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CGIAR RESEARCH PROGRAM ON Climate Change, Agriculture and Food Security
CGIAR RESEARCH PROGRAM ON Livestock

Protocol for generating region-specific Tier 2 emission factors for methane (CH_4) and nitrous oxide (N_2O) emissions from cattle manure

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Centre

Protocol for generating region-specific Tier 2 emission factors for methane (CH_4) and nitrous oxide (N_2O) emissions from cattle manure

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Abbreviations and acronyms

MMS manure management system

SSA sub-Saharan Africa

IPCC Intergovernmental Panel on Climate Change

AEZ agroecological zone

FAO Food and Agriculture Organization of the United Nations

HH household

GHG greenhouse gas

EF emission factor

MCF methane conversion factor

1 Background

Livestock manure is a substantial source of the three greenhouse gases (GHG)—methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). The highest CH_4 emissions are typically associated with liquid-based manure management systems (MMS), where a large portion of manure decomposes anaerobically. In contrast, N_2O emissions vary significantly between individual MMS, and can also originate indirectly from nitrogen (N) that is lost during manure storage and handling (i.e. volatilization and leaching). For simplification, the term "manure" in this protocol includes both the solid (dung) and liquid (urine) component of animal excreta, since the separation of liquid and solid excreta remains yet uncommon in smallholder and pastoral farming systems in sub-Saharan Africa (SSA). CO_2 emissions from livestock manure are not accounted for in this protocol because these emissions ultimately originate from CO_2 that has been fixed during plant photosynthesis and therefore annual net CO_2 emissions are assumed to be zero.

2 Objective

The objective of the data collection and calculations described below is to generate more accurate region-specific emission factors (EF)—i.e. the amount of CH_4 or N_2O originating from livestock manure produced in kilograms per head of animal and per year—for manure management systems in sub-Saharan Africa. This protocol is predominantly based on the Intergovernmental Panel on Climate Change (IPCC) Tier 2 calculations, which are more precise than the commonly used Tier 1 approach (for a more detailed description, the reader is advised to consult the IPCC Guidelines for National Greenhouse Gas Inventories (2006), or any later available version). The present protocol on manure GHG emissions is directly linked to the Protocol for generating improved region-specific emission factors (EF) for cattle enteric methane emissions based on on-farm activity data collection (Marquardt et al. 2019), hereafter called "Protocol for cattle enteric methane emissions", which is based on approaches of Goopy et al. (2018) and Ndung'u et al. (2018), and uses equations published in CSIRO (2007), which are different from the IPCC approach for enteric CH_4 emission estimation (IPCC 2006). The approach presented here allows to include seasonality—i.e. changes in feeds and animal performance, and subsequently manure quality—which is currently not included in the IPCC approach. As there is an overlap in the data that are required to estimate both emission sources, and because manure emissions cannot be estimated without animal data, some of the equations for manure GHG emission estimation in this protocol have been modified to match the data collected for enteric CH_4 emissions.

Please note that this protocol is designed for cattle data. For small ruminants, partially different equations are required.

Data requirements

For Tier 1 and Tier 2 manure EF calculations, the following data on climate and livestock characteristics must be collected for the target region. This should be done jointly with the data collection for enteric CH_4 emissions calculation ("Protocol for cattle enteric methane emissions").

2.1 General data

- Climate information for the target region must be collected including, at a minimum, mean annual temperature, mean annual precipitation, start and end of dry and wet seasons and relative distribution of rain over the seasons. This can be done via your own climate stations (there are simple models that record precipitation and air temperature as a minimum), or via external data sources (e.g. from local meteorological services, government agencies, nearby weather stations, universities, etc.). The climate information is used to allocate the target region to an agroecological zone (AEZ) to make results comparable across different regions and countries. For this, it is strongly recommended to follow the Food and Agriculture Organization of the United Nations (FAO) Agro-Ecological Zoning Guidelines (FAO 1996) as this allows comparability to other studies.
- Total livestock numbers per category (i.e. species, sex, age class, purpose) in the target region are essential for GHG emission calculations. Livestock categories are specified in Table 1. These data can be obtained from

national or regional livestock census data, provided by ministries of agriculture/livestock or local authorities, or from FAOSTAT. If no such data are available, then livestock numbers must be approximated via extrapolation from surveys performed during the data collection for enteric CH_4 emission calculation ("Protocol for cattle enteric methane emissions").

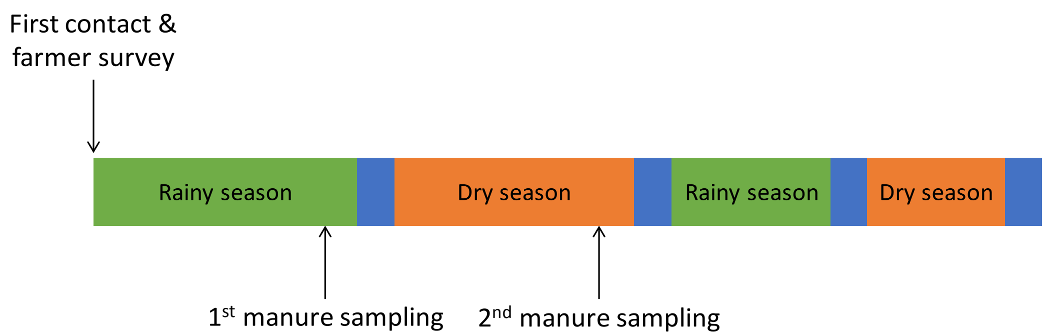
2.2 Data to be collected in the field

- A household (HH) survey on manure management (farmer interview, see supplementary material) to identify the type and contribution of different MMS in the target region must be conducted. This survey must be done in all the HHs included in the study, which must be the same as the HHs that are investigated for the estimation of enteric CH_4 emissions. A description of HH selection is given in the "Protocol for cattle enteric methane emissions".

- Manure characteristics can be determined in the laboratory as described in section 4. For this, samples of fresh manure (≤24 hours after excretion) are taken on a subsample of the farms under investigation. While not every farm needs to be sampled, the collected manure in the field should originate from a minimum of 12 farms with the same MMS and located within the same AEZ. To reflect seasonality, samples should be collected at least in one rainy and one dry season, in the second half of the season (Figure 1). If laboratory measurements are not feasible, default factors of manure characteristics in Africa can be taken from the IPCC Guidelines for National Greenhouse Gas Inventories (2006) and its recent refinement (IPCC 2019). However, readers should be aware that true Tier 2 GHG emission estimation, at a minimum, needs country-specific data on manure characteristics.

2.3 Example sampling schedule for data collection and farm visits

Figure 1: Example of a sampling schedule for a study region with bimodal rainfall (i.e. two rainy and two dry seasons)



- First contact and manure survey: this includes the introduction to the farmer/head of the HH and the researcher who estimates enteric CH_4 emissions (can be the same person if the number of sampled HHs is <50), and farmer interview on manure management

- First manure sampling: this is the first onfarm sampling of fresh manure or slurry. It should be done in the second half of the first season (either dry or rainy season), before the start of the transition period.

- Second manure sampling: the second onfarm sampling of fresh manure or slurry should be done in the second half of the other season, before the start of the transition period.

3 Definition of livestock categories and manure management systems (MMS)

Table 1. Definitions of livestock categories (based on Goopy et al. 2018)

<table>
<tr><th>Category*</th><th>Subcategory</th><th>Definition</th></tr>
<tr><td rowspan="5">Dairy cattle</td><td>Adult female (>2 years)</td><td rowspan="5">Dairy cattle are cattle breeds that are either high-producing purebreds or have been improved to produce more milk via crossbreeding of local breeds with high-yielding breeds (e.g. Holstein-Friesian and Ayrshire).</td></tr>
<tr><td>Adult male (>2 years)</td></tr>
<tr><td>Heifer (1–2 years)</td></tr>
<tr><td>Young male (1–2 years)</td></tr>
<tr><td>Calves (<1 year)</td></tr>
<tr><td rowspan="5">Other cattle</td><td>Adult female (>2 years)</td><td rowspan="5">“Other cattle” are all cattle that are not improved breeds. This also includes indigenous cattle (e.g. Zebu and Boran), which produce milk for human consumption but whose main purpose is something other than dairy production (e.g. meat, ploughing and draught power).</td></tr>
<tr><td>Adult male (>2 years)</td></tr>
<tr><td>Heifer (1–2 years)</td></tr>
<tr><td>Young male (1–2 years)</td></tr>
<tr><td>Calves (<1 year)</td></tr>
</table>

*The present protocol focuses on emissions from cattle manure only. A version for small ruminants (sheep and goats) is in preparation and will be published later.

Table 2/IPCC Table 10.18 Definitions of manure management systems (with modifications to highlight MMS which are relevant for SSA)

System	Definition
Manure management systems commonly found in SSA	
Pasture/range/paddock	The manure from pasture and range grazing animals is allowed to lie as deposited and is not managed. See Figure 4.
Daily spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. See Figure 4.
Solid storage (manure heap or stockpile)	The storage of manure, typically for a period of several months, in unconfined heaps or stacks. Manure can be stacked due to the presence of bedding material or loss of moisture by evaporation (see Figure 3). This is one of the major MMS in Kenya (Owino et al., personal communication).

System	Definition
Dry lot (boma/kraal)	A paved or unpaved open animal confinement area without any significant vegetative cover where accumulating manure may be removed periodically. Manure often accumulates over weeks or months before it is removed and either used for fertilization of own crop fields, sold, or burned. Corrals like "bomas" (Kiswahili) and kraals (Afrikaans) typically found in pastoral systems, belong to this category. See Figure 5.
Pit storage below or behind animal confinements	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility, or behind the facility, usually for periods less than one year. See Figure 6.
Anaerobic digester	Animal excreta with or without straw are collected and anaerobically digested in a containment vessel or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4, which is captured and flared or used as a fuel.
Burned for fuel	The dung and urine are excreted on fields, in bomas or in barns. The sun-dried dung is collected and burned for fuel, for example for cooking or baking bread. See figure 6.
Composting – passive windrow*	Manure and other farm waste is stacked on heaps or in long piles (windrows) with infrequent turning for mixing and aeration (O_2 supply). Composting material is turned mechanically or manually (Misra, Roy and Hiraoka 2003). This MMS can sometimes be found in smallholder farms in SSA.
Liquid/slurry	Manure is stored as excreted or with some minimal addition of water in either tanks or earthen ponds outside the animal housing, usually for periods less than one year.
Manure management systems that are more common in industrialized, large-scale farming operations	
Uncovered anaerobic lagoon	A type of liquid storage system designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields.
Deep bedding	As manure accumulates, bedding is continually added to absorb moisture over a production cycle and possibly for as long as six to 12 months. This MMS is also known as a bedded pack MMS and may be combined with a dry lot or pasture.
Composting (static pile)*	Composting in piles that are not mixed for the duration of the composting process and have forced aeration via aeration pipes or fans that deliver O_2 to the composting material and provide air circulation for controlled aeration.
Composting (intensive windrow)*	Manure and other farm waste is stacked in long piles (windrows) that are regularly (at least daily) turned for mixing and aeration. The composting material is often turned with a front-end loader, bucket loader, or special compost turner.
Composting (in vessel)	Composting, typically in an enclosed channel, with forced aeration via aeration pipes and continuous mixing via an automated stirring system.
Aerobic treatment of slurry	The biological oxidation of manure collected as a liquid with either forced or natural aeration. Natural aeration is limited to aerobic and facultative ponds and wetland systems and is due primarily to photosynthesis. Hence, these systems typically become anoxic during periods without sunlight.
*Contrary to the colloquial use of the term "compost" for the combined storage and decomposition of manure in a pile with other waste (kitchen waste, green waste, stover, etc.), composting is, strictly speaking, the biological oxidation of a solid waste and therefore requires a form of aeration either via manual or mechanic turning of the composting material, or via aeration structures such as pipes and fans.	

The following are some examples of manure management systems commonly found in East Africa.

Figure 2: Solid storage of manure in dry heaps, together with bedding material that soaks up urine in the animal confinement (photo credit: ILRI/Sonja Leitner)

Figure 3: Daily spread of manure from animal barn to an adjacent maize field (left). Pasture/range/paddock where animals can graze freely and deposited manure remains in the field uncollected (right) (photo credit: ILRI/Sonja Leitner)

Figure 4: Dry lot (also called corrals, bomas or kraals) typically found in pastoral systems. Usually, animals are confined there overnight to protect them from wild animals and theft. Manure often accumulates over weeks or months before it is removed and used for fertilization of crop fields, sold, or burned. These pictures were taken during the rainy season and show the high moisture content of the manure, which promotes CH_4 and N_2O formation (photo credit: ILRI/Sonja Leitner)

Figure 5: Pit storage below animal confinement, typically located below a slatted floor (left). Pit storage behind an animal barn (the pit is shown on the left side of the picture, the pit edges are overgrown by vegetation), where manure and bedding are deposited when the barn is cleaned out on a daily or weekly basis (in this case, manure is first thrown over the barn wall and then moved into the pit) (left). Depending on manure moisture content, pit storage can promote anaerobic conditions and with that CH_4 and N_2O emissions. (Photo credit: ILRI/Sonja Leitner)

Figure 6: Manure burned as fuel. Here manure is collected from a barn and dung cakes are formed by hand, then left in the sun to dry. In other regions, manure deposited by grazing animals is left on the pasture to dry and then is collected later. Dried manure is often stacked for storage before it is used as fuel for cooking or baking. (Photo credit: ILRI/Sonja Leitner)

4 Manure sampling and sample transport

The following is a description of manure sample collection, transport, storage, sample preparation, and analysis of manure properties in the field and laboratory.

4.1 Manure sample collection

- To derive data about manure chemistry used by the IPCC emission factor (EF) calculations, fresh manure must be sampled within 24 hours of excretion. To determine the effect of seasonality, manure must be sampled at least twice a year, during one rainy and one dry season (in the second half of the season and when the weather is representative, for example not during a dry spell in the rainy season or directly after a heavy rain in the dry season).
- To derive information on total manure quality on the farm (e.g. to determine nutrients available for fertilization after manure storage), a composite sample of the MMS on the farm (e.g. solid storage in a manure heap) must be obtained. This is not the focus of this protocol. For more details on sampling of manure storage systems in SSA please refer to Teenstra et al. (2015).

4.2 Manure sample transport and storage

Because manure is rich in C, N and other nutrients while simultaneously containing many active microorganisms, it must be kept cool to avoid degradation (nutrient loss etc.) during transport and before laboratory analysis. If possible, manure samples should be kept in Ziploc bags or (in the case of slurry) in plastic bottles in the fridge at 4°C or in a cooling box on ice, and it should be analysed within 7–14 days. If longer storage is unavoidable, then the manure sample should be split into two aliquots; aliquot 1 should be kept in closed Ziploc bags in a cool box for determination of the field moisture content (section 3), and aliquot 2 should be air dried by keeping the Ziploc bags open. Use of paper bags is not feasible, unless the manure sample is already very dry. Before laboratory analysis, manure samples must be thoroughly mixed to ensure a homogeneous sample. If manure samples are sent to the laboratory by mail, transit should not take longer than two days. Therefore, only collect samples until Wednesday so that shipping can be scheduled, and samples do not get held during weekends.

5 Manure laboratory analyses

5.1 Manure moisture content

Weigh 10 g of fresh manure in triplicates into pre-weighed weighing pans and dry in an oven at 60°C until constant weight (usually 72 h, can be longer if the sample is very wet). Put the hot pans into a desiccator to cool down for at least 30 min, then weigh them again. The moisture content is expressed on a fresh weight (FW) basis as follows (Equation 1):

Equation 1 $$Moisture\ content\ (\%) = \frac{weight_{wet}\ (g) - weight_{dry}\ (g)}{weight_{wet}\ (g)} * 100$$

Note: Manure should not be dried at temperatures >60°C as this will lead to loss of organic matter and overestimation of the moisture content. When results are presented (e.g. in a publication), it should, however, be noted that the moisture content was determined after drying at 60°C.

5.2 Concentration of ash and volatile solids (VS) in manure samples (total combustion)

Use manure that has been dried at 60°C (see section 5.1 Manure moisture content). Weigh aliquots of 1 g in triplicates into pre-weighed porcelain crucibles and place them into a muffle furnace. Slowly heat the furnace up to 575°C over a period of 2 hours, then maintain temperature at 575°C for 4 hours. Slowly let the furnace cool down. Do not open the furnace door during the cooling down period as this can damage the furnace! Transfer the crucibles into a desiccator using forceps and let them cool to room temperature. Determine the weight of the remaining material ($weight_{ash}$). Manure ash and VS concentrations are expressed on a dry-matter basis as described below (Equation 2 and Equation 3):

Equation 2 $$ASH\ [\%\ dw] = \frac{weight_{crucible+ash}\ [g] - weight_{crucible}\ [g]}{weight_{dry}\ [g]}$$

Equation 3 $$VS\ [\%\ dw] = 100 - ASH\ \ [\%\ dw]$$

6 Calculation of CH_4 emissions from manure

This section describes the calculation of CH_4 emissions from manure, which is in principle based on the IPCC Tier 2 approach from 2006 (IPCC 2006). The IPCC guidelines from 2006 are currently being revised with a new version from 2019. Once these new guidelines are available, the equations in this protocol will be updated accordingly. Wherever equations are taken from the IPCC Guidelines, the numbering, as in this document, is retained (e.g. Equation 8/IPCC 10.22 corresponds to the 8th equation in this manual, which is equal to Equation 10.22 in the IPCC 2006 Guidelines). Furthermore, some equations have been modified to match the variables used for estimation of enteric CH_4 emissions (following the “Protocol for cattle enteric methane emissions”). Whenever possible, actual input variables must be determined for the respective livestock species, MMS, and target region, as these vary with climate, animal category and forage quality. However, if this is not feasible, default values for SSA from the IPCC (2006) are provided, but the reader must be advised that using default values reduces the validity of calculated emissions.

How to calculate total CH_4 emissions from manure management (Equation 4):

Equation 4/IPCC 10.22

$$CH_{4\ manure} = \sum_{(T)} \frac{(EF_T * N_T)}{10^6}$$

Where

$CH_{4\ manure}$ = total CH_4 emissions from manure management in the target region [Gg CH_4 yr^{-1}]

EF_T = emission factor for entire livestock population in the target region [kg CH_4 $head^{-1}$ yr^{-1}]

N_T = number of head of livestock per species and category *T* in the target region.

T = species and category of livestock

According to the IPCC Tier 1 approach, the default EF for CH_4 from cattle manure for SSA is 1 kg CH_4 $head^{-1}$ yr^{-1} (IPCC 2006, p. 10.39), assuming that cattle in SSA spend most their life grazing on pastures and that manure remains unused on the pasture, where it rapidly dries out and CH_4 production is low. However, this is a strong oversimplification and underestimates manure CH_4 emissions in regions where zero-grazing (cut-and-carry) systems are common and manure is managed in heaps or pits (Tongwane and Moeletsi 2018). And even in pastoral regions cattle are commonly kept in enclosures (corrals, kraals or bomas) overnight, where manure piles up to thick layers that after their abandonment are nutrient hotspots for centuries (Muchiru et al. 2009; Vuorio et al. 2014) or even millennia (Marshall et al. 2018) and are important sources of CH_4 emissions at the landscape level. Therefore, it is important to determine region-specific emission factors (EF) for CH_4 for each animal category, which consider the MMS used in reality and their associated manure characteristics, as well as the effects of seasonality (e.g. changes in feed basket composition and their consequences for digestibility) and AEZ (e.g. a warm and humid climate promotes CH_4 formation).

The IPCC Tier 2 approach relies on two manure characteristics that affect the formation of CH_4 in manure: (1) the total amount of volatile solids (VS) that are excreted with the manure, and (2) the maximum or potential methane producing capacity of the manure itself (B_o).

VS is the amount of dry organic matter that is stored on the farm in a MMS and can be converted to CH_4. VS can be indirectly estimated based on feed intake and digestibility (see "Protocol for cattle enteric methane emissions") to calculate the amount of VS that is excreted by the animals every day (Equation 7).

B_o is the maximum amount of CH_4 that can potentially be produced under conditions that promote methanogenesis. These are anaerobic conditions (without any O_2) at ideal moisture and temperature (which varies with latitude). B_o is rarely reached under ambient conditions where factors such as the drying of manure, the formation of a crust on the manure that is inhabited by CH_4 consuming bacteria, or the aeration during turning of manure heaps, reduce CH_4 formation. Therefore, different MMS are associated with a respective methane conversion factor (MCF), which represents the fraction of B_o that is achieved during manure management. MCF can theoretically range from 0 to 100% and is highly dependent on temperature, duration of manure storage and manure quality. For example, when manure is stored as a liquid in a warm climate, MCF can be as high as 60 to 80%. When it is managed as dry material under colder temperatures, MCF is about 1% (Woodbury and Hashimoto 1993).

The following equation (Equation 5) describes the calculation of region-specific EF for animal categories and MMS.

Equation 5/IPCC 10.23

$$EF_T = (VS_T * 365) * \left[B_{o(T)} * 0.67 * \sum_{S,k} \frac{MCF_{S,k}}{100} * MS_{T,S,k}\right]$$

Where

EF_T = annual CH_4 emission factor for livestock category *T* [kg CH_4 animal^{-1} yr^{-1}]

VS_T = daily volatile solid excreted from livestock category *T* [kg dry matter animal^{-1} day^{-1}]

365 = conversion factor for calculating annual VS production

B_o = maximum CH_4 production capacity for manure produced by livestock category *T* [m^3 CH_4 kg^{-1} VS]

0.67 = density of CH_4 gas to convert from m^3 to kg (kg m^{-3})

$MCF_{S,k}$ = methane conversion factor for manure management system *S* by climate region *k* [%]

$MS_{T,S,k}$ = fraction of the manure from livestock category *T* that is handled using manure management systems *S* in climate region *k*

Daily VS excretion can be estimated from feed intake and digestibility as follows (Equation 6):

Equation 6/IPCC 10.24

$$VS = \left[GE * \left(1 - \frac{DE\%}{100}\right) + (UE * GE)\right] * \left[\frac{1-ASH}{18.45}\right]$$

Where

VS = volatile solid excreted per animal per day based on gross energy intake and feed digestibility [kg dry matter day^{-1}]

GE = gross energy intake [MJ day^{-1}]

DE% = digestibility of the feed [%]. This should be assessed for each season depending on the dry matter digestibility of the feed basket, which is determined by the "Protocol for cattle enteric methane emissions".

UE*GE = urinary energy expressed as fraction of GE. For most ruminants, urinary energy excretion is 0.04*GE, while it is 0.02*GE for ruminants fed with >85% grain.

ASH = ash content of manure calculated as fraction of dry matter feed intake (0.08 for cattle, IPCC 2006)

18.45 = conversion factor for dietary GE per kg of dry matter [MJ kg^{-1}]

The above Equation 6/IPCC 10.24 can be rewritten as follows (Daemmgen et al. 2012) to use dry matter intake of feed (DMI, in kg, as is determined by the "Protocol for cattle enteric methane emissions"), instead of gross energy intake of feed (GE, in MJ), by dividing GE by 18.45 (conversion factor for dietary GE per kg of dry matter, in MJ kg^{-1}). Furthermore, manure ash content (ASH, in %) can either be directly measured in the lab, or the default factor of 8% for cattle can be used. Furthermore, according to Kool et al. (2006) 90 to 95% of the VS in urine are urea and allantoin, which are hydrolyzed to CO_2 and NH_3 within hours after excretion and are therefore not relevant for CH_4 production.

Equation 7

$$VS = \left[DMI * \left(1 - \frac{DE\%}{100}\right)\right] * \left[1 - \frac{ASH\%}{100}\right]$$

Where

VS = volatile solid excreted per animal per day based on dry matter intake and feed digestibility [kg dry matter day^{-1}]

DMI = daily dry matter intake [kg $animal^{-1}$ day^{-1}]

DE% = digestibility of the feed [%]. This should be assessed for each season (see "Protocol for cattle enteric methane emissions").

%ASH = ash content of manure (default value is 8% for cattle, IPCC 2006)

B_o is the maximum methane producing capacity of the manure. It can either be obtained from country-specific published sources, or it can be measured in the laboratory using a standardized method (ISO11734 1995). It is important to standardize the B_o measurement, including the method of sampling, incubation temperature and incubation time. If laboratory measurements of B_o are not possible, or if country-specific values for VS and B_o are not available, the IPCC recommends the use of the following VS and B_o factors for Africa (Table 3).

Table 3/IPCC Table 10A-4 through 10A-9: Default values for animal live weight (LW), maximum CH_4 producing capacity (B_o), and total excreted volatile solids (VS) for Africa

Livestock category	LW (kg)	B_o (m^3 CH_4 kg^{-1} VS)	VS (kg $head^{-1}$ day^{-1})
Dairy cattle	275	0.13	1.9
Other cattle	173	0.1	1.5
Sheep	28	0.13	0.32
Goats	30	0.13	0.35
Camels	217	0.21	2.49

The last factor that is required for the Tier 2 CH_4 emission calculation is the methane conversion factor (MCF). This factor describes the percentage of the maximum methane producing capacity (B_o) that is reached under field conditions. It strongly depends on the type of MMS, because methanogenesis is very sensitive to O_2 exposure, moisture, temperature, and duration of storage (Le Mer and Roger 2001). Therefore, the IPCC provides MCF values for every MMS and a wide range of mean annual temperatures (Table 4). To account for seasonality, the MCF value for the mean temperature of each season should be used to calculate CH_4 emissions per season, and then the emissions of the different season are added to give annual CH_4 emissions.

Table 4/IPCC Table 10.17: Methane conversion factors (MCF) for different manure management systems and temperatures

Manure management system*		MCFs by mean annual temperature (°C)																		
		Cool					Temperate											Warm		
		≤ 10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	≥ 28
Manure management systems commonly found in SSA																				
Pasture/Range/Paddock		1.0%					1.5%											2.0%		
Daily spread		0.1%					0.5%											2.0%		
Solid storage (manure heap or stockpile)		2.0%					4.0%											5.0%		
Dry lot (boma/kraal)		1.0%					1.5%											2.0%		
Pit storage below or behind animal confinements	<1 month	3%					3%											30%		
	>1 month	17%	19%	20%	22%	25%	27%	29%	32%	35%	39%	42%	46%	50%	55%	60%	65%	71%	78%	80%
Anaerobic digester[a]		0–100%					0–100%											0–100%		
Burned for fuel		10%					10%											10%		
Composting – passive windrow		0.5%					1.0%											1.5%		
Liquid/Slurry	With natural crust	10%	11%	13%	14%	15%	17%	18%	20%	22%	24%	26%	29%	31%	34%	37%	41%	44%	48%	50%
	Without natural crust	17%	19%	20%	22%	25%	27%	29%	32%	35%	39%	42%	46%	50%	55%	60%	65%	71%	78%	80%
Manure management systems that are more common in industrialized large-scale farming operations																				
Uncovered anaerobic lagoon		66%	68%	70%	71%	73%	74%	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%	80%	80%
Deep bedding	<1 month	3%					3%											30%		
	>1 month	17%	19%	20%	22%	25%	27%	29%	32%	35%	39%	42%	46%	50%	55%	60%	65%	71%	78%	80%
Composting (in vessel)		0.5%					0.5%											0.5%		
Composting (static pile)		0.5%					0.5%											0.5%		
Composting (intensive windrow)		0.5%					1.0%											1.5%		
Aerobic treatment of slurry[b]		0%					0%											0%		

* System definitions can be found in Table 2/IPCC Table 10.18

[a] Should be subdivided into different categories, considering the amount of recovery of the biogas, flaring of the biogas, and storage of the remaining manure ("bio-slurry") after digestion. Calculation with Formula 1 below (timeframe for inputs should reflect operating period of digester):

$$MCF = [\{CH_{4\,prod} - CH_{4\,used} - CH_{4\,flared} + (MCF_{storage} / 100 * B_o * VS_{storage} * 0.67)\} / (B_o * VS_{storage} * 0.67)] * 100$$

Where:

$CH_{4\,prod}$ = methane production in digester (kg CH_4). Note: when a gas-tight coverage of the storage for digested manure is used, the gas production of the storage should be included
$CH_{4\,used}$ = amount of methane gas used for energy (kg CH_4)
$CH_{4\,flared}$ = amount of methane gas flared (kg CH_4)
$MCF_{storage}$ = methane conversion factor for the methane gas emitted/leaked during storage of digested manure (%)
$VS_{storage}$ = amount of volatile solids excreted that goes to storage prior to digestion (kgVS)
When a gas-tight storage is included: $MCF_{storage}$ = 0; otherwise $MCF_{storage}$ = MCF value for liquid storage at respective ambient temperature

[b] Aerobic treatment can result in the accumulation of sludge, which may be treated in other systems. Sludge requires removal and has large VS values. It is important to identify the next management process for the accumulated sludge and to estimate the emissions from this management process.

7 Calculation of N_2O emissions from manure

There are both direct and indirect N_2O emissions from manure that occur after excretion in the animal facility, during manure storage, and during manure treatment before it is applied to land or otherwise used for fuel or construction purposes (Chadwick et al. 2011). Furthermore, there are N_2O emissions from manure after application to soils, but these are not covered in the present protocol. Direct N_2O emissions result from microbial nitrification and denitrification of N in the manure. Nitrification is the oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-) and requires O_2 availability. Denitrification is the reduction of NO_2^- or NO_3^- to N_2O and dinitrogen (N_2), a process that requires anaerobic conditions and availability of labile carbon (C), which is easily available in animal manure. Both processes depend on temperature, moisture, O_2, pH and storage duration (Butterbach-Bahl et al. 2013). Therefore, direct N_2O emissions from manure are highly variable for different MMS.

Indirect emissions of N_2O result from volatile N losses in the form of ammonia (NH_3) and nitric oxides (NO_x) that are lost during manure storage and management and deposited somewhere else, where those subsequently can lead to additional N_2O emissions. Ammonia emissions stem from the volatilization of NH_4^+, which in turn is produced during decomposition of organic N. This can be urea (mammals) and uric acid (poultry), that can be rapidly mineralized to NH_4^+, or more complex organic N substrates such as proteins. NH_3 is highly volatile and can contribute substantially to manure N losses. Nitrogen losses start after the excretion in animal confinements or pastures, continue through manure storage and treatment, and after application of manure onto fields. In addition to gaseous losses, N can also be lost via runoff and leaching into soils around animal confinements, on pastures, and at the location of manure storage and management. Nitrogen that is lost from manure decreases the amount of remaining N that is available for soil fertilization (FAO 2018).

The Tier 2 calculations of N_2O emissions from manure management are based on total amount of N excreted from all livestock categories that is handled in different MMS and which is multiplied with specific emission factors for each MMS. The livestock categories and MMS are the same as for calculation of CH_4 emissions from manure (Table 1 and Table 2).

Direct N_2O emissions from manure management (Equation 8):

Equation 8/IPCC 10.25

$$N_2O_{D(MM)} = \left[\sum_S\left[\sum_T\left(N_T * Nex_T * MS_{T,S}\right)\right] * EF_{3,S}\right] * \frac{44}{28}$$

Where

$N_2O_{D(MM)}$ = direct N_2O emissions from manure management in the region [kg N_2O yr^{-1}]

N_T = number of head of livestock species/category *T* in the region

Nex_T = annual N excretion rate per head of livestock category *T* [kg N $animal^{-1}$ yr^{-1}]

$MS_{T,s}$ = fraction of Nex for livestock category *T* in manure management system *S*

$EF_{3,S}$ = emission factor for direct N_2O emissions from manure management systems *S* in the region [kg N_2O-N kg^{-1} N] (Table 6)

S = manure management system

T = species/category of livestock

44/28 = conversion of N_2O-N to N_2O emissions (two N atoms per N_2O molecule)

step 1 To complete above Equation 8, use the same livestock categories (Table 1) and manure management classification (Table 2) as for the estimation of manure CH_4 emissions.

step 2 For annual N excretion rate per head (Nex), there are three options: it can be estimated using (i) a Tier 1 (Equation 9/IPCC 10.30) or (ii) a Tier 2 (Equation 10) approach, or (iii) default Nex values from the IPCC can be used (see Table 5 below).

step 3 Calculate fraction of Nex that is stored in each MMS based on animal number and class.

step 4 Use default N_2O EFs or – if available – use country-specific N_2O EFs for MMS.

step 5 For each manure management systems S, multiply its N_2O EF by the total amount of Nex from all livestock categories T that is managed in this system. Then sum over all manure management systems from each AEZ and season to get the direct N_2O emissions from manure management in that AEZ and season. Sum up over all AEZs and seasons to get total direct N_2O emissions for a region and year.

Estimation of annual N excretion rates (Nex):

Annual N excretion rates should be determined for each livestock category as they vary greatly between livestock species and diets. If no country- or region-specific Nex values are available, they can be estimated using the average animal weight and a default N excretion rate (Tier 1 approach):

Equation 9/IPCC 10.30

$$Nex_T = N_{rate(T)} \frac{LW_T}{1000} * 365$$

Where

Nex_T = annual N excretion for livestock category *T* [kg N $animal^{-1}$ yr^{-1}]

$N_{rate(T)}$ = default N excretion rate [kg N (1000 kg animal mass)$^{-1}$ day^{-1}]

LW_T = animal live weight for livestock category *T* in the region [kg $animal^{-1}$]

Live weight (LW) is determined during data collection for enteric CH_4 emissions ("Protocol for cattle enteric methane emissions"), or default values can be taken from Table 3 (Tier 1).

If the feed basket (contribution of available feeds to total diet) for the region is available, then the Tier 2 approach can be used, in which Nex is calculated based on animal N intake via feed (N_{intake}) and N retained for growth and milk production ($N_{retention}$) (Equation 10):

Equation 10/IPCC 10.31

$$Nex_T = N_{intake(T)} * (1 - N_{retention(T)})$$

Where

Nex_T = annual N excretion for livestock category *T* [kg N animal^{-1} yr^{-1}]

$N_{intake(T)}$ = annual N intake per head of animal of category *T* [kg N kg animal^{-1} yr^{-1}], see Equation 11

$N_{retention(T)}$ = fraction of annual N intake retained by animal of category *T*, see Equation 12

Total N intake (N_{intake}) is estimated based on dry matter intake (DMI) and nitrogen content (%N) of the feed (Equation 11). This should be calculated separately for each season.

Equation 11

$$N_{intake(T)} = DMI * \frac{N\%}{100}$$

Where

DMI = dry matter intake of the animal [kg animal^{-1} day^{-1}]

N% = N content of the feed basket in percent.

Total nitrogen retention ($N_{retention}$) for growth and milk production can be estimated as shown below (Equation 12). This should be calculated separately for each season:

Equation 12/IPCC 10.33

$$N_{retention(T)} = \left[\frac{Milk * \frac{Milk\ CP\%}{100}}{6.38}\right] + \left[\frac{LWG * \left[268 - \left(\frac{7.03 * NE_g}{LWG}\right)\right]}{6.25}\right]$$

Where

$N_{retention(T)}$ = daily N retained per animal of category *T* [kg N animal^{-1} yr^{-1}]

Milk = milk production [kg animal^{-1} day^{-1}] (applicable to lactating cows only). This information is derived from farm milk records (see “Protocol for cattle enteric methane emissions”).

Milk CP% = percent of crude protein in milk (applicable to lactating cows only). This is either directly measured (e.g. with a Lactoscan, see “Protocol for cattle enteric methane emissions”) or can be calculated as [1.9 + 0.4 * %Fat], where %Fat is either measured or assumed to be 4 %.

6.38 = conversion from milk protein to milk N [kg protein kg^{-1} N]

LWG = live weight gain per animal and season for each livestock category *T* [kg day^{-1}], calculated from animal LW measurements (“Protocol for cattle enteric methane emissions”).

268 and 7.03 = constants from Equation 3–8 in (NRC 1996)

NE_g = net energy for growth, based on current weight, mature weight, live weight gain, and IPCC constants; see Equation 13 [MJ day^{-1}]

6.25 = conversion from kg dietary protein to kg dietary N [kg protein (kg N)$^{-1}$]

Net energy for growth for cattle (NE_g) can be estimated as follows (Equation 13), which should be calculated separately for each season:

Equation 13/IPCC 10.6

$$NE_g = 22.02 * \left(\frac{LWmean}{C*MW}\right)^{0.75} * WG^{1.097}$$

Where

NE_g = net energy needed for growth [MJ day^{-1}]

LW_{mean} = mean live weight of the animals in the population for each season [kg], calculated from seasonal animal LW measurements ("Protocol for cattle enteric methane emissions").

C = coefficient with a value of 0.8 for females, 1.0 for castrates, and 1.2 for bulls (NRC 1996)

MW = mature live body weight of an adult female in moderate condition (BCS = 3) [kg]

WG = average daily weight gain of the animals in the population for each season [kg day^{-1}]

If the above mentioned methods for the estimation of Nex (Tier 1 or Tier 2) are not feasible, then the default values for Africa should be used:

Table 5/IPCC Table 10.19: Default values for nitrogen excretion rates (Nex) for different livestock categories for Africa

Livestock category	Nex (kg N (1000 kg animal mass)$^{-1}$ day^{-1})
Dairy cattle	0.60
Other cattle	0.63
Sheep	1.17
Goats	1.37
Camels	0.46

Table 6/IPCC Table 10.21: Default emission factors for direct N_2O emissions from manure management

System	EF_3 (kg N_2O-N kg^{-1} N excreted)	Uncertainty ranges of EF_3
Pasture/range/paddock	Direct and indirect N_2O emissions associated with the manure deposited on agricultural soils and pasture, range, paddock systems are treated in IPCC 2006, Chapter 11, Section 11.2, N_2O emissions from managed soils	
Daily spread	0	Not applicable
Solid storage	0.005	Factor of 2
Dry lot	0.02	Factor of 2
Liquid/slurry With natural crust cover Without natural crust cover	 0.005 0	 Factor of 2 Not applicable
Uncovered anaerobic lagoon	0	Not applicable
Pit storage below animal confinements	0.002	Factor of 2
Anaerobic digester	0	Not applicable
Burned for fuel	The emissions associated with the burning of the dung are to be reported under the IPCC category "Fuel combustion" if the dung is used as fuel and under the IPCC category "Waste incineration" if the dung is burned without energy recovery	

System	EF_3 (kg N_2O-N kg^{-1} N excreted)	Uncertainty ranges of EF_3
Cattle and swine deep bedding No mixing Active mixing	 0.01 0.07	 Factor of 2 Factor of 2
Composting – in vessel	0.006	Factor of 2
Composting – static pile	0.006	Factor of 2
Composting – intensive windrow	0.1	Factor of 2
Composting – passive windrow	0.01	Factor of 2
Aerobic treatment Natural aeration systems Forced aeration systems	 0.01 0.005	 Factor of 2 Factor of 2

Indirect N_2O emissions due to N volatilization from MMS:

First, calculate the amount of N that is lost via volatilization of NH_3 and NO_x (Equation 13):

Equation 13/IPCC 10.26

$$N_{Volatilization-MMS} = \sum_S \left[\sum_T \left[\left(N_T * Nex_T * MS_{T,S}\right) * \left(\frac{Frac_{GasMS}}{100}\right)_{T,S}\right]\right]$$

Where

$N_{Volatilization–MMS}$ = amount of manure N lost due to volatilization of NH_3 and NO_x [kg N yr^{-1}]

N_T = number of head of livestock species/category *T* in the region

Nex_T = N excretion rate per head of livestock category *T* [kg N $animal^{-1}$ yr^{-1}] (Equation 9)

$MS_{T,S}$ = fraction of annual N excretion for livestock category *T* managed in manure management system *S* in the region

$Frac_{GasMS}$ = percent of managed manure N for livestock category *T* that volatilizes as NH_3 and NO_x from manure management system *S* [%] (see Table 8 for IPCC default values)

S = manure management system

T = species/category of livestock

From this, calculate indirect N_2O emissions from N volatilization as follows (Equation 14):

Equation 14/IPCC 10.27

$$N_2O_{G(MM)} = \left(N_{Volatilization-MMS} * EF_4\right) * \frac{44}{28}$$

Where

$N_2O_{G(MM)}$ = indirect N_2O emissions from N volatilization in manure management [kg N_2O yr^{-1}]

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N onto soils and water surfaces [kg N_2O-N (kg NH_3-N +NO_x-N)$^{-1}$]. The default EF_4 is 0.01 (Table 8).

Indirect N_2O emissions due to N leaching from MM:

First, calculate the amount of N that is lost via leaching from manure (Equation 15). This should be calculated only for the rainy season.

Equation 15/IPCC 10.28

$$N_{Leaching-MMS} = \sum_S \left[\sum_T \left[\left(N_T * Nex_T * MS_{T,S}\right) * \left(\frac{Frac_{leachMS}}{100}\right)_{T,S}\right]\right]$$

Where

$N_{Leaching–MMS}$ = amount of manure-N that is lost due to leaching from manure [kg N yr^{-1}]

N_T = number of head of livestock species/category *T* in the region

Nex_T = N excretion rate per head of livestock category *T* [kg N $animal^{-1}$ yr^{-1}] (Equation 9)

$MS_{T,S}$ = fraction of Nex for livestock category *T* in manure management system *S*

$Frac_{leachMS}$ = % managed manure N losses for livestock category *T* due to run-off and leaching during storage from manure management systems *S* in the region [%, the typical range is 1-20 %]. Use country-specific values or default values (Table 8).

S = manure management system

T = species/category of livestock

From this, calculate indirect N_2O emissions from N lost via leaching as follows:

Equation 16/IPCC 10.29

$$N_2O_{L(MM)} = \left(N_{Leaching-MMS} * EF_5\right) * \frac{44}{28}$$

Where

$N_2O_{L(MM)}$ = indirect N_2O emissions due to leaching and run-off of N from manure management in the region [kg N_2O yr^{-1}]

EF_5 = emission factor for N_2O emissions from N leaching and run-off [kg N_2O-N (kg N leached)$^{-1}$]. The default EF_5 is 0.0075 (Table 8).

Table 7/IPCC Table 10.22: Default values for N loss due to volatilization of NH_3 and NO_x from manure management

Animal type	Manure management system[a]	N lost to volatilization of NH_3 and NO_x (%) $Frac_{GasMS}$ (Range of $Frac_{GasMS}$)
Dairy cattle	Dry lot (corrals/bomas/kraals)	20 % (10–35)
	Solid storage	30 % (10–40)
	Daily spread	7 % (5–60)
	Pit storage	28 % (10–40)
	Liquid/slurry	40 % (15–45)
	Anaerobic lagoon	35 % (20–80)
Other cattle	Dry lot (corrals/bomas/kraals)	30 % (20–50)
	Solid storage	45 % (10–65)
	Deep bedding	30 % (20–40)

[a]Manure management system here includes associated N losses at housing and final storage system

Table 8/IPCC Table 11.3: Default emission factors for N volatilization and redeposition (EF_4), N leaching (EF_5), N volatilization from organic fertilizer (applied manure and slurry) and dung and urine deposited by grazing animals ($Frac_{GASM}$), and N lost to leaching ($Frac_{LEACH}$). Please note that the calculation for N leaching should only be done for the rainy season.

Factor	Default value	Uncertainty range
EF_4 for N volatilisation and re-deposition [kg N_2O-N (kg NH_3-N + NO_x-N volatilized)$^{-1}$]	0.01	0.002–0.05
EF_5 for leaching and runoff [kg N_2O-N (kg N leaching/runoff)$^{-1}$]	0.0075	0.0005–0.025
$Frac_{GasM}$ for volatilization from dung + urine deposited by grazing animals [(kg NH_3-N + NO_x-N) (kg N deposited)$^{-1}$]	0.2	0.05–0.5
$Frac_{leachM}$ for N losses by leaching/runoff from N deposition by grazing animals during the rainy season [kg N (kg N deposited)$^{-1}$]	0.3	0.1–0.8

Finally, the amount of managed N remaining in manure available for application to managed soils or for use in feed after manure management can be estimated as follows (Equation 17):

Equation 17/IPCC 10.34

$$N_{MMS\_Avb} = \sum_S \left\{ \sum_T \left[\left[\left(N_T * Nex_T * MS_{T,S} \right) * \left(1 - \frac{Frac_{LossMS}}{100} \right) \right] + \left[N_T * MS_{T,S} * N_{beddingMS} \right] \right] \right\}$$

Where

N_{MMS_Avb} = amount of managed manure-N available for soil application [kg N yr^{-1}]

N_T = number of head of livestock per species and category *T* in the target region

Nex_T = annual N excretion rate per head of livestock category *T* [kg N animal^{-1} yr^{-1}] (Equation 9)

$MS_{T,S}$ = fraction of Nex for livestock category *T* managed in manure management systems *S*

$Frac_{LossMS}$ = amount of managed manure N for each livestock category *T* that is lost in manure management systems *S* [%] (see for IPCC default values)

$N_{beddingMS}$ = amount of N from bedding (only relevant for solid storage and deep bedding MMS) [kg N animal^{-1} yr^{-1}]. IPCC default values are shown in Table 9.

S = manure management system

T = species/category of livestock

Table 9. Default values for amount of nitrogen from bedding ($N_{beddingMS}$) for different livestock categories (IPCC 2006)

Livestock category	Manure management system	$N_{beddingMS}$ (kg N animal^{-1} yr^{-1})
Dairy cattle	Solid storage	7
	Deep bedding	14
Other cattle	Solid storage	4
	Deep bedding	8

Table 10/IPCC Table 10.23: Default values for total nitrogen loss from manure management

Animal category	Manure management system[a]	Total N loss from MMS $Frac_{LossMS}$ (Range of $Frac_{LossMS}$)
Dairy cattle	Dry lot (corrals/bomas/kraals)	30% (10 – 35)
	Solid storage	40% (10 – 65)
	Daily spread	22% (15 – 60)
	Pit storage	28% (10 – 40)
	Liquid/slurry	40% (15 – 45)
	Anaerobic lagoon	77% (55 – 99)
Other cattle	Dry lot (corrals/bomas/kraals)	40% (20 – 50)
	Solid storage	50% (20 – 70)
	Deep bedding	40% (10 – 50)

[a]Manure management system here includes associated N losses at housing and final storage system

8 Documentation and quality control

- Always document every step of the entire process from field work, sample analysis in the lab, data cleaning/quality control up to emission calculation with as much detail as possible. This includes noting problems that occurred at the various steps as well as potential modifications of the described methods that might become necessary when unforeseen situations occur.
- When doing household interviews, make sure that the interviewee is well informed about the purpose of this study and the expected duration of the interview to avoid unpleasant surprises for both you and the interviewee. Also keep in mind that due to cultural differences, different people will understand interview questions differently. Therefore, take time to make sure the interviewee understands the question well before they answer it. If a person does not want to give an answer to one or more questions, do not force them but try to understand why they are hesitating. Maybe a solution can be found. If not, move on to the next question and respect their privacy.
- When taking samples in the field, always ensure that all samples are properly labelled with date, location, household ID, researcher name, and sample type. Also keep a proper field book and record any additional information that might be useful for analysis or interpretation of the data (e.g. weather conditions).
- When doing any type of laboratory analysis, always make sure to use proper protective equipment where required. Only perform analyses after being trained and after having undergone laboratory induction by your supervisors or a laboratory technician. Keep a proper lab protocol and make sure to document all the performed analysis steps. Also take technical notes regarding used chemicals, equipment, duration, etc. The more information you document, the easier it will be to solve problems later.
- Calculations of emissions need to be cross-checked by your supervisors. To avoid complications at the end of the data analysis, this should happen on a regular basis during one-on-one meetings. If you have questions, be proactive and contact your supervisor for clarification.
- This protocol is work in progress. Currently, the authors of this protocol have some experience with different MMS in livestock systems from Kenya, Tanzania, Ethiopia and Uganda (e.g. cut-and-carry systems, semi-pastoral systems), and this protocol tries to reflect this knowledge by providing guidance on how to best determine manure GHG emissions from these systems. As more livestock systems in sub-Saharan Africa are investigated, our knowledge on the peculiarities of these systems will increase and the present protocol will be refined and updated. However, the authors emphasize that this protocol should not be taken as a universal "cookbook" for all of sub-Saharan Africa because each country or region may have special conditions that require adaptation of the described approaches.

9 Packing list of items to be taken to the field

- Tablet for manure management survey
- Field book and pen
- Navigation device to find GPS coordinates (can be a mobile phone with Google maps)
- Camera to take pictures in the field (after obtaining consent from the farmer)
- Shovel for collecting manure samples (if laboratory analyses are planned)
- Ziplock bags for packing manure samples (if laboratory analyses are planned)
- Permanent marker to label sample bags (if laboratory analyses are planned)
- Cooling box and ice for manure sample storage and transport (if laboratory analyses are planned)

10 Parameters required by this protocol that are derived from the "Protocol for cattle enteric methane emissions"

All parameters should be derived separately for each season (at least one rainy and one dry season).

- LW (animal live weight) = TAM (typical animal mass) [kg]
- LGW (animal live weight gain) [kg day^{-1}]
- DMI (dry matter intake) [kg $animal^{-1}$ day^{-1}]
- $\%N_{feed}$ (nitrogen concentration of the feed) [%]
- $\%DE_{feed}$ (digestibility of the feed) [%]
- Milk (milk production) [kg $animal^{-1}$ day^{-1}] → applicable to lactating cows only
- Milk CP% = percent of crude protein in milk → applicable to lactating cows only

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