by microbes with urease activity. A considerable part of this ammonia is lost due to volatilization.

Precision feeding is a tool to establish the nutrient requirement and intake of the animals and to control these. Subsequently, with a given nutrient requirement and dry matter intake, the farm manager formulates rations that fulfill the nutrient requirements of the animals. The choice of feed ingredients and the concentrations of NDF and NFC (non-fiber carbohydrates) in the ration, influence the volatile fatty acid production (VFA) and determine to a large extent the enteric methane emissions.

Furthermore, feed additives such as nitrates, sulfates, 3NOP, ionophores, secondary plant metabolites (e.g., essential oils, condensed tannins) may in potential reduce enteric methane production through influencing metabolic pathways in rumen fermentation.

3.1.1 Technical principles

Precision feeding is about getting the right nutrient to the right animal at the right time. For precision feeding it is necessary to know the nutrient requirements (energy, protein, minerals) of an individual animal at any age or stage of lactation and to have an insight in the nutrient supply and intake (Subnel et al. 1994). In order to calculate the animals nutrient requirements recording of health and reproduction data, growth (live weight), milk production and milk composition of individual animals is an indispensable prerequisite. This information allows the farmer to create homogenous feeding groups of animals with a similar age, stage of lactation and milk production and thus similar nutrient requirements. Housing animals in homogenous feeding groups has the advantage that a tailormade TMR ration can be composed and fed to each group. Group feeding allows easy control over the amount of feed (TMR) delivered and consumed. In order to have a good control over the nutrient supply intake it is also necessary to keep records of the composition of the TMR (Subnel et al.1994). That is, recording the amount and proportions of each ingredient in the TMR. Furthermore, routine analysis of feed composition (i.e., ash, crude protein, ether extract, fiber, water soluble carbohydrates, starch, minerals) and determination of feeding values (net energy, metabolizable protein) is crucial. In summary, monitoring the nutrient intake relative to the requirements, gives the opportunity for the farm manager to adjust the ration in the right way in order to prevent dairy cattle from over- or underfeeding and thereby reducing both off-farm green gas emissions and feeding costs.

3.1.2 Technical considerations relevant to implementation

Precision feeding requires an infrastructure on the farm to collect and process electronic data (animal data, electronic milk recording, body weights, feed weight recorders), and a well-educated staff able to handle farm protocols for recording feeding (feed delivered and consumed) and feed sampling to assess feed quality. Furthermore, methods for rapid feed analysis must be available. It is also very important that rations are carefully formulated and composed. Feed mixers must be fitted with accurate weighing equipment. Not only to weigh the correct amounts of roughage and concentrates, but especially when feed additives and minerals are used and added to the feed mixtures. Feed additives and minerals are expensive and therefore require accurate dosing to avoid the risk of overdosing (toxicity) or underdosing (low effectivity, deficiencies). In addition, automated weighing systems and weight recording may support the farm manager to keep records of the amounts of feed used and in stock. This provides useful information to control feeding costs and feed utilization.

Proper grouping (e.g., young calves, heifers, pregnant cows, transition cows and lactating cows in different lactation stages) in a herd is of great importance when it refers to providing cows a suitable diet to meet the requirements. Therefore, farmhouse layout and animal routing should be organized in a way that it is possible to separate animals in groups according to their nutrient (energy, protein) requirement, age and physiological state.

3.1.3 Advantages and disadvantages of precision feeding

To pursue a high milk yield, cows may be overfed with large quantities of concentrates. However, the marginal response in milk yield diminishes with the increase of each unit of concentrate intake according to the law of diminishing marginal returns. This may result in lush diets with overfeeding as a result. This will cause negative effects on profitability as well as on GHG emissions. Precision feeding can prevent from overfeeding and underfeeding. However, precision feeding requires investment in new technologies, and corresponding knowledge and management practices. Access to information and up-skilling of farm managers requires knowledge transfer and training programs; successful implementation can also depend on adequate supply chains and infrastructure.

3.1.4 Mitigation potential of precision feeding

When assessing the mitigation potential of different strategies and measures it should be kept in mind that in most situations the single effects of different measures such as precision feeding, optimized composition of rations, improved roughage quality and feed additives cannot always be added together.

The impact of precision feeding on reduction of GHG emission acts mainly through a reduction of the input of purchased concentrates. Thus, precision feeding will mainly have off-farm effects on greenhouse gas emissions. The inputs of purchased concentrates are approximately responsible for 40-50% of the indirect fossil energy use of a dairy farm (Hageman & Mandersloot, 1995). Furthermore, the production of concentrate feeds causes GHG emissions as result of deforestation and land use change. The impact of reduced or optimized concentrates input will therefore strongly depend on the origin of the concentrate ingredient and the carbon footprint associated with cropping, land use and land use change, deforestation, processing and transportation.

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3.2. Optimize diets, feeding low emission feeds

Ronald Zom and Wei Wang

Diet composition has a major impact on enteric methane which is the major source of greenhouse gases from dairy farming. Methane represents an energy loss for the ruminant constituting 3 to 10% of its gross-energy intake (Niu et al. 2018). Enteric methane production is closely associated to the profile of VFA formed during fermentation. There is a positive correlation between enteric methane production and the ratio of ruminal acetate to propionate (Russell, 1998). Propionate is a hydrogen sink in rumen fermentation, whereas acetate and butyrate yield hydrogen that can be utilized by methanogens to reduce $CO_2$to CH_4 (Janssen, 2010). Therefore, stimulating rumen fermentation towards more propionate and less acetate and butyrate production may reduce enteric methane emissions. This can be achieved by increasing the proportion of starch (concentrates) in the ration (Hristov et al., 2013) or by reducing of NDF relative to non-fiber carbohydrates (NFC) in the ration (Bannink et al., 2006).

Important starch sources are concentrates based on cereal grain (e.g., maize, wheat, barley and oats) and roughage like whole crop corn-silage and wheat-silage. Compared to other cereals starch from corn is relatively slowly degraded in the rumen (Nocek and Tamminga, 1991; Huntington, 1997). Therefore, a substantial part of the starch in corn is by-pass starch that reaches the small intestine unfermented. Starch in the small intestine is digested enzymatically to glucose adding to the energy supply of the cows without fermentation losses of energy associated with methane production (Dijkstra et al., 2011). Therefore, increasing the starch content in ruminants' diet is an effective measure to reduce methane emission intensity (Hristov et al., 2013). Whole-crop corn silage is the most important roughage-based starch and the major energy source in dairy cattle rations. Increment of the proportion of corn silage is a viable option to reduce enteric methane and to improve the roughage quality (van Gastelen et al. 2019). Higher organic matter digestibility and crude protein content and lower NDF content in grass silage is associated with a lower enteric methane production and methane production intensity (CH_4/kg ECM). Similarly, corn silage quality by reducing the NDF content resulted also in a lower methane yield (van Gastelen 2019).

Increased dietary fat concentration may also reduce enteric methane production (Beauchemin et al., 2009; Moate et al., 2011). Dietary fat reduces methane production through reduced fiber degradation and thereby reducing activity of methanogens, and act as a hydrogen sink through biohydrogenation of unsaturated fats.

Another, often overlooked measure to reduce greenhouse gas emissions, is a reduction of the losses of feed during storage. The direct emission from silages are only 0.2-0.3% of the total emissions of greenhouse gasses (van Schooten and Philipsen, 2010). However, the losses of dry matter, energy and protein during ensiling, fermentation, storage and feed-out can be considerable with poor silage management. Good silage management involves that lactic acid bacterial fermentation must be promoted. This means that maintaining anaerobic conditions, sufficient water-soluble carbohydrates for lactic acid bacteria and promotion of a high osmotic pressure which favors lactic acid bacteria compared to clostridial bacteria. This means in practice that the ensiling phase should take at maximum one day. During ensiling, the silages must be compacted with heavy equipment. Silages must be airtight sealed immediately. Do not open the silages before the fermentation process has ended (at least 6 weeks). Maintaining an undisturbed silage face (use silage cutters) is also a way to avoid feed losses.

3.2.1 Technical considerations relevant to implementation of optimized diets

Manipulation of the composition of dairy cattle diet is focused on shifting rumen fermentation towards more propionate production in the rumen, by means of reducing NDF to NFC ratio, more starchy roughages (e.g., corn silage, whole crop cereal silage), and more digestible roughages. Therefore, it is important that roughages have the desired quality and composition. This requires that roughages are harvested at the right stage of maturity. Prior to harvest, crops should be monitored regularly. The optimum stage to harvest grass for silage is just before heading. Alfalfa should be harvested when the first flowers appear (maximum 2 % flowers). Corn silage should be harvested at least 2/3 milk line (approximately 50-60% DM in cob, 34-38% DM in the whole crop). Improvement of roughage quality is a typical ‘no regret’ option. Additional treatment on the roughage can also improve the forage digestibility, such as chopping, grinding of straw, and steam treatment.

3.2.2 Advantages and disadvantages of optimized diets

Improvement of diet composition and roughage quality is a typical ‘no regret’ option. A better roughage quality together with more efficient use through precision feeding results in lower inputs of purchased concentrates per unit milk and an increased feed efficiency (less feed DM per unit milk). Both a reduced input of concentrates and an improved feed efficiency may result in less food-feed competition (e.g., less cereal grains in concentrate feed). Use of some feeds with multiple roles in food production could negatively affect regional food security through land-use changes and food prices and increase indirect emissions off-farm. Furthermore, improvement of the roughage quality and feeding value of home-grown roughage may reduce the imports of good quality of roughages like alfalfa, oat hay and soybean from abroad.

The provision of better-quality feed ingredients and better feeding management is beneficial for improvements in forage digestibility and nutrient quality. Improvement of feed quality can be achieved with low investments but requires high competence of farm management staff.

3.2.3 Mitigation potential of optimized diets

Recently, van Gastelen et al. (2019) reviewed the effects of different feeding strategies, roughages, rations and additives to mitigate enteric methane emissions. Improvement of feed quality of corn silage and larger proportions of corn silage in the ration showed that enteric methane emission intensity (methane/kg ECM) can be reduced in a range between 5 and 20%. Improved roughage quality of grass-based roughage resulted in 10-20% lower enteric methane emission intensity, whereas improved roughage quality in corn silage resulted in a 5-10% % lower enteric methane emission intensity. Replacing grass pasture, grass silage, or alfalfa silage with corn silage generally decreased methane emission intensity around 8% (Van Gastelen et al. 2019).

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3.3. Feed additives to reduce enteric methane

Ronald Zom and Wei Wang

Feed additives may also be helpful to reduce methane emissions. There is solid evidence that adding nitrates and sulphates as an additive to ruminant rations reduces ruminal methane production within in a range of 10-40%. The mode of action of nitrates and sulphates is that they compete for hydrogen with methanogenesis in the rumen (Zijderveld et al. 2010, 2011). Feeding nitrate additives should be done with caution. In animals not adapted to nitrate, it may increase the risk of nitrite accumulation in the rumen. Nitrite converts blood hemoglobin (Hb) to methemoglobin (MetHb). The MetHb molecule is incapable of transporting oxygen to the tissues resulting in methemoglobinemia, which may depress animal performance.

Recently, Duval and Kindermann (2014) invented the feed additive 3-nitrooxypropanol (3-NOP). This additive blocks the last step of methanogenesis in the rumen by oxidizing the enzyme methyl-coenzyme M reductase (Duin et al., 2016). Adding 3 NOP tot the diet of dairy cows reduced methane emission by 19 %, together with higher apparent total-tract digestibility and improved metabolizable energy supply (van Gastelen et al. 2020).

Essential oils, such as garlic, cinnamon, rhubarb and frangula, may have a suppressing effect on methanogens. However, most evidence on the methanogen suppressing effect of essential oils is based on in vitro experiments. Unfortunately, in vivo methanogen suppressing activity of essential oils has been equivocal to date. Probably because rumen microbes may adapt to these essential oils and degrade them (Benchaar and Greathead, 2011; Benchaar, 2020).

Saponins and condensed tannins in the ration may also influence rumen microbial populations, rumen fermentation and methane emissions. However, the efficacy of saponins to manipulate enteric methane emissions is not clear. Holtshausen et al. (2009) concluded that saponin did not provide a viable option to reduce enteric methane emissions. Plant tannins, as feed supplements or as tannin rich forage, have shown a potential for reducing enteric methane emissions (Waghorn et al., 2002). However, the effects on anti-methanogenic potential of tannins have been inconclusive to date, probably due to a large variation of the structural characteristics of the tannins (Verma et al., 2021). Furthermore, tannins have antinutritional properties which result in a reduced absorption of amino acids in the small intestine (Waghorn, 2008).

3.3.1 Technical considerations relevant to implementation feed additives

Feed additives are usually fed in very small quantities sometimes less than 50 grams per animal per day. Therefore, proper dosing can be very challenging in farm practice. When additives are mixed through a TMR a proper mixing is essential. Uneven distribution of the additive through a feed mixture may result in underdosing or overdosing. In case of underdosing, the efficacy of the additive is insufficient. Overdosing may affect animal health and feed intake. Overdosing of nitrates may result in methemoglobinemia. Whereas overdosing of tannins, which are in fact antinutritional agents, have a negative effect on feed intake and utilization of protein. Therefore, when feed additives are used as a mitigation measure for enteric methane emissions, procedures must be available to guarantee the exact dosing of additives. In addition, accurate weighing and dosing equipment must also be available in order to avoid over- or underdosing.

3.3.2 Advantages and disadvantages of feed additives

The main advantage of feed additives is that immediate results can be achieved with regard to the reduction of enteric methane emissions. Provided the additives are actually effective. In situations in which the possibilities of reducing enteric methane emissions via the composition of the ration (e.g., increasing the proportion of maize silage) are available, that option can also be a useful measure.

It should be taken into account that additives only reduce enteric methane emissions but have no effect on off-farm emissions of greenhouse gases. Furthermore, it is important to point out that additives are not a substitute for measures such as precision feeding, optimization of the ration, and improvement of the nutritional value and digestibility.

3.3.3 Mitigation potential of feed additives

The feed additives 3NOP and nitrates may reduce enteric methane emission intensity around 20-25%. Secondary plant metabolites have variable effects. Tannin extract may reduce methane emission intensity with 10%, whereas saponins are not effective. However, it should be noticed that tannins may have an adverse effect on intake and protein digestibility.

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3.4. Water quantity and quality

Yue Wang

Water is an essential nutrient for life and plays an extremely important role in the metabolism of dairy cow. Water occupies about 65% of the dairy cow weight and accounted for about 87% of the raw milk. Water quantity and quality has important influence on the health of the dairy cow, and also on the milk production. It's reported that 3.5-5.0 kg of drinking water would be consumed for lactating 1 kg of milk (Qi et al., 2010). Therefore, enough water is the prerequisite of high milk production efficiency. Meanwhile, the water quality will also influence the quality of the lactated milk. If the nitrite or nitrate content in the water exceeds the standard, the nitrate nitrogen in raw milk will exceed the standard; when nitrate in water reaches 221 ~ 660 mg/L, cows drinking this water can be in danger or even die (Qi et al., 2010).

3.4.1 Technical considerations relevant to water quantity and quality

In general, the drinking water demand of a dairy cow is 100-150 kg/day in summer and 50-70 kg/d in winter. Dairy farms should install autodrinker in the barn and yard so that cows can drink water ad libitum. If there is no autodrinker, water can be supplied regularly every day, usually 5-6 times in summer and 3-4 times in spring and winter. High-yield cows should be supplied with an increased amount of drinking water. Drinking water should also be supplied in the playground to ensure the water will be available to the dairy cows at any time.

Keep drinking water clean. Wash water trough daily and disinfect it regularly. The suitable temperature is also important for the health of dairy cows. The suitable water temperature is 12-14°C for adult dairy, 15-16°C for lactating cow, and 35-38°C for calves below one month old.

3.4.2 Advantages and disadvantages

Keep enough and clean water to dairy cows will help to keep dairy cows healthy and will also increase the milk production of the cows.

3.4.3 Mitigation potential

Enough water of good quality keeps the dairy cow healthy, thus avoiding the diseases and maintaining a high milk yield. Therefore, the GHG emission intensity will be reduced.

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4. Stable

Stable is an important source of GHG emission in the dairy sector, because of the enteric fermentation by the cows in the stable and the manure management practices that take place in the stable. In recent years, the free-stall type stable is generally adopted by large scale Chinese dairy farms. The main source of CH_4 in a dairy stable is rumen fermentation, so the concentration of CH_4 in dairy stable is mainly related to the metabolic activities of dairy cows. Good metabolic activities will increase the health of cows and then increase the milk yield. The higher milk production per cow means less emissions per kg milk. Therefore, well managed stable environment such as keeping low barn temperature (cooling to reduce heat stress), better bedding material, and reduction of manure accumulation (through better floor type or more frequently manure removal) can help improve animal health and performance, which in turn reduce the GHG emission.

The stable system may affect GHG emissions through the construction and through the methods used to collect, store, litter and remove manure. Farmyard manure and deep litter manure handling systems tend to produce higher N_2O emissions than slurry-based systems. Straw-based bedding and solid manure handling systems also tend to increase N_2O emissions compared with liquid manure handling systems. In general, manure storage systems in which manure is stored for prolonged periods of time, produce greater NH_3 and CH_4 emissions compared with systems in which manure is removed daily. Slatted floor stables tend to decrease GHG and NH_3 emissions compared with deep litter systems.

4.1. Cooling to reduce heat stress of cows

Sha Wei and Yue Wang

4.1.1 Technical principles

Cooling facilities prevent or alleviate heat stress to cows in a high temperature environment. Heat stress reduces the feed intake of dairy cows, resulting in reduced milk yield and poorer reproduction cycle of dairy cows (Dash et al., 2016) that will lead to a higher emission intensity. Mechanical ventilation with wet curtain and evaporation cooling (including covering a wet straw curtain on the roof of stable, spraying cold water on and around the stable floor, spraying water directly onto the cows and brushing the cow with cold water) are the main cooling methods. For animal welfare reasons the ventilation capacity should be sufficient to provide fresh air, sufficient humidity and to remove unwanted gases.

4.1.2 Technical considerations relevant to implementation

The considerations relevant for the implementation of cooling system are as follows:

- When using cooling methods, the relative humidity of the stable should be monitored in time and should not be higher than 80% to hinder dissipation of the cow body by evaporation.
- Evaporation cooling methods are suitable for areas with relatively dry climate. Excessive air humidity will decrease the evaporation rate and reduce the effect of evaporation cooling. It is not recommended to use it in humid and warm areas.
- Cooling methods using fans combined with spraying water is recognized as an effective way. The suggested cooling option in stable is using fans when the temperature is higher than 21℃ and using fans combined with spray when the temperature is higher than 25℃. The suggested cooling option in milking parlors is using fans combined with spray when the temperature is higher than 21℃.

4.1.3 Advantages and disadvantages

In free-stalls cows can walk freely and manage themselves, and the animal welfare level is high. Compared with tie stalls (where cows are tethered) with playground, the free stall occupies less area and has higher feed conversion rate.

In addition to the cooling effect, there are the following benefits for water spraying combined with fans: (1) dust abatement; (2) additive products can be sprayed simultaneously with water; and (3) cleaning of slatted floors is easier. Spraying water is also expected to reduce GHG emissions from manure on the (slatted) floor.

The fogging system at medium pressure (< 70 bar) has a good cost efficiency but presents risks of litter moistening. The fogging system at a high pressure (> 70 bar) is more sensitive to the water quality and the clogging of the nozzle.

4.1.4 Mitigation potential

The better animal health and lactating performance achieved through cooling during hot weather conditions is expected to result in a lower GHG emission intensity, for the same reasons mentioned before about the positive impact of better animal health and optimized rations. Available research results data to underpin this are still lacking.

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4.2. Manure collection and removal

Sha Wei and Yu Zhang

4.2.1 Technical principles

There are different methods for collecting/removing manure from a barn floor namely using scraper, flushing, slatted floor and litter system. The manure removal frequency, the share of feces and urine in the manure are different for different manure collecting methods, which has a significant impact on CH_4, NH_3 and N_2O emissions produced by the barn or stable. Here are some more details about the two main collection/removal systems in Chinese dairy farms:

- Scraper for frequent manure removal on solid and/or slatted floors
  - Slurry is removed frequently (e.g., daily or more times per day) by a scraper to the manure pit at the end of barn. The scraper is driven by a stationary mechanical or hydraulic power unit. Housing systems with slatted floors collect manure in liquid form, which is commonly stored for longer periods of time and therefore tends to increase the production of CH_4 (Wang et al., 2017).
- Manual dry collection on bedding floor is the main collection/removal system.
  - The manure in housing systems with solid floors that use hay or straw for bedding is usually collected manually, as this manure usually has higher DM and is commonly stored in piles creating conditions conducive for nitrification and denitrification resulting in higher N_2O emissions.

4.2.2 Technical considerations relevant to implementation

Reducing slurry surface and the frequent removal of slurry from barn to an external store and separation of urine from feces will reduce NH_3 and GHG emissions. The slat material, frequency of removal and smoothness of the pit floor all contribute to the reduction of emissions. The functioning of the system is vulnerable due to the wear of the floor. The addition of a coating on the scraped floor is recommended in order to achieve a smooth surface.

4.2.3 Advantages and disadvantages

Operating the scraper requires energy. The power consumption of scraping varies with the frequency. Frequent maintenance is required for this type of equipment, with a consequent increase in the demand for labor resources.

4.2.4 Mitigation potential

A GHG emission measurement campaign was carried out by Baldini et al. (2016) for 27 months in four naturally ventilated dairy cattle buildings with different floor types, layouts and manure management systems, representing the most common technologies in the north of Italy. The results showed that the CH_4 emission from perforated floor (slatted floor) was the highest, which was 38.71 mg/m^2/h, followed by scraper on concrete floor and flushing, which were 21.59 mg/m^2/h and 19.12 mg/m^2/h. The highest N_2O emission was also found in the perforated floor, which was 0.91 mg/m^2/h, followed by scraper on concrete floor and flushing, which were 0.32 mg/m^2/h and 0.22 mg/m^2/h.

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4.3. Management of playground on open air dairy lots

Sha Wei and Seyyed Hassan Pishgar-Komleh

4.3.1 Technical principles

Open lots (also called open dry-lots) are typical for the walk and feed area for cattle on Chinese dairy farms. Many different types of open-lot systems exist in China, including hard ground (concrete ground, cement ground, vertical brick ground), soft ground (sandy soil ground, grass surface, bark surface and dry manure ground) and tabia floor (composed of lime, clay (or broken brick or gravel) and fine sand). In such a system, a large amount of solid and liquid manure from the animals is usually excreted on the ground surface, and cleaned from days to months, depending on the climate and ground systems (Ding et al., 2016). Therefore, the open lot is also an important source of CH_4, NH_3 and N_2O emissions (Ding et al., 2016). The different types of ground and surface materials on the ground can impact the gas emissions. For example, among three different cover materials, the shredded tree bark surface emits higher CH_4 and N_2O emission than the sand and soil surfaces, which may be caused by the higher C content of bark. Meanwhile, relatively lower aeration and higher moisture in soil of barnyards provided the anaerobic conditions that enhanced N_2O emissions compared with sand-surface barnyards. Choosing the suitable ground type and removing the manure more frequent can help reduce the GHG emission.

4.3.2 Technical considerations relevant to implementation

Lying time for cows on the open lot need to be 14 to 16 hours a day to increase feed intake (6%) and subsequently milk yield (6-15%). With the long-time spending on the open lot, the hygiene of the lot is quite important to ensure the health of the cows.

Meanwhile, the comfort of the cows needs to be assessed more fully before recommending beneficial practices for barnyard surface type and management (Powell and Vadas, 2016). In addition, tradeoffs between gas emissions, nutrient runoff and leaching, and cow comfort and health should be considered when optimizing the floor type in the open lot.

4.3.3 Advantages and disadvantages

Effectively disinfect the playground twice a week to reduce the number of bacteria in wet feces and ensure the health of dairy cow’s udders. Timely clean-up of the loose manure in the playground area can reduce the GHG emission and also avoids the cow's hoofs to be impregnated with manure. Meanwhile, cows on an improved playground can fully relax and exercise, increase feed intake, prolong the peak time of lactation, so as to improve milk yield. Appropriate playground floor can also enhance the physical fitness, improve body condition, reduce the incidence of limb and hoof and improve the cure rate. Playground is an animal welfare improvement measure.

30% of manure in summer and 10% of manure in winter was drained in the playground. If manure is not cleaned in time, the discharged manure will runoff to the surface water and leach to the ground water after rain. The nitrogen and phosphorus pollution in the aquatic environment has the potential threat.

4.3.4 Mitigation potential

Among three surface materials (bark, sand and soil), the average CO_2-eq flux from bark (3188 $mg/m^2.h$) was 2.5–3.0 times greater than sand or soil (Powell and Vadas, 2016). The type of the playground affects the milk yield. The average annual milk yield of cow raised on day manure playground was 6-15% higher than that of brick-faces playground (Cong et al., 2012), therefore, the according GHG emission intensity per kg of milk reduced.

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5. Manure management

Manure management includes all activities involving the handling, storage and disposal of urine and faces (other than manure deposited directly onto pastures by grazing animals). Sound manure management is important to mitigate GHG emissions, but also offers important benefits for reducing nutrient losses from manure and reduces other detrimental environmental impacts of livestock production such as air and water pollution. Manure management accounts for 39% of total livestock GHG emissions, being lower than the enteric fermentation part (MEE of China, 2019). However, it offers technologically mature opportunities for GHG mitigation in livestock sector, and the good management of manure can also deliver benefits from economic, social and environmental aspect.

Poor manure collection and storage results in loss of valuable nutrients in manure. Improved manure storage facilities – with proper floors and roof coverage to prevent run-off and volatilization, and well managed practices such as solid-liquid separation for reducing the DM of manure in slurry, reducing manure storage time and storage temperature, using manure aeration to reduce anaerobic condition for CH_4 forming, and customized technologies to apply manure to land would enhance production of food and feed crops. In addition, improved manure storage improves the hygienic conditions for animals and humans and enables the recycling of nutrients. Capturing biogas and using it as a source of energy provides a cost-effective low-carbon energy source and supports access to energy in remote rural areas; the benefits of it depend on herd size, housing system and initial capital investment costs.

Manure management techniques are mostly mature technologies, with customized improvements for all systems already available. Transferring the basic principles, education, information, policies and an enabling environment (financial and technical infrastructure) are fundamental to the success of improving manure collection, storage and application. Especially for small-holders, customized training programs are needed (in combination with training on health/hygiene, feeding, access to finance, opportunities to share equipment, etc.). Broader environmental regulations (for odor and water quality) can be important drivers for adoption of manure management practices, as can be energy access through the use of biogas digesters in remote rural areas.

It is common practice for farmers to have storage facilities for dairy slurry or liquid manure with a sufficient capacity to hold the slurry/liquid manure until further treatment or application is carried out. The required capacity depends on the climate, and the duration of the periods in which land application is not possible or land area for application is not enough available. GHG emissions during the storage period can be reduced by applying the measures given below related to the design and management of the slurry/liquid manure store.

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5.1. Cover lagoon to avoid methane emission

Sha Wei and Yu Zhang

5.1.1 Technical principles

The main abatement technique to reduce CH_4, NH_3 losses and odor from slurry storage consists of covering open storages, which reduces emissions to atmosphere. A distinction is made between covers, as various types of covers can be applied. The main types are rigid covers, tent covers, floating covers, or a floating layer of straw or natural crust.

Rigid covers are tight covers (e.g., a roof or a lid) which are made from inflexible material such as concrete, fiberglass panels or polyester sheets with a flat deck or conical shape.

A cover made from flexible or pliable sheet material such as reinforced plastic sheeting or strong canvas that is stretched taut over the store. The main types include tent covers, dome-shaped covers and flat covers.

Floating covers comprise a substance or material that rests on the surface of the slurry. There are different types of floating covers, including natural crust, straw (crust), peat, light bulk material (e.g., LECA, LECA-based products, perlite, zeolite), plastic pellets (polystyrene balls), oil-based liquids (e.g., rapeseed oil), floating flexible cover (e.g., plastic sheets, blankets), geometrical plastic tiles, and air-inflated cover.

5.1.2 Technical considerations relevant to implementation

Care must be taken to prevent the temperature of the slurry from rising to a point at which biochemical reactions can occur, otherwise these may result in unwanted odorant production and a degradation of the quality of the slurry.

Closed impermeable covers prevent rainfall diluting the slurry, so that a reduced volume of slurry is achieved, and an increased effective storage period is provided by the storage. In areas with moderate to high rainfall, these types of cover can be cost-effective, limiting transportation and spreading costs.

Given that the collected CH_4 from manure storage is highly flammable, the safety measure should be considered. Some small openings (which do not undermine the minimum sealing required), or a facility for venting, are needed to prevent the build-up of such gases.

Plastic sheeting is well tested on small earth-banked lagoons. Plastic sheets can be difficult to fit and manage on larger lagoons. If lagoon walls are not accessible or structurally sound to allow anchoring of the plastic sheet, secured covers cannot be used; then the application of floating materials is possible. Therefore, plastic sheets may not be applicable to large existing lagoons due to structural reasons.

Straw and light bulk materials may not be applicable to large lagoons where wind drift does not permit the lagoon surface to be kept fully covered.

Agitation of the slurry during stirring, filling and emptying may preclude the use of some floating materials which may cause sedimentation or blockages in the pumps. Natural crust formation may not be applicable in cold climates and/or on slurry with low dry matter content. Natural crusts are not applicable to lagoons where stirring, filling and/or discharging of slurry frequently disturbs the surface.

5.1.3 Advantages and disadvantages

In China, funds from the County-wide Promotion Project will be used to support sealed or covered storage of liquid manure from 2020 onwards (MARA and MF, 2020).

Covering reduces or eliminates the oxygen exchange between manure and air and results in an increase of temperature of the slurry by approximately 2°C. Under these conditions, CH_4

can be formed; its recovery and use for energy production is possible such as the application of black membrane biogas digester.

Semi-permeable storage covers are useful for reducing CH_4, NH_3 and odor, but tend to increase N_2O emission because the aerobic conditions for nitrification at the cover surface and at the same time create a low oxygen environment just below the cover favorable for denitrification and production of N_2O.

Impermeable membranes, such as sealed plastic covers, is an effective mitigation option if the CH_4 captured under the cover is collected for energy or electricity production, otherwise it can be burned using a flare system.

5.1.4 Mitigation potential

All kinds of cover material have a significant emission reduction effect on NH_3. The cover material of straw, wood cover and straw + wood cover combination reduced NH_3 emission in liquid manure storage by -13.1% ± 19.8%, -36.9% ± 8.9% and -43.2% ± 21.7%, respectively (Amon et al., 2006; Clemens et al., 2006). However, different coverings have different effects on the emission reduction of CH_4 and N_2O, and some even promote the release of CH_4 and N_2O. Wood mulching and straw mulching combined with wood mulching could reduce CH_4 emission in liquid manure, which were -15.0% ± 1.5% and -19.3% ± 7.8%, respectively. However, straw mulching alone could promote CH_4 emission in liquid manure (mean ± 9.1% ± 6.1%; Amon et al., 2006; Clemens et al., 2006). Straw mulching had a certain promoting effect on N_2O release from liquid manure of dairy cows and increased the N_2O release by 37.7% ± 20.6% (Amon et al., 2006; Clemens et al., 2006). Wood mulching and the combination of straw plus wood mulching had different effects on N_2O release in different seasons.

Sound storage should be supported with good cover (concrete, wood or possibly as simple as banana leaves), although implications on emissions are complex and variable as effectiveness depends on cover permeability, thickness, degradability, porosity and management. Semi-permeable covers decrease NH_3, CH_4 and odor emissions, but can increase N_2O emissions. Impermeable covers give the opportunity to flare CH_4 or collect as biogas. For Dutch dairy systems, frequent manure removal to a closed manure storage with thermic oxidation of methane is expected to reduce CH_4 emissions from manure by 75% (Lesschen et al., 2020).

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5.2. Manure acidification

Sha Wei and Seyyed Hassan Pishgar-Komleh

5.2.1 Technical principles

Manure acidification is a technique for reducing ammonia emissions by adding sulphuric acid to the manure. The equilibrium between NH_4-N and NH_3 in solutions depends on the pH (acidity). A low pH favours retention of NH_4-N (in the form of ammonium sulphate) at the expense of ammonia (NH_3-N) volatilization.

Acidification can be applied in a storage tank by means of a valve pit or during land spreading of the manure. On farm, the manure is pumped from the houses to a process tank, where the right dose of sulphuric acid is added to lower the pH to 5.5. The amount of sulphuric acid is controlled by a pH sensor. Another way, sulphuric acid is transported and stored in a suitable container mounted on the front of the tractor that pulls the liquid manure spreader/slurry tanker, and manure is pumped on the soil after mixed with sulphuric acid. The amount of spread slurry and pH is also continuously measured.

5.2.2 Technical considerations relevant to implementation

In general, the amount of sulphuric acid needed for a ton of slurry is approximately 2.5–3 L, corresponding to about 4.6–5.5 kg of acid. Other sources report a consumption of sulphuric acid in the range of 5 kg to 7 kg for each ton of raw slurry, to reduce the pH to between 5.5 and 6 (Kai et al., 2008).

In the storage tank, manure is also aerated and homogenized by injecting compressed air, to prevent sulphate ions changing into noxious hydrogen sulphide and to improve the fluidity of the slurry as part of the dry matter content is degraded. In the case of acidification inside the slurry storage tank, due to foaming of the slurry, a freeboard of 0.8–1 m is required in the tank; therefore, the storage capacity of the tank cannot be fully utilized.

In commercial operations, the pH is often brought down to a value of 5.5, in consideration of the instability of acidified slurry and its varying buffer effect. The target pH depends on the time span from acidification until spreading on the land. Therefore, slurry that is acidified to below 5.5 in cases when the slurry is not spread on the fields within 21 to 90 days. If spreading of the acidified slurry is delayed more than 90 days, then the pH should be verified in order to ensure that it is still less than 6.0, or more acid should be added. a pH below 6.0 should be applied as fertilizer within 24 hours; the pH should be maintained

5.2.3 Advantages and disadvantages

In theory, methane emissions from housing and outdoor storage could be substantially reduced, due to inhibition of methanogenic bacteria at the low pH. Similarly, potential nitrous oxide emissions from storage could be reduced, if acidification prevents a surface crust formation, due to the reduced microbial activity in the slurry.

Moderate decrease in manure pH through acidification significantly reduces NH_3 volatilization and CH_4 losses from stored manure. The effect on N_2O emissions following soil application is not well studied and may be increased if the inverse relationship between NH_3 and N_2O emissions holds in this case.

Emissions of VOCs and odors from the oxidation reaction occur due to the addition of a strong acid. Manure acidification leads to qualitative changes in odor emissions, rather than an increase in overall odor. Odor peaks can arise as a result of daily aeration/mixing and pumping of manure. There is a potential for gaseous hydrogen sulphide emission if sulphate is reduced to H_2S in stored slurry, provoking odor problems (Denmark, 2012). If acidified slurry is used in a biogas plant, there is a theoretical risk of bacterial inhibition based on the high proportion of acidified slurry.

The economic cost of H_2SO_4 should also be considered when applying this technology. Meanwhile, this technology should be managed carefully as H_2SO_4 is a material with a high safety risk.

5.2.4 Mitigation potential

Petersen et al. (2012) studied the effect of acidification on CH_4 (and NH_3) emission from fresh and aged cattle manure during three months of storage. Acidification had a dramatic effect on emissions, reducing CH_4 by 67% to 87% (more pronounced with aged manure) and almost completely eliminating NH_3 emissions. The authors concluded that manure acidification may be a cost-effective GHG mitigation practice.

From a whole-farm assessment carried out in Denmark on the basis of laboratory tests simulating slurry storage, the reduction of methane is reported as being from 3.29 kg to 2.2 kg per ton of slurry stored in houses, and 1.94 kg to 0.78 kg per ton of slurry in storages. The reduction of N_2O is reported as being from 0.013 kg to 0.0022 kg per ton of slurry from housing, and 0.033 kg to 0.021 kg per ton of slurry from storages.

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5.3. Anaerobic digestion

Sha Wei and Seyyed Hassan Pishgar-Komleh

5.3.1 Technical principles

Anaerobic digestion is the process of degradation of organic materials by archaea in the absence of oxygen, producing biogas (CH_4, CO_2) and other gases as by-products and is a promising practice for capturing GHG gasses from collected manure. The main components of biogas are methane (50–70%) and carbon dioxide (40–50%) depending on the substrate used and pathogens conditions (like pH and temperature) (Zhang et al., 2014). Other minor components are: H_2S, H_2O, NH_3 and N_2O.

In general, digesters operate with a maximum dry matter content of 12%, and at a constant temperature (with up to 2°C variation) of 30–45°C (mesophilic) or 52–55°C (thermophilic, with an accepted temperature variation of only 0.5°C). Biogas plants operating at mesophilic temperatures are therefore easier to run.

Co- and mono digesters are both used in animal industry. Mono-digestion means only one type of manure is used as raw material. Co-digestion means more than two types of raw material is used for digestion, including manure from different sources, straw, silage, food waste, etc. Usually, the co-digester can achieve a balanced raw material for digestion, such as with a suitable C/N ratio of 20-30 (Li et al., 2011). The biogas output is low when using mono-digester, and co-digestion can considerably increase biogas output (Hoang et al., 2020).

5.3.2 Technical considerations relevant to implementation

A high level of technical knowledge is needed on-farm to proper manage the production of medium and large-scale biogas digesters. The medium and large-scale biogas digesters are usually installed in intensive dairy farms which may produce large amounts of manure, requiring high investments in the installation.

The process of mesophilic anaerobic digestion takes place in large digestion tanks, in one or two stages, and the hydraulic retention time is 15–40 days. Propellers are normally installed in the digestion tanks to ensure the digestate remains homogeneous and gives a maximum release of biogas. In case of thermophilic digestion, the digester is heated to 55 °C and digestion takes 12–14 days. However, the technology is more expensive, since more energy and more sophisticated control instruments are needed. The advantages of thermophilic plants are higher levels of biogas production, faster throughput, improved hygienisation of the digestate, and lower viscosity during the process, facilitating mixing.

The condition necessary for the successful formation of methane is minimum water content of 50% in the initial substrate (373, UBA). The biogas production potential depends largely on the type of manure. Around 14–25 m^3 of biogas production per m^3 of slurry may be obtained (or even higher when pig slurry is digested), containing around 60–65% methane. Calculations for biogas plants in Denmark show an average production of 22 m^3 of biogas per ton of pig slurry containing 6% dry matter (on average).

There are a few side notes that should be considered related to this measure:

- The digestate manure at the end of biogas production process is still biologically active and contains large amount of degradable organic matter, thus causing the high remained CH_4 producing potential during the latter storage period. The CH_4 emission from the storage of the digestate and digested slurry should be eliminated such as using cover or acidification.
- Biogas installation requires investment in technological equipment. For industrial-scale biogas digesters used to produce renewable energy for towns, sound infrastructure is needed.
- In regions with high temperatures, fermentation processes go faster, and gas production can be high. Many practical initiatives currently focus on providing biogas installations. However, maintenance of such installations and knowledge needed to operate the installation is a point for attention. By contrast, in regions with average temperatures below 15°C, anaerobic digesters are not recommended without supplemental heat control, since lower temperatures reduce the production of biogas (Sommer et al., 2007).

5.3.3 Advantages and disadvantages

An airtight vessel can prevent anaerobic methane from being released into the environment. Using digested slurry instead of raw slurry can reduce NH_3 emissions during land spreading stage (Chantigny et al. 2007), and NH_3 is the indirect emission resource of GHG. Meanwhile, anaerobic digestion improved bioavailability of nitrogen, leading to decreased use of mineral fertilizers which can reduce GHG emission caused by mineral fertilizer use. Odors during both the slurry storage period and manure land application period will be reduced after anaerobic treatment (due to lower dry material content).

Ammonia emissions from storage of the digested slurry can be high. The higher content of NH_4-N can lead to higher ammonia losses from storage and/or land spreading, compared with raw slurry. Due to the reduced content of organic matter, a natural crust is seldom formed on top of the liquid when it is stored in tanks, leading to a higher potential for emissions to air. Other typical uncontrolled losses of CH_4 from biogas production systems, including gas leakages and gas collection areas, were reported to range from 5 to 20 percent of total biogas produced (Bjurling and Svärd, 1998; Sommer et al., 2001). Storages should be covered and/or slurry should be immediately cooled.

5.3.4 Mitigation potential

Due to the general manure management required by the anaerobic digester, it is estimated that total farm emissions are reduced by 40% for ammonia, while odor and methane are reduced by 80% (Santonia et. Al., 2017). N_2O emissions associated with anaerobic digestion are reported to be negligible, compared to the overall annual N_2O emissions from the farm.

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5.4. Composting

Sha Wei and Yue Wang

5.4.1 Technical principles

Composting is the controlled aerobic degradation of organic matter. Solid manure, mixed or not with vegetal organic matter is used in the process. The aim of the technique is to facilitate naturally occurring microflora to degrade cellulose and other carbon compounds in the manure to produce a material that is friable and sufficiently stable for storage and transport and that has a reduced volume. Composted solid manure (following manure separation into solid and liquid fractions) is also being used as bedding in some dairy production systems to reduce cost of bedding material and provide cow comfort.

Different composting systems include: (1) composting with mechanical reversal of heaps, (2) static aerated piles, and (3) composting in-vessel (with forced aeration). For heap composting, the manure is usually arranged in windrows (long heaps with a trapezoidal or triangular section, typically 1–3 m high, 2–5 m wide and of indeterminate length) and monitored for temperature and moisture. The windrows are turned over and mixed periodically using conventional loading machinery (e.g., a bucket loader) or another available farmyard machinery (e.g., windrow turner). Static aerated pile is an alternative method, which uses air supplied by perforated piping or a porous floor below the pile, therefore avoiding the reversal and mixing. Aeration can be forced (air is forced into the composting material) or passive (convective movement of air into the composting material). For composting in-vessel, composting is carried out in closed, aerated vessels (e.g., concrete silos/tanks, channels or film). The bottom of these modules is equipped with a system of perforated pipes, allowing forced aeration by blowing air into the substrate.

5.4.2 Technical considerations relevant to implementation

The key operating parameters and transformation requirements are reported below: (1) Moisture content between 40% and 70%; (2) Oxygen supply > 0.5 mg/l; (3) Porosity of the heap between 30% and 60% (as air-filled porosity); (4) Carbon/Nitrogen ratio (C/N) in the range of 20–35; and (5) Temperature of the heap above 50°C for 1 week or above 45°C for 2 weeks (NY/T 1168-2006).

The technique requires enough space available for windrows to be established. Composting should not be carried out on filtering soils, on waterlogged soils, or on sloped land. The process is relatively simple and can be applied on small-scale individual farms, using standard farm equipment, but it needs proper control to avoid anaerobic processes that could lead to an odor nuisance.

Air scrubbing systems for manure composting facilities are well tested as an additional method to reduce NH_3 emissions from this source but have substantial costs. No composting installation at the farm scale is reported to be equipped with air cleaning systems.

Hardened ground or anti-seepage measures are necessary for heap composting. If the heap is put on soil and not on an impermeable base, part of the nitrogen that sinks into the soil is evaporated, and plants use part of it after removal of the heap. Depending on the amount of run-off, the soil surface and the soil type, part of the nitrogen may also leach into the surface waters or groundwater.

5.4.3 Advantages and disadvantages

Composted solid manure has little odor, is more stable, contains fewer pathogens and is relatively dry. This improves handling, storage, transportation and land spreading without the risk of transferring diseases (e.g., land spreading on ready-to-eat crops) and bring additional farm income (TWG ILF BREF 2001; DEFRA 2011). Transport costs are reduced due to the significant reduction of mass due to water evaporation.

In partly aerobic conditions, such as in unsealed manure heaps, a part of the inorganic nitrogen (10–55 % of the nitrogen) is lost through volatilisation as ammonia emissions. N_2O emissions and NO_3- losses as leachate may also occur (IRPP TWG 2013).

There is an obviously trade-off by using composting. Aeration of composting heap reduces CH_4 emissions (Thompson et al., 2004; Jiang et al., 2011b; Park et al., 2011) but can increase NH_3 and N_2O losses (Tao et al., 2011). Depending on the intensity of composting, NH_3 losses can be particularly high, reaching up to 50% of the total manure N (Peigné and Girardin, 2004).

5.4.4 Mitigation potential

30% DM, 53% C, and 42% of the initial N are being lost during composting of straw-bedded manure. Methane losses accounted for 6% of the C losses and N_2O losses represented 1 to 6% of the total N losses (Hao et al., 2004). Usually, N_2O is the major contributor of GHG during manure composting process (Pattey et al., 2005).

It was found that CH_4 emission could be reduced by increasing the frequency of turning every 1, 3 and 7 days (Jia, 2015). Increasing the turning frequency from 1 to 2 times a week results in 50% reduction in CH_4 (Jiang et al., 2011; 2015). Reducing turning frequency not only reduce NH_3 and N_2O emissions, but also increase CH_4 emissions.

When the ventilation rate increased from 0.18 L/min/kg DM to 0.54 L/min/kg-1DM, CH_4 was reduced by 90% (Jiang et al., 2011; 2015).

When the material moisture content is 60%-70%, it is beneficial to N_2O emission reduction (Wu et al., 2012). Increasing water content from 45% to 66% resulted in 49-60% reduction in N_2O emission (El Kader et al., 2007).

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5.5. Manure application: from spreading to injection

Sha Wei and Seyyed Hassan Pishgar-Komleh

5.5.1 Technical principles

Manure (liquid or solid) land spreading, and the irrigation of wastewater are commonly applied techniques. Slurries and solid manures are valuable fertilizers but may also be potential sources of pollution. Different amounts of valuable mineral elements (i.e., plant nutrients) contained in the manure can be lost as emissions during and after land spreading, if land-spreading is not done properly. Typically, solid manure is applied to the soil surface. Liquid manure or slurry can be applied to the soil with different methods including i) surface spreading, ii) surface spreading + tillage, where the applied manure is tilled into upper layer of soil, ii) shallow injection, and iv) deep injection to a depth more than 10 cm. These approaches can be applied before planting (or after harvest season) and during growing period (just between rows). However, tillage is not an option in perennial crops due to root damage. Surface spreading is a common practice of manure application but results in the loss of N and P components (e.g., loss of ammonia due to volatilization and phosphorus runoff) and can cause odor issues. Placing manure below soil surface reduces these environmental issues. Before application of manure on land, various factors such as storage conditions (temperature and duration) can have influence on organic matter content, nutrients and also emissions after application of manure on soil. Manure application is the last stage of farm manure handling and represents a crucial step to reduce emissions. Besides application methods, some other parameters such as manure composition and soil conditions (soil type, moisture and management) play important roles on the emission potential of manure applied to soil. Therefore, a set of factors (pre-application treatments and soil and manure conditions) along with the method of applying manure on soil should be considered to reduce GHG emissions of manure. Generally, CH_4 and N_2O (direct and indirect) are the main gases produced due to improper manure application methods. Emissions of CH_4 after application on soil is not significant due to large losses from enteric fermentation and manure storage. Manure application method has impact on direct and indirect N_2O emissions and dilution, and injection are the most common approaches to reduce GHG emission potential during manure application on soil.

Besides the application method, some other strategies can be considered which in combination with the application method will lead to lower level of GHG emissions. Applying manure based on the needs of the plant reduces the N_2O losses. Manure application timing is also important. The emissions are high when the manure is applied during autumn or winter seasons. Therefore, it is strongly recommended to shift the application to spring season as the nutrient can being absorbed timely by the plant. Emissions can also be reduced by avoiding manure application on wet soils. Urease and nitrification inhibitors have been shown to be effective in reducing N_2O production and also reduce nitrate leaching, with important co-benefits for water quality, though the identification of some inhibitor residues in milk has raised concern about food safety.

5.5.2 Technical considerations relevant to implementation

Overall, lowering the concentration of N in manure, preventing anaerobic conditions or reducing concentration of degradable manure C are successful strategies for reducing GHG emissions from manure applied to soil (Gerber et al. 2013). As it has been mentioned, pre-application treatments have impact on effectiveness of manure application methods. For example, separation of manure solids, dilution and anaerobic degradation pre-treatments can mitigate CH_4 and N_2O emission from subsurface-applied manure, which may otherwise be higher than from surface-applied manure. Injection of manure slurries into the soil results in anaerobic conditions and together with the high degradable C pool increases the production of CH_4 and N_2O compared to the surfaces applied methods (Amon et al. 2006; Clemens et al. 2006). Timing of the manure application (e.g., avoiding application before a rain) and maintaining soil pH above 6.5 may decrease N_2O emissions.

5.5.3 Advantages and disadvantages

The main advantage of manure injection into soil is reduction in production of CH_4 and N_2O from applied manure. Sub-surface injection leads to higher control on the amount of available nitrogen for nitrification and denitrification in soil as well as the availability of degradable carbon and soil oxidation reduction-potential which reduce N_2O emissions. Injection of manure can greatly reduce odor issues compared to spreading of manure on land. Liquid manure injection in a proper time (prior to seeding or during the growing season) reduces N volatilization losses and provides the plant the required N. Therefore, indirectly it reduces the consumption of N fertilizer on arable lands. Injection also reduces the risk of P runoff and loss of particulate P due to less tillage operation. Since for manure injection no tillage operation is needed, it allows farmers to apply manure to the growing crops such as grass, alfalfa, etc. Injection preserves more soil organic matter compared to the tillage-based manure application methods. Besides the advantages, there are some disadvantages or limitations regrading manure injection method. Initial investment of injection equipment is high. Moreover, manure injection is a time-consuming operation. Compared to surface manure application, ground speed of machinery is lower, therefore injection requires more time, fuel and labor. It also may delay planting crops. Applying manure injection machineries and equipment requires high skills and farmers may need extra training for applying the manure with related equipment.

5.5.4 Mitigation potential

One of the main advantages of manure injection is reduction of N losses (in forms of NH_3, NO_3-and etc.) during land application. Emissions of NH_3 can be minimized if the slurry/manure was incorporated into soil immediately after being applied on the soil. Based on previous studies around 40-90% of total NH_3 lost on the first two days after surface application of cattle slurry (Menzi et al., 1998; Meisinger and Jokela, 2000). Deep injection of slurry reduces NH_3 losses to 0.02 of total N applied on average which is equal to a 90% reduction compared to surface application (Rotz, 2004). On grasslands, shallow injection leads to around 70-73% reduction in NH_3 losses (Rotz, 2004; Misselbrook et al., 2002). Regarding the direct N_2O losses, the soil condition (moisture content) plays an important role where the results of Sistani et al. (2010) and Flessa and Beese (2000) have shown that slurry injection decreases N_2O losses in dry soil (well drained soils) while in moist soils, anaerobic conditions facilitate N_2O production. However, improper management during manure injection results in increasing N_2O emissions of manure in soil as the formed anaerobic conditions together with the high degradable C pool increases the production of CH_4 and N_2O compared to the surfaces applied methods (Amon et al. 2006; Clemens et al. 2006). Dilution, solid separation and anaerobic digestion pre-treatment reduces the availability of degradable C and leads to reduction of N_2O emissions.

Table 1. Mitigation potential with manure land injection

Type of injection	Type of gas	Mitigation potential (%)
Shallow injection (open slot)	NH_3	70-73% compared to surface application
	N_2O	Depending on the soil condition, it varies
Deep injection (closed slot)	NH_3	90% compared to surface application
	N_2O	Depending on the soil condition, it varies

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6. Energy management

6.1. Production of renewable energy (biogas/wind/solar)

Yue Wang and Sha Wei

6.1.1 Technical principles

The potential use of heat produced by cogeneration of heat and power using biogas and the use of other biogenic energy or renewable energy (wind, solar and geothermal energy) to cover part of the energy demand of the farm are also options with positive effects on the environment.

Solar or wind-driven generators are more frequently installed in China. Solar radiation can easily be converted into heat, either being used for heating water or generating electricity. Solar power supply depends very much on the weather conditions, while windmills attached to a generator can supply power, particularly in areas with relatively high wind speed. For an animal farm, biogas can be easily achieved if the produced manure was treated by anaerobic fermentation. The resulting biogas (approximately 50–75 % methane and 30–40 % carbon dioxide) provides a source of renewable energy. This power can replace fossil fuel use, which can be used for heating and/or for generating electricity, thus reducing the CO_2emission sourcing from the fossil fuel use.

6.1.2 Technical considerations relevant to implementation

Solar heating panel technology used for electricity is unsuitable for use in areas with low light intensity and short sunshine duration, meanwhile, the technology can’t be used in areas with hard water.

Solar and wind power may not be steady because of the weather conditions. The biogas production was usually abundant in summer, while the biogas production would be low in winter especially in small farms with no advanced technology and infrastructure; leading to the situation that the biogas production can’t meet the demand of the farm in the winter. Therefore, the fossil fuel and electricity should be supplemented timely under these conditions.

6.1.3 Advantages and disadvantages

For the livestock farms located in rural areas with no adequate supply of electricity, but with abundant solar energy or wind power, this renewable energy can help the development of the livestock farming in these areas. The produced energy can be used to substitute the purchased fossil fuel or electricity, which help reduce the cost of the farm, also reducing the fossil fuel and electricity caused GHG emission. Meanwhile, the solar heating panel can be installed on the roof of the barn, which can avoid the extra land needed; the panels on the roof can also protect the barn from direct sunshine, thus helping to cool or giving shade for animals during hot summer periods.

Besides the unsteady production of the energy, the high investment of the infrastructure is also a disadvantage of these technologies.

6.1.4 Mitigation potential

Li et al. (2014) reported a solar warm-water project used in Heilongjiang Province in cold winter, with water being heated by solar heating panel, and then being used for dairy cow drinking. With an outdoor temperature of -25.3^{o}C and an indoor temperature of -2- -3^{o}C, solar warm-water project was able to supply drinking water with a temperature of 14.6^{o}C, which can increase milk yield by 2.6 kg per cow daily, and also earn 9.0 more RMB per cow daily. With the increased milk yield, the GHG emission per kg of milk was reduced accordingly.

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6.2. Energy saving technologies to reduce fossil energy use

Sha Wei and Yue Wang

6.2.1 Technical principles

This paragraph is about measures to reduce the use of fossil energy, as well as the selection and application of appropriate equipment and proper design of the animal housing. Measures taken to reduce energy use often also contribute to a reduction of the annual operating costs.

The opportunities for savings in energy use can be ranked as reported:

- **Cooling**

  The energy demand can be reduced in hot climates, where there is a need to cool the buildings, by trees with a shadowing effect, preferably native species, planted along the long sides of the sheds. Such trees also favor the reduction of dust emissions and the dilution of odor emissions as well as mitigating the impact on the landscape.

  Control of ventilation rates is the simplest method of controlling the indoor temperature of animal housing. Energy-saving fans can also be part of the application of measures for cooling the cows in the buildings.
- **Lighting**
  - to replace conventional tungsten incandescent bulbs with more energy-efficient lights, such as fluorescent, sodium and LED lights.
  - to use dimmers for adjusting artificial lighting.
  - to adopt lighting controls using sensors or room entry switches.
  - to apply lighting schemes, for example using intermittent lighting of one period of light to three periods of darkness instead of 24 hours of light per day reduces the amount of electricity used by 30–75 % [IRPP TWG, 2011].
  - to allow more natural light to enter, e.g., by the installation of vents or roof windows.
- **Heat recovery**
- **Other consumption**

- The energy consumption level is also linked to the high-pressure cleaning devices for livestock houses and the removal of manure. The latter includes the stirring devices used to mix the manure in the storage tank before spreading.

6.2.2 Technical considerations relevant to implementation

Where electrical heating and lighting installations are still manually controlled, the adoption of simple thermostatic controls with 'dimmers' can return considerable energy savings. The use of automatically controlled management systems yields further energy savings. Investment costs and cultural resistance to the use of such equipment (which is often viewed as complex and difficult to operate) are impeding uptake.

6.2.3 Advantages and disadvantages

Electricity demand can be significantly reduced if houses are equipped with natural ventilation, rather than with forced ventilation systems. However, this is not always possible or desirable for every livestock type, in all climate zones and for all farm types.

6.2.4 Mitigation potential

The achieved energy savings are significant when the ventilation rate is properly managed.

Reference

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7. Carbon sequestration in soils

Theun Vellinga

7.1 The role of soil organic carbon

Soil organic carbon (SOC) is part of the soil organic matter (SOM); SOC is about 50 % of the SOM. SOM is very important in agricultural soils, it improves the soil structure, increases the soil fertility and increases the water holding capacity. Another important role of SOC is the sequestration of atmospheric carbon, which can help to mitigate climate GHG emissions.

7.2 The basic technical principle

The basic principle of SOM is the balance between addition of fresh organic matter to the soil and the mineralization of existing SOM (Tang et al, 2019). When addition is larger than mineralization, the soil acts as a sink, otherwise it is a source of atmospheric CO_2. The increase in SOM is not infinite, in the case of stable management situation and land use, there is a long-term equilibrium of SOM. This implies that C sequestration is only a short-term solution for mitigation (for a few decades).

This ultimate equilibrium depends on:

- the land use type (C stocks in forest, grassland or arable land will differ)
- the soil type: clay soils have a higher equilibrium than sandy soils
- climate (rainfall and temperature): the more rainfall, the higher SOM equilibrium value, the warmer the lower the SOM equilibrium.
- soil management: practices to change inputs and to change mineralization rate

Land use type and soil management can be affected by the farmer or other land users.

Due to the large variation in soil types, climatic conditions, location etc., it is necessary to tailor general guidelines.

7.3 Technical considerations relevant to implementation

Management options to increase SOM content in soils

General: a) avoid soil compaction, b) promote use of organic manures or other amendments, c) apply balanced fertilization (reduce high N applications, take care of P, K and other nutrients)

Grassland: a) keep permanent pastures as they are. Don’t change to rotation of grass and arable crops; b) grazing: see special section below; c) prevent grassland renovation; d) if necessary, deep rooting grasses can be used, although the benefits of these grasses can be offset by the higher fertilizer application rates.

The impact of grazing is often discussed. Due to a wide variation in local conditions (soil, climate etc.) the optimal stocking rate can be variable. Preventing overgrazing and shifting to light or moderate grazing is important. Stocking rates at an annual basis have to be adjusted, continuous grazing or rotational grazing are both applicable. The core is to reduce the perturbation by grazing animals to levels allowing the grass sward to recover. C4 grasses (warm season grasses) are more resilient to heavy grazing then C3 grasses (cold season grasses). Hence, customized solutions are necessary.

Arable land: a) no tillage or reduced tillage (with risk of increased N_2O emissions). This is not possible or risky for certain crops such as potatoes, onions etc. Some authors mention the need of low frequency tillage; b) crop selection or crop rotation; pay attention to the organic matter balance per crop and decisions about leaving crop residues in the field; c) application of cover crops/green manuring; d) irrigation, via the increase in biomass production, but also via addition of Ca^{2+} and Mg^{2+}, acting as components of soil inorganic carbon (SIC).

Use of biochar is often mentioned. Biochar is biomass after pyrolysis. Biochar converts fresh organic matter to a very stable C product. Effects of biochar can be positive till neutral. Biochar production in general competes with fresh organic matter and in case of biofuel production with animal feed (protein rich residues). Hence, advantages at a micro level can have its trade-offs at the macro level (Jeffery et al., 2015).

All practices mentioned above are ready for implementation. The key is careful management, organic matter balances at micro and macro level and tailoring practices to local conditions.

7.4 Advantages and disadvantages

The advantages of increased SOM contents are a) the better soil productivity, due to a higher fertility, higher water storage and better soil aeration; b) the higher resilience to extreme weather conditions like drought and heavy precipitation; and c) a lower susceptibility to wind erosion.

In general: the reduction of GHG emissions is important for sustainability reasons.

Although expectations regarding mitigation are high, the main reason for farmers to improve carbon sequestration first of all should be the agronomic benefits. A better soil quality pays off by better resilience of the soil, resulting in more stable crop yields.

- Mitigation of GHG emissions via C sequestration is a onetime event and cannot be continued for very long periods. As soon as an equilibrium is realized, the C sequestration stops and the art of maintaining that high SOC level becomes important. It means that in regions where high SOC stocks are present, the C sequestration potential is limited.
- Carbon sequestration is reversible: converting pasture into arable land, mismanagement and crops with negative organic matter balances can lead to a higher mineralization than sequestration rate. Especially land use change can cause high SOC release rates. Along with this, there is substantial risk of nitrate leaching to groundwater.
- Increasing SOC levels is a slow process, it takes many years before the agronomic benefits are clear. It is also a dynamic process, depending on actual growth and weather conditions. It requires patience and in some years the effect can be limited.
- Increasing SOM requires an investment in N and other nutrients. SOM is not only C. Moderate nutrient surpluses are required to allow plant material to be converted to SOM. These nutrients will be released via mineralization and contribute to soil fertility.
- Addition of organic matter from other locations can be beneficial. Please take into account that the amount of fresh organic matter is limited and that adding extra fresh organic matter on your locations can occur at the expense of additions to other locations. This is especially the case for organic manure and straw. The most beneficial way is to produce as much fresh organic matter as possible on the own farm. In arable

cropping, the choice of a crop and the application cover crops as green manure are important factors.

- Monitoring of SOC changes in soils is difficult: measurements show large variations within fields and over time (within one year) and the annual SOC additions are small compared to the standing stock, changes in SOC are often within the uncertainty range of the measurements. So, monitoring can (for now) only be based on calculations in relation to farm specific data on carbon balances and management. Hence, the monitoring is currently an uncertain basis for payments of bonuses or fines connected to the change in SOC on farm level.

7.5 Mitigation potential

Expectations about mitigation potential are high. Many publications, especially from commercial businesses, pretend to produce carbon neutral milk or beef due to carbon sequestration. This is not correct as shown by Garnett et al. (2018): even at low stocking rates the C-sequestration per ha will not outpace C-emission per ha caused by methane coming from enteric fermentation (see also table below).

- Preconditions to harvest full potential
- Due to variation in local conditions: collecting knowledge of local conditions, estimate sequestration potential and develop customized solutions, based on the aforementioned recommendations.
- Commitment to apply these solutions for a long time and land use has to change drastically compared to the current situation.
- Reduction in CO_2-eq per kg FPCM and in percentages

The mitigation potential in CO_2-eq per kg of milk is related to the stocking rate. Garnett et al (2018) have reviewed global studies and found a range of 0 – 3 tons of CO_2equivalents per ha per year in grasslands. The higher values will occur when current carbon stocks are low, e.g., on degraded pasture or former arable land.

With a milk production of 7000 kg per cow per year, the carbon footprint of the milk is about 1.5 kg CO_2-eq per kg. With an assumed stocking rate of 1 cow including replacement stock per ha, the total GHG emissions per ha will be 10500 kg CO_2-eq. The maximum sequestration potential will be about 28 %. But this is the absolute maximum, based on a pure grass-based system starting on former arable land. And it will decrease with time.

In more realistic combinations of existing permanent grassland and arable land (for fodder crops), the sequestration rate will be probably in the range of 0 to 500 kg CO_2-eq per ha, which results in maximum reductions as can be seen in the table below (table 2).

Table 2. Milk per cow: 7000 kg; GHG/kg milk: 1.5 kg; Sequestration/ha: 500 kg

Stocking rate	Milk /ha	GHG, kg/ha excl Cseq	GHG, kg/ha incl Cseq	GHG/kg milk, incl Cseq	Reduction in g/kg	Reduction in %
0.5	3500	5250	4750	1.357143	143	10
1	7000	10500	10000	1.428571	71	5
1.5	10500	15750	15250	1.452381	48	3

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Glossary

Age at first reproduction	The time spent between birth and first calving (farrowing).
Anaerobic	In the absence of oxygen, i.e., conditions conducive to the conversion of organic carbon into methane (CH_4) rather than carbon dioxide (CO_2).
Anaerobic digesters	Equipment where anaerobic digestion is operated, i.e., the process of degradation of organic materials by microorganisms in the absence of oxygen, producing CH_4, CO_2 and other gases as by-products.
Crop residue	Plant materials left in an agricultural field after harvesting (e.g., straw or stover).
Dairy herd	Consistent with definitions used in other assessments, this includes all animals in a milk-producing herd: milked animals, replacement stock and surplus calves that are fattened for meat production.
Emissions	Release to air and discharges to water and land that result in greenhouse gases entering the atmosphere. The main emissions concerning GHGs from agriculture are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4).
CO_2-equivalent emissions	Where several gases are being emitted, absolute greenhouse gas emissions are often expressed in an aggregated unit called "CO_2-equivalent" emissions, or CO_2-eq. CO_2-eq emissions are commonly calculated by multiplying the emission of each gas by its Global Warming Potential (GWP), which is a multiplier that accounts for the different warming effects and lifetimes of non-CO_2 greenhouse gases over a given time horizon compared to CO_2. GWPs are being updated regularly by the Intergovernmental Panel on Climate Change (IPCC). This brochure uses GWPs with a time horizon of 100 years, with values from the IPCC's Fourth Assessment Report issued in 2007. This is also used for reporting of emissions from 2013 onwards under the United Nations Framework Convention on Climate Change. GWP values are: 1kgCO_2 =1kgCO_2-eq; 1kgCH_4 =25 kg CO_2-eq; 1 kg N_2O = 298 kg CO_2-eq

On-farm emissions	Direct emissions generated within the boundaries of a farm.
Off-farm emissions	Direct emissions generated outside the boundaries of a farm but used to support production within that farm (e.g., emissions arising from supplementary feed produced off-site).
Enteric fermentation	A natural part of the digestive process for many ruminant animals where anaerobic microbes, called methanogens, decompose and ferment food present in the digestive tract producing compounds that are then absorbed by the host animal.
Feed balancing	The action of selecting and mixing feed materials (e.g., forages, concentrates, minerals, vitamins, etc.) to produce an animal diet that matches animal’s nutrient requirements as per their physiological stage and production potential.
Feed digestibility	Determines the relative amount of ingested feed that is actually absorbed by an animal and therefore the availability of feed energy or nutrients for growth, reproduction, etc.
Greenhouse gases	Greenhouse gases (GHG) are gaseous constituents of the atmosphere (both natural and resulting from human activities) that absorb and emit thermal infrared radiation. A build-up of the concentration of those gases due to human activities causes global average temperature to increase and the climate to change; this is also referred to as the enhanced greenhouse effect. Agriculture is primarily responsible for the direct on-farm emission of two green- house gases, methane (CH_4) and nitrous oxide (N_2O), with additional direct on-farm and off-farm emissions or removals of carbon dioxide (CO_2) from changes in soil carbon, energy use, and indirect CO_2 emissions from the production of fertilizer and deforestation.
Inhibitor	A chemical substance that reduces the activity of some micro-organisms. In agriculture, urease and nitrification inhibitors are used to reduce the break-down of animal excreta into nitrate and nitrous oxide in soils, while methane inhibitors are intended to reduce the activity of methane-generating microbes in the rumen of animals.

LCA	Life cycle assessment (LCA) is a tool for evaluating environmental effects of a product, process, or activity throughout its life cycle or lifetime, which is known as a ‘from cradle to grave’ analysis. In this report about the LCA of milk the system, boundaries are “from cradle to farm gate”. This means the whole life cycle of raw milk from the production of inputs to products leaving the farm-gate, i.e., excluding transport or processing of raw milk. Related transport associated with the production of purchased inputs was included.
Mitigation potential	In the context of climate change, the mitigation potential is the number of emissions reductions that could be – but are not yet – realized over time. In this report, the mitigation potential is given as those emissions reductions that are technically feasible at relatively low costs, but without taking account of barriers that may make it difficult to achieve those emissions reductions in practice.
Productivity	Amount of output obtained per unit of production factor. In this report, it is mostly used to express amount of product generated per unit of livestock and time (e.g., kg milk per cow per year).
Ruminant	Ruminants are mammals that are able to acquire nutrients from plant-based food by fermenting it in a specialized stomach (the rumen) prior to digestion, principally through bacterial actions. The process typically requires the fermented ingesta (known as cud) to be regurgitated and chewed again. The process of rechewing the cud, which further breaks down plant matter and stimulates digestion, is called rumination. Major ruminant animals considered in this report include cattle, sheep and goats. See also Monogastric.
Replacement rate	The percentage of adult animals in the herd replaced by younger adult animals each year.
Trade-off	The negative effects that a policy or measure aiming at one objective might have on other objectives. For example, the primary goal of a change in farm practice may be to increase profitability per hectare, but it may result in increased leaching of nitrate into waterways.

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