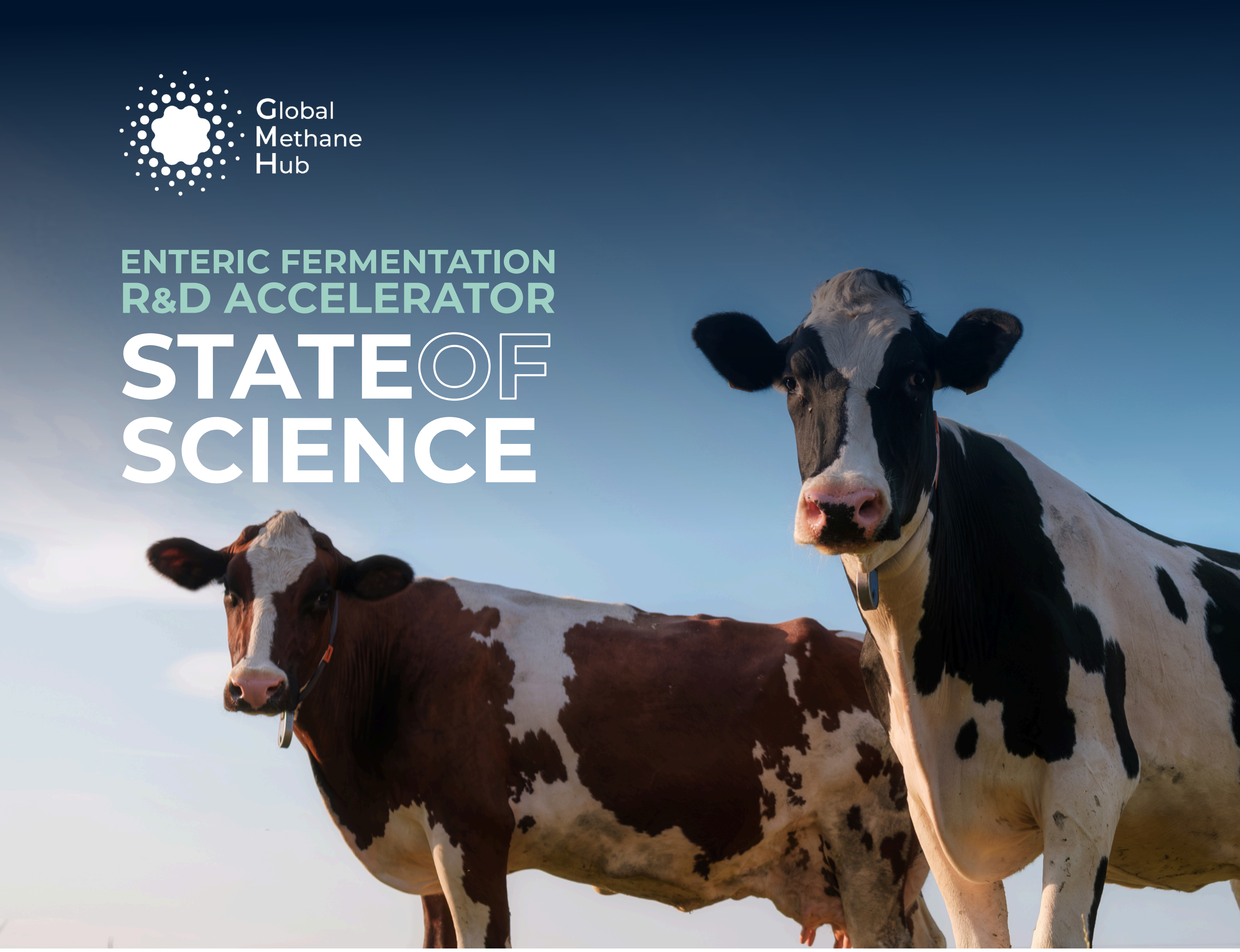

ENTERIC FERMENTATION R&D ACCELERATOR

STATE OF SCIENCE

Enteric Methane Measurement

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There is a critical need to develop simple to use, low-cost, reliable and accurate methods of measuring enteric CH_4 from individual animals and from groups of animals, especially for grazing ruminants. The current lack of cost-effective measurement tools is a major limitation to developing CH_4 mitigation techniques, assessing on-farm responses to mitigation, and refining CH_4 emission factors for GHG inventories. Development of CH_4 measurement technology is a high priority for meeting the global commitment to CH_4 reduction. The measurement techniques currently in use have important limitations, as discussed in detail by Tedeschi et al. (2022) and Patra (2016). The techniques are briefly described below with the main uses of each technique listed in Table 1. There is no single "gold" standard measurement technique; rather the selection of a specific technique depends on cost, technical skill, constraints imposed by the measurement conditions, and the purpose of the measurement.

Table 1. Summary of the main uses of the various enteric CH_4 measurement techniques

Technique	Research: Diet and feed additive assessment	Research: Animal breeding	On-farm assessment	Refining GHG inventories
Respiration chambers	yes	no	no	yes
Hoods	yes	no	no	yes
Portable accumulation chambers	no	yes	yes	no
Tracer gas technique	yes	no	yes	yes
GreenFeed system	yes	yes	yes	yes
Sniffers	no	yes	yes	no
Hand-held laser	no	no	possibly	no
Inverse dispersion technique	possibly	no	yes	yes
Drones	possibly	no	yes	yes
Eddy covariance technique	no	no	yes	yes
Aircraft	no	no	yes	yes
Satellite	no	no	no	yes

Techniques used to assess CH_4 emissions from individual animals

The characteristics of the techniques used to measure CH_4 from individual animals is summarized in Table 2.

Respiration chambers

Respiratory chambers are enclosures or rooms that house a single animal with many different chamber designs in use around the world. When properly calibrated and operated, chambers provide accurate and precise measurements of daily CH_4 emissions from individual animals (grams/day), as well as diurnal patterns of emissions. Assessing the diurnal pattern of emissions can help researchers understand whether a particular feed additive needs to be dosed more frequently to maintain a persistent CH_4 reduction. A major advantage of chambers is that the dry matter intake is known, and therefore the CH_4 emission can be scaled to intake. However, chambers are expensive to construct, require advanced technical know-how to operate, and are limited to research. Also, animals may decrease intake while in the chamber and thus the chamber may not represent a farm environment. Using chambers limits the number of animals that can be used in a study. The main advantage of chambers is their accuracy and precision, as they can be calibrated using a gas release and recovery technique. One serious limitation is that in some research labs the recovery is poor (< 90%), and thus a large correction factor needs to be applied.

Hoods

Ventilated hoods and headboxes use principles similar to respiration chambers. The hood covers the animal's head while providing access to feed and water. Depending upon the design of the hood, measurements may be continuous or mainly during feeding events, in which case the emission may overestimate the daily emission (Troy et al., 2016). The main advantage is that they are considerably less expensive to construct than whole animal chambers, but the disadvantage is the disruption to the normal behavior of the animal. Not all animals can be trained to use these systems.

Portable accumulation chambers (closed chambers)

A portable respiration chamber is a large box-like enclosure that can be placed over an animal (usually sheep) for a short period of time (~2 h) to enable the gas to build up. The air is sampled and CH_4 is measured at the end of the period. The advantage of the system is its portability allowing it to be used with grazing animals particularly small ruminants. The limitation is that only a portion of the 24 h cycle is represented, and thus the technique is more useful for animal breeding studies for which daily CH_4 production is not always needed unlike for mitigation studies.

Tracer gas technique

The tracer gas technique can be used to estimate a daily emission (grams/day) for individual animals; however, it uses the potent greenhouse gas SF6 as a tracer. A known quantity of SF6 is released over time from a bolus placed into the animal's rumen. The animal's breath is continuously sampled into an evacuated container which is usually replaced

Table 2. Summary of pros/cons of various measurement techniques used to measure enteric CH_4 from individual animals.

	Respiration chambers	**Hoods**	**Portable accumulatio n chambers**	**Tracer gas technique**	**GreenFeed system**	**Sniffers and hand held lasers**
Whole animal emissions	yes	no	yes	no	no	no
No. of animals that can be measured	few	few	moderate	moderate	moderate	large
Individual feed intake	yes	yes	depends	depends	depends	depends
Accuracy	high	moderate	moderate	moderate	moderate	low
Grazing	no	no	possible	possible	possible	no
Restricts animal behavior and movement	yes	yes	yes	no	no	no
Technically demanding	high	high	high	high	low	low
Portability	low	low	high	high	moderate	depends
Cost/animal	high	moderate	moderate	low	high	low

daily. The CH_4 emission is calculated from the known release rate of the tracer gas and the ratio of expired CH_4 and tracer gas concentrations in the collection container while accounting for background concentrations of these gases. Accuracy of the technique is often affected by inconsistent release of SF6 and equipment failure, thus measurements need to be repeated over a number of consecutive days with animals handled daily. It is difficult to use the tracer gas technique in buildings because of interference from background gas concentrations in ambient air. The technique is relatively inexpensive, but requires technical skill and a gas chromatograph is needed to analyze the gas samples. The SF6 boluses have a relatively short life expectancy (6 to 8 months). Also, there is no way to perform a whole-system calibration. Another major limitation is that when used with grazing animals, the dry matter intake is not known (or is crudely estimated) and therefore the CH_4 emission cannot be scaled to intake. The technique is useful for assessing CH_4 mitigation as it provides an estimate of the daily emission of individual animals.

GreenFeed system (manufactured by C-Lock, Rapid City, SD)

The GreenFeed system estimates an average daily CH_4 emission over time by averaging spot sample measurements taken at various times during a 24-h cycle and over many consecutive days. Its growing popularity stems from its ease of use, the ability to make measurements on a large number of animals, and the fact that the animals can be maintained in farm-like conditions. An advantage of the GreenFeed system is that it can be used with animals that are grouped in pens or maintained on pastures (approx. 25 animals/system). However, it is very expensive per animal due to the initial equipment purchase and yearly user fee. Another limitation is that it is not possible to perform a whole-system calibration. The system consists of a head chamber with an overhead hopper programmed to deliver a small amount of "bait" feed to the animal. Once the animal's head is near the sensor, the increase in CH_4 and CO_2 concentration due to the animal's breath is measured. The gas concentrations and airflow rate in the collection pipe are used to calculate a flux each time the animal visits the system. The fluxes determined at each visit are then averaged over the measurement period (multiple days) to determine an average daily CH_4 emission (rather than an emission on a specific day as is the case with chambers). It is important that animals visit the GreenFeed system over the 24 h day such that the diurnal pattern of CH_4 is represented. However, animals tend not to enter the system at night when emissions are typically low, which creates bias in the calculations of the daily emission. Additionally, grazing animals may not be enticed to enter the system when pastures are lush. Similarly to the tracer technique, when used with grazing animals, the dry matter intake is not known (or is crudely estimated) and therefore the CH_4 emission cannot be scaled to intake. Also the "bait" feed used in the GreenFeed system represents about 10% of the feed intake, and therefore influences diet composition. The technique is useful for assessing CH_4 mitigation as it provides an estimate of the daily emission of individual animals.

Sniffers

Sniffers can be installed at automatic milking machines or feeders to provide spot readings of CH_4 and CO_2 concentrations every time the animals access the equipment. Therefore, numerous repeated measures can be made on a large number of animals over time. The ratio of CH_4:CO_2 is useful for animal breeding studies that rank animals as low-emitters based on concentration ratios. Concentration ratios do not provide a daily CH_4 emission value for the animals, but daily CH_4 production is not always needed for animal breeding studies unlike mitigation studies. Some have proposed using CO_2 as a tracer gas to calculate the flux, similar to using SF6 with the tracer gas technique, but in this case the daily production of CO_2 is estimated from the heat produced by the animal (Madsen et al., 2010). Heat production is used to estimate O_2 consumption and CO_2 emission, which requires detailed information on body weight, milk production and composition, body weight gain, and feed intake. However, feed intake is difficult to measure in grazing and group-penned animals and is generally therefore roughly estimated, which creates uncertainty in the estimate of CH_4 production.

Hand-held laser

The operator manually holds the laser at 1 to 3 m from the animal's mouth/nostrils and the CH_4 concentration is determined. The advantage is that the laser is non-obtrusive, easy to operate, a large number of animals can be measured, animals are in their normal environment, and the measurement of concentration is immediate. However, the hand held laser technique is similar to a sniffer in that it measures concentration and does not provide a flux. Some studies have developed prediction equations to estimate a daily CH_4 emission rate from the CH_4 concentration. However, accuracy is low and the technique is not useful for assessing CH_4 mitigation.

Techniques used to assess CH_4 emissions from groups of animals

The characteristics of the techniques used to measure CH_4 from groups of animals is summarized in Table 3.

Inverse dispersion technique

An open-path laser (i.e., open path means that the air is measured along a path; the laser measures the absorption of the gas at a specific wavelength along the path) is used to measure CH_4 emissions from groups of animals that are grazing or in outdoor pens within intensive livestock operations. The laser measures the concentration of CH_4 and the dispersion of CH_4 is determined from atmospheric conditions to establish an emission rate, using an "inverse dispersion" modeling approach. Measurements are frequent within a day but can be hampered by changes in wind direction and atmospheric instability. It can also be difficult to make measurements during the night time, and thus the sampling period may not represent the full 24 h cycle creating bias in the measurement. The advantage of the technique is that it is non-obtrusive allowing animals to be maintained in their regular farm environment. Using the technique with grazing animals requires that the stocking density is sufficient to create a measurable plume. The technique provides an average emission for the group of animals, and therefore individual animal variation cannot be assessed. The technique requires expensive equipment and operations are limited to highly trained personnel. It is mainly used to verify on-farm emissions for GHG inventories, although it has been used to compare relative treatment effects at a large scale (McGinn et al., 2019). This requires that the groups (pens) of animals are physically separated such that their plumes do not overlap.

Drones

Researchers are currently exploring the use of drones for measuring the CH_4 emissions from animals that are grazing or in outdoor pens within intensive livestock operations. The drones are equipped with CH_4 sensors that provide real-time concentration measurements, or air sampling devices enabling the CH_4 concentration to be measured later with a gas chromatograph. The flight path of the drone is programmed such that it monitors the plume above the animals at a single height or at different heights. The CH_4 concentrations are used with an "inverse dispersion" modeling approach to estimate the CH_4 emission during the measurement period. The relatively short battery life of the drone (approx. 1-2 h) limits the sampling duration. As the sampling period does not represent the full 24 h cycle, the technique is useful mainly for determining relative differences between treatment groups, rather than absolute emissions. The advantage of the technique is that the animals are monitored in their normal environment, and the technique is non-evasive.

Eddy covariance technique

The Eddy covariance method is widely used to quantify CO_2 fluxes over pastures. Ultrasonic wind meters and high-performance gas analyzers are used to measure the air turbulence over a surface area by measuring the fluctuations of vertical wind velocity and gas concentrations. The method has been adapted to measure CH_4 emissions from grazing cattle (Coates et al., 2018). The CH_4 concentration and wind information are used to calculate the emission from the animals within the pasture. Because the animals continually move within the measurement area, information about the cattle's location within the pasture is needed to estimate their contribution to the measured flux. Alternatively, if the measurement period is extended over a long period of time (weeks) it is assumed that the animals graze all areas within the pasture, and the fluxes represent an average emission. The terrain also needs to be uniform without trees or undulating hills to disrupt the atmospheric boundary layer. As the technique measures the flux from the entire pasture, it is not useful for comparing mitigation effects.

Aircraft

Aircrafts equipped with an on-board analyzer are used with a dispersion model or Eddy covariance to measure concentration of CH_4 above and downwind from a concentrated source, such as a feedlot. A major limitation is that the spot measurements are usually made during the daytime, when emission rates are highest. Also, because of the high cost, the number of repeated measurements is limited. The technique is mainly used for GHG inventory.

Table 3. Summary of pros/cons of various measurement techniques used to measure enteric CH_4 from groups of animals and their manure.

	Inverse dispersion technique	Drones	Eddy covariance technique	Aircraft	Satellite
No. of animals that can be measured	large	large	large	large	large
Individual feed intake	no	no	no	no	no
Accuracy	medium	medium	medium	low	low
Grazing	yes	yes	yes	yes	yes
Restricts animal behavior and movement	no	no	no	no	no
Technically demanding	yes	yes	yes	yes	yes
Portability	yes	yes	yes	yes	no
Cost/animal	moderate	moderate	moderate	high	not animal level

Satellite

Satellites are useful for locating sources of CH_4 emissions, which is important in remote areas where ground-based measurements are few and infrequent. Satellite observations are limited by low measurement frequency and retrieval accuracy. Newer satellites offer enhanced resolution in the order of several kilometers and with greater sensitivities. Satellites are mainly used to identify "hotspot" areas of emissions, rather to measure emissions form individual feeding operations, and hence are presently limited to enhancing GHG inventories (Nisbet et al., 2020).

Indirect approaches

In addition to direct measurement techniques, biomarkers and prediction equations can be used to indirectly estimate CH_4 production. Accuracy is generally low and it is difficult to use these approaches to evaluate mitigation effects. Of the biomarkers under investigation, mid-infrared analysis spectroscopy of milk may offer some promise, although it is limited to dairy cows enrolled in a milk recording scheme (Negussie et al., 2017). The mid-infrared spectrum reflects milk fatty acid composition. In ruminants, milk fatty acids come from two sources (approx. 1:1): 1) uptake from circulation, and 2) de novo synthesis within the mammary gland. Short and medium-chain fatty acids (4 to 14 carbons) arise totally from de novo synthesis and reflect acetate and butyrate produced during ruminal fermentation, resulting in CH_4 production. Mid-infrared spectra have been used in animal breeding schemes to identify low-emitting cows, but most studies show accuracy is generally low. Prediction equations that are based on animal characteristics and feed evaluation are mostly used to refine CH_4 inventories, but their use to evaluate CH_4 mitigation is very limited.

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