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CONTENT

PREFACE

Agriculture contributes significantly to greenhouse gas (GHG) emissions and plays an important role in climate change. As the world's population grows and demand for food increases, it is imperative to accurately assess and mitigate GHG emissions from agricultural practices. In recent years, there have been notable advances in the methods used to estimate these emissions, allowing scientists, policy makers, and farmers to gain a better understanding of their environmental impact. These advances include a wide range of technologies, from improved measurement techniques and remote sensing to sophisticated modelling tools and the use of big data and machine learning. Using these innovative approaches, researchers can evaluate the effectiveness of mitigation strategies, identify emissions hotspots, and develop sustainable agricultural practices. In addition, standardization and harmonization efforts provide consistent emission estimates that facilitate global comparisons and decision-making. This research bulletin compiles recent advances in methodologies for estimating GHG emissions from agriculture and highlights their importance in combating climate change and promoting sustainable agricultural systems.

Climate change monitoring in the rice agroecosystem aims to understand and respond to the complex interactions between climate variables and rice production. Monitoring involves the systematic collection and analysis of climate data, including temperature, precipitation, humidity, and extreme weather events, to assess how changing conditions affect rice growth, yield, and quality. Data collected through monitoring contributes to early warning systems that help farmers prepare for climate-related challenges such as droughts, floods and pest infestations. In addition, monitoring facilitates the identification of climate-resilient rice varieties and the development of adaptation strategies, including modified planting dates, altered irrigation practices, and improved pest management.

The authors believe that the results will be of interest to scientists, students, researchers, academics, donors, and funding agencies. The authors gratefully acknowledge financial support from the Global Challenge Research Fund-South Asian Nitrogen Hub (GCRF-SANH) project funded by the United Kingdom Research and Innovation, Centre for Ecology & Hydrology (UKRI-CEH) for conducting experiments on reactive nitrogen loss including GHG from rice soil under diverse nitrogen management practises.

Authors

1. Introduction

Global climate change caused by rising temperatures and increased greenhouse gas (GHG) concentrations results in an increase in the occurrence of extreme weather events such as droughts, cyclones, floods, cold waves, and heat waves, which have a negative influence on agricultural production and quality. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the most essential agriculturally relevant GHGs that must be monitored on a regular basis so that suitable decisions and activities may be taken to mitigate these negative consequences (IPCC, 2007).

Carbon dioxide is the primary GHG responsible for the atmosphere's rising greenhouse effect. Ocean-atmosphere interaction, animal and soil respiration (microbial respiration), and volcanic eruption are all important natural sources of CO_2. The pre-industrial value of CO_2 in the earth's atmosphere was consistent, averaging at 280 ppm. The onset of industrialization disrupted the equilibrium of atmospheric composition, and CO_2 concentrations in the air began to rise as a result of tremendous economic expansion. Methane is a prominent GHG released by both natural and human activities. Wetlands, termite activity, and the ocean are all natural sources of CH_4 emissions. The main anthropogenic sources of CH_4 are rice paddy fields, landfills, livestock production systems, and fossil fuels. N_2O is the third major GHG from agriculture having the highest global warming potential (Zaman et al. 2012). It is a prominent ozone-depleting gas (Ravishankara et al. 2009). Non-anthropogenic sources of N_2O include the soils under natural vegetation and oceans. Yet, on a global scale, anthropogenic agricultural and other land-use activities are the primary source of N_2O emissions. It is critical to estimate and quantify these GHG emissions in order to develop effective strategies for reducing GHG emissions from agriculture, mitigating climate change, and promoting sustainable agricultural practices.

Manual chamber methods have largely been used to measure gas emissions to the atmosphere from agricultural sources at the field level. This method is inexpensive, simple, and widely used by researchers. However, because data from manual chamber methods is discontinuous and requires extrapolation to obtain information on a non-sampling day, advanced techniques such as the eddy covariance method were brought in practice, which is basically an ecosystem-level measurement. This method entails installing sensors above the environment and measuring the flux of gases in and out of it. Furthermore, regional/national assessments can be performed utilizing the Intergovernmental Panel on Climate Change (IPCC) recommendations for National GHG Inventories for Agriculture, Forestry, and Other Land Use Sectors (AFOLU) using a three-tiered method. GHG measurements by aerial platforms, remote sensing, and global modelling. Satellite-based remote sensing provides information about the distribution of trace gases in the atmosphere with unprecedented spatial and temporal coverage, yielding orders of magnitude more observations than typical ground-based measurement networks. Movable GHG measuring platforms aid in-situ atmospheric measurements or remote sensing of GHG concentrations on a regional scale. Process-based models, on the other hand, are used to estimate GHG emissions by combining empirical data, theoretical calculations, and mathematical equations to estimate the amount of GHG emitted from a certain process or activity. Microbial molecular techniques can be used to identify and quantify the microbial communities responsible for the production of GHGs in soil or other environments. By understanding the genes and metabolic pathways involved in these processes, researchers can develop more effective strategies to reduce GHG emissions. This bulletin will provide a thorough summary of the present level of knowledge as well as the various methodologies for measuring GHGs in agriculture at local to global levels.

2. Field level measurements of GHG

Measurement of greenhouse gas (GHG) emissions at the field level typically entails quantifying the released GHGs from various sources, including agricultural lands, forests, wetlands, and livestock operations. For developing effective mitigation strategies, effective climate change policies, and preventing the advancement of climate change, field-level assessment of GHGs are essential.

2.1 Measurement of CO_2

On-field CO_2 measurement typically involves using a portable CO_2 meter or sensor to measure the concentration of CO_2 in the air there itself. There are several methods for measuring CO_2 at field level, including collection of gas sample by manual chamber method followed by its measurement in gas chromatography; in-situ infrared absorption method using infrared gas analyzer (IRGA), non-dispersive infrared spectroscopy (NDIR) and mass spectrometry.

2.1.1 Manual chamber method

Principle

The manual chamber method is the most widely used method for determining GHG fluxes, especially CO_2, CH_4, and N_2O from soils (Chatterjee et al. 2018). The basic idea of this technique is to enclose a given volume of soil in a closed chamber that allows gaseous exchange between the chamber head and the soil below. The flow rate into or out of the soil is represented by a flow rate calculated from the variation over time of the gas concentration in the airspace of the chamber.

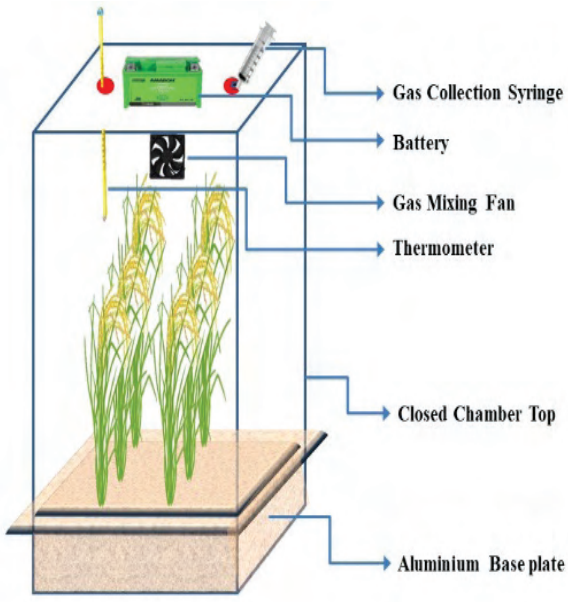
Materials

- *Closed chamber:* Materials such as plastic or acrylic sheets can be used to make chambers for collecting gas from the field. Typically, chambers of 50 x 30 x 100 cm made of 6-mm acrylic sheets are used to collect gas samples from agricultural fields, especially rice fields (Nayak et al. 2017) **(Table 1)**.
- *Base plate:* The base plates should be placed at least 10 cm below the soil surface and are often made of aluminium. To seal the system, the channels must be filled with water.
- *Thermometer*: A general °C thermometer is used to monitor the temperature inside the chamber and is required for volume correction.
- *Pulse pump/ fan*: A battery operated pulse pump or fan is needed to homogenize the inside air of the chamber. Pulse pump can be fitted outside the chamber and the battery-operated fan should be placed inside the chamber with difference in height.
- *Measurement scale*: A measurement scale of 0-50 cm range may be used to measure the depth of the water inside as well outside of the chamber.
- *Tedlar bag*: A Tedlar bag is used to collect gas samples from the closed chamber.
- *Syringe*: Use to collect gas samples from the tedlar bag.
- *Needles:* After placing the chamber on the aluminium channel, gas samples are taken with a needle every 0, 15, and 30 minutes.
- *Stopcock*: A three-way stopcock is placed at the top of the chamber to collect gas samples. The syringes are airtightly sealed with a three-way stopcock after the sample has been taken.

Table 1. Chamber characteristic for measuring GHG in different crops

Crop	Chamber Size	Reference
Rice	Closed Chamber of 53 × 37 × 71 cm were placed on aluminium bases covering 6 hills.	Mohanty et al. 2020
Wheat	Based on the crop height, the flux chambers were 50 × 50 × 50 cm or 50 × 50 × 100 cm and were installed on a stable PVC frame	Li et al. 2010
Maize	Each chamber was made up of two components: a base collar with a 5 cm internal diameter mounted to the ground and the chamber cylinder (30 × 30 × 60 cm) constructed of natural glass	Fagodiya et al. 2019
Black gram and Green gram	The closed chamber of 52 × 31.7 × 34.5 cm to capture gas samples	Sahoo et al. 2010
Cereal and Potato	Transparent PVC chambers (60 × 60 × 41 cm) mounted on top of each collar for 45 minutes to measure gas fluxes	Petersen et al. 2012
Mustard	Between the rows of mustard plants, small, closed chambers (1000 cm^2) were established	Haque et al. 2022
Pigeon pea and Sugarcane	The cylindrical steel chambers (20 cm diameter, 15 cm height) placed with a separable steel base	Department of Agriculture Fisheries and Forestry -2013
Groundnut	Aluminium base plate employed in the ground with chambers of 50 × 50 × 100 cm.	Pathak et al. 2002; Bhatia et al. 2010

Method



- A base plate is sunk into the ground for each rice plot before the first gas sampling and chamber is set up during the gas sampling only.
- The chamber is placed on the aluminium base plate already sunk to measure the flux. By using a syringe to take gas samples from the chamber headspace over time, it is possible to determine how the concentration of CO_2, CH_4, or N_2O has changed in the chamber.
- Generally, pharmaceutical syringes with a volume of 20-50 mL made of plastic with a 2- or 3-way loop are used. After sealing, gas samples should be taken from the headspace at regular intervals for a maximum of two hours.
- Greenhouse gas emissions at the rice field are monitored for 3-7 days interval throughout the growing season up to 15 days before harvesting using the static chamber method.
- However, additional samples are generally collected for one day before and one day after fertilizer application.

- A gas collection valve and a thermometer to record the internal temperature of the chamber, and the head are also attached to the lids.
- Gas samples are collected between 8 A.M. and 12 P.M. each sampling period, as studies have demonstrated that this provides typical daily emission estimates.
- For transplanted rice, the chambers covered at least 6 rice hills.
- Gas samples (60 ml) are collected from the headspace using a polypropylene syringe connected to a clamp at 0, 15 and 30 min after the lids are placed.

Analysis of concentration of GHGs in gas chromatography

GHG flux from soil is evaluated using closed chambers by periodically sampling gasses from the chambers and measuring the change in gas concentration over the linear concentration change period. Subsequently, the analysis is performed using a gas chromatography (GC) system installed with a flame ionization detector (FID) as well as a methanizer for CO_2, FID for CH_4, and an electron capture detector (ECD) for N_2O (Nayak et al. 2016).

Equations for the Calculation of GHG fluxes:

$$CO_2\text{ - C flux} = \frac{\Delta X \times EBV_{(SPT)} \times 12 \times 10^3 \times 60}{10^6 \times 22400 \times T \times A}$$

$$CH_4\text{ - C flux} = \frac{\Delta X \times EBV_{(SPT)} \times 12 \times 10^3 \times 60}{10^6 \times 22400 \times T \times A}$$

$$N_2O\text{ - N flux} = \frac{\Delta X \times EBV_{(SPT)} \times 28 \times 10^3 \times 60}{10^6 \times 22400 \times T \times A}$$

Where, ΔX = Gas concentration difference between 0, 15 and 30 min

$EBV_{(SPT)}$ = Effective box volume at standard pressure and temperature

T = Flux measurement time in min (15, 30 min)

A = Box base area in m^{-2} (L × B)

The $EBV_{(SPT)}$ is calculated using the following equation, $\frac{(P_1 \times V_1)}{T_1} = \frac{(P_2 \times V_2)}{T_2}$

Where, P1 = Barometric pressure at the time of sampling in mm Hg

V_1 = EBV (Effective box volume)

T_1 = 273° K + temperature inside the box at the time of sampling in ^{0}C

P_2 = Standard barometric pressure (760) in mm Hg

$V_2 = EBV_{(STP)}$

T_2 = 273° K

The EBV is measured using the following equation: $EBV = Box\,[(H - h) \times L \times B] - V$

Where, B = Box breadth (cm)

L = Box length (cm)

h = Height of the field water level (cm)

H = Box height (cm)

V = Crop (e.g., rice) biomass volume (mL) inside the box (above ground biomass only).

Errors

Measurements made by chamber methods are susceptible to a wide range of possible errors and disturbances. They can be described as follows:

- The error regarding the volume of the chamber has been taken into account. Both the original measurement of the total capacity of the chamber and the uncertainty related to the water level in the chamber are the sources of this error.
- Disturbances in the physical and biological systems caused by the measurement procedures.
- Sample handling errors and improper chamber design.
- Problems in sample analysis and inappropriate procedures for calculating the flux.

Advantages

- The manual chamber method is inexpensive and can be used in remote locations because it does not require a power source.
- It can be used for large-scale GHG estimation, which is an essential part of national emission inventories, and for measuring emissions at the field and farm level.
- The chamber's dimensions and size are adjustable and can be changed to meet the requirements of the research.
- The chambers are simple, affordable, and easy to make from materials that are readily available.
- Even in small plots, treatment differences and even very small flux variations could be detected.
- It is a self-contained system with a small battery that can be powered by solar energy, so no additional power source is required.
- Because it is easy to use, sampling does not require any special knowledge or experience.
- There is minimal disturbance to the crop during sampling.

Disadvantages

- The manual chamber method is a time-consuming process that requires a significant amount of manual labour, particularly in the preparation and analysis of samples and requires skilled technicians, making it a labour-intensive process.
- In other hand, limited in the sample volume that can be analysed at a time with limited accuracy, which can lead to variability in the results obtained.
- Gas concentrations in the chamber may rise to the point of preventing normal emissions. However, short collection times can reduce this problem.
- Because of the turbulence of air flow that naturally exists at the ground surface, closed chambers alter atmospheric pressure variations. Therefore, an enclosed chamber may exaggerate gas flux. An appropriately designed vent that allows pressure equalisation inside and outside the chamber can solve this problem.
- Temperature fluctuations are possible both inside the chamber and in the soil. However, temperature fluctuations can be minimised by insulating the chamber and coating it with a reflective substance.

2.1.2 In-situ infrared absorption method using infrared gas analyzer (IRGA)

Principle

The in-situ infrared absorption method using an infrared gas analyzer (IRGA) is a technique used to measure the concentration of CO_2 (also for CH_4 and water vapour) in the atmosphere. The CO_2 absorbs a part of the infrared radiation at specific wavelengths. The absorption of infrared by CO_2 reduced the transmission of infrared radiation, which is proportional to the CO_2 concentration in the sample air.

Materials

The materials required for in-situ infrared absorption method using infrared gas analyzer (IRGA) are:

- Infrared gas analyzer (IRGA)
- Sample cell: It is a chamber that holds the gas being analyzed. It is designed to allow the infrared radiation to pass through the gas and into the IRGA.
- Inlet and outlet tubing: These are tubes that connect the sample cell to the gas source (air sample) and the IRGA.
- Gas sampling pump: A gas sampling pump is used to pull the gas through the sample cell and into the IRGA.
- Gas calibration standards (both pure and mixture of gases) are used to calibrate the machine
- Power source: It is either battery-operated or requires an external power source.
- Data logger for data storage and analysis.
- Accessories such as filters, flow meters, and valves

Method

- In this method, the IRGA is placed in direct contact with the air containing CO_2 at a specific wavelength. First, the air sample is collected and passed through a sample cell in the analyzer.
- An infrared light source is passed through the sample cell.
- As part of the infrared radiation is adsorbed by CO_2, the detector in the analyzer measures the reduction in transmission of infrared light.
- The amount of light absorbed is converted to a CO_2 concentration using Beer's Law.
- The display unit then displays the CO_2 concentration in the gas sample, typically in units of parts per million (ppm) or percentage (%). However, with a known standard calibration of IRGA is prerequisite of this measurement.

Advantages and Disadvantages

In comparison to other techniques for gas analysis, the in-situ infrared absorption approach using an IRGA has a number of benefits, including the ability to provide real-time measurements and its high sensitivity and accuracy. However, the accuracy of the readings using this method may be impacted by variables like temperature, humidity, and atmospheric pressure.

2.1.3 Non-dispersive infrared spectroscopy (NDIR)

For detecting CO_2 concentration, non-dispersive infrared spectroscopy (NDIR) is a widely employed technique. This technique involves passing an IR light through a sample of air to determine how much

IR light is absorbed by CO_2 molecules. The quantity of light absorbed is then used to calculate the CO_2 concentration. These sensors are typically more accurate and reliable than other types of CO_2 sensors, and can provide real-time data with high precision. This sensor can be integrated with handheld meters, portable instruments, and fixed monitoring systems. They are also widely used where accurate measurement of CO_2 concentration is critical.

2.1.4 Mass spectrometry method

A sample's carbon dioxide (CO_2) content can be determined using a mass spectrometer. By bombarding the sample with electrons, the molecules lose their electrons and change into positively charged ions. After that, a magnetic field is used to accelerate these ions, which causes them to curve in a direction that is inversely proportionate to their mass-to-charge ratio (m/z). The ions are detected at the end of this path, and the signal is recorded and analyzed to determine the relative abundance of the different ions. The molecular ion of CO_2 (CO_2^+), produced by losing one electron during ionization, is characterized by a mass-to-charge ratio of 44. The intensity of this ion in the mass spectrum is proportional to the concentration of CO_2 in the sample.

This method can be used to determine CO_2 in air, water and other biological fluids commonly available in agricultural research. This is a very sensitive method and can detect CO_2 at a very low concentration.

2.2 Measurements of CH_4

Waterlogged rice fields are an important source of CH_4 emissions to the atmosphere (**Figure 1**). Methanogenesis is the process that controls the synthesis of CH_4 gases under anaerobic conditions, and the major contributors to CH_4 emissions from rice fields are methanotrophic bacteria. These microorganisms

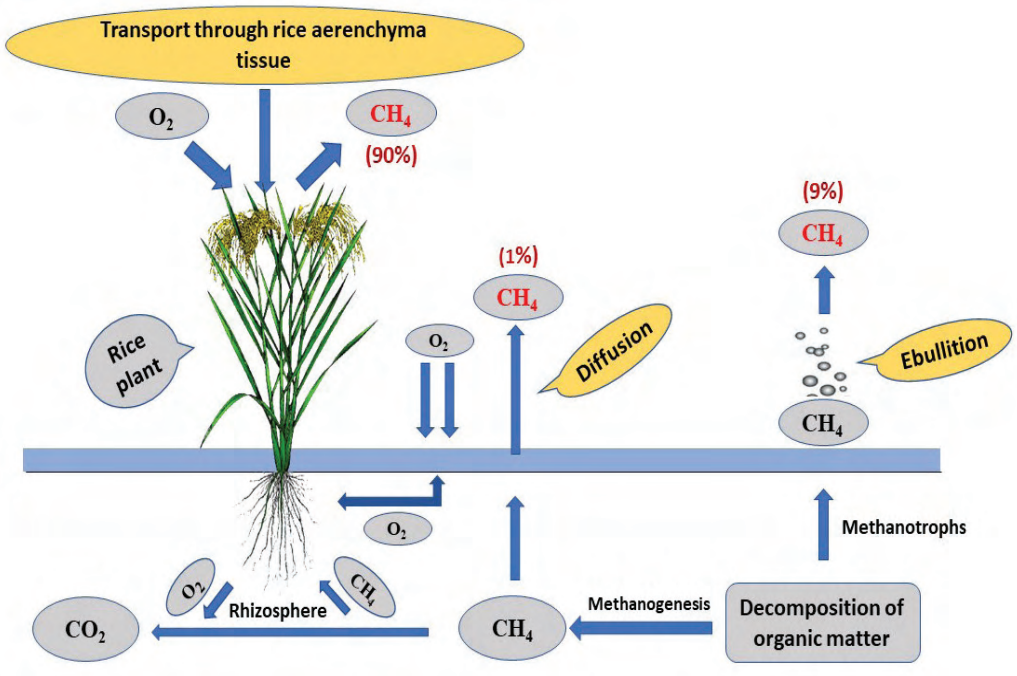


Figure 1. Schematic diagram of CH_4 emission from rice field

function well under anaerobic conditions and are responsible for the utilization of organic carbon and its conversion to CH_4 through biochemical pathways. The free oxygen diffused into the soil by the rice plants can oxidise the CH_4 gas produced in the soil. Flooding fields reduces soil O_2 levels and increases the activity of methanogens, which use CO_2 instead of oxygen as the final electron acceptor for their metabolic activities.

Methane gas can escape into the atmosphere after it is formed in three ways: through the aerenchyma tissue of the rice plant, ebullition and diffusion. The methane produced in anaerobically flooded rice soil is mainly transported into the atmosphere by the aerenchyma of the rice plants which has been described as the most important phenomenon. Ebullition is the formation and release of bubbles (mainly CH_4) from the sub-surface soil to water table of paddy soil thereafter environment. Methane loss by ebullition from rice soils is a significant and important release mechanism during soil preparation and the initial growth of rice, especially when the soil texture is not clayey. Methane loss by diffusion between soil and atmosphere across the water surface in the rice field is the least important process.

2.2.1 Measurement of methane escape through the aerenchyma tissue

Lowland plants have a kind of tissue, the aerenchyma, that facilitates the movement of CH_4 from roots to aboveground plant tissues as well as gas transport within the plant itself. Several techniques can be used to measure CH_4 transport across the aerenchyma, including:

2.2.1.1 Manual chamber method

This method has been discussed thoroughly in 2.1.1

2.2.1.2 Stable isotope tracing

In this method, the CH_4 is labelled with stable isotopes and the mobility of the labelled CH_4 in the plant is monitored with a mass spectrometer (Gupta et al. 2013). In this way, the rate and direction of CH_4 transport within the plant can be measured. Due to the complexity and variability of the process, overall measurement of CH_4 transport through the aerenchyma can be difficult. However, these measurements are critical for understanding the role that wetland plants play in the global CH_4 cycle and for developing strategies to mitigate CH_4 emissions.

2.2.2 Measurement of methane escape through ebullition

The process by which gas bubbles rise to the water surface and escape into the atmosphere is called ebullition. Ebullition, which can be an important source of CH_4 emissions, is the release of CH_4 bubbles from sediments at the bottom of lakes, marshes, or other lowland agroecosystems such as rice paddy fields. There are a number of techniques for measuring CH_4 ebullition, including direct and indirect measurements. Direct measurements that measure the amount of CH_4 that rises to the surface using methods such as:

2.2.2.1 Bubble-collection chamber method

Principle

Gas bubbles can be easily and inexpensively trapped to assess GHG emissions (including CH_4) in mangrove systems in coastal areas (Bhattacharyya et al. 2020; Baron et al. 2022). By trapping the bubbles in the bottoms of the tidal system, the amount of GHGs released during the ebullition process can be quantified.

Materials

- A long pipe connected with a collection funnel
- Base for collection funnel
- Septum

Method

- An inverted plastic funnel with a cylindrical bottom and a septum at the top of the stem is used to collect the gas samples.
- Bubble gas samples are taken in two cases: prior to and during flooding. To obtain the 30-minute flow, the gas samples are taken at minute '0' and at minute '30'.
- The gas samples are then analysed in a gas chromatograph (GC) to determine CO_2, CH_4 and N_2O concentrations.

Calculation

The GHGs fluxes are calculated by using the formula,

$$GHGs\ flux = \frac{\Delta X \times EBV_{(SPT)} \times MW_{GHG}}{A \times T}$$

Where, ΔX = Gas concentration difference between 0, 15 and 30 min

$EBV_{(SPT)}$ = Effective box volume at standard pressure and temperature

$MW_{(GHG)}$ = Molecular weight of GHGs

T = Measurement time of flux in min (15 or 30)

A = Base area in m^{-2} (L × B)

Advantages

- Portable in nature.
- Easy to collect gas samples.
- Measure a different range of ebullition fluxes.

Disadvantages

- Temperature correction is required.
- Ensuring an airtight environment during gas collection is sometimes difficult.

2.2.2.2 Bubble-size sensor method

Principle

This method optically monitors bubble rise time, velocity, volume using bubble size sensor (Delwiche et al. 2015). Bubble dissolution model is used to measure the percentage of CH_4 dissolved in the water column and the percentage of CH_4 that released to the atmosphere. It is an autonomous and simple instrument that can be left in place unattended for a prolonged period of time.

Materials

- Methane ebullition sensor to measure the gas bubbles size
- Data logger for methane ebullition sensor
- Cables, connectors, and mounting brackets for connecting the sensor and data logger
- Methane gas detectors for real time monitoring or field tools such as chambers and a 50-mL syringe for single point measurement

Methods

- The sensor is placed under water where rising CH_4 bubbles are collected by an inverted glass tube.
- The volume of larger bubbles is determined by measuring their elongated length and the area of the glass tube as they move through it, where they assume an approximately cylindrical shape.
- Although bubbles with diameters smaller than the tube diameter are not significantly elongated, accurate volume estimates are still provided by appropriate signal processing.
- The bubble size sensors are left in place at 3-week intervals.
- After three weeks, a 50-mL syringe is used to collect the total gas from the chambers, and the collected volume is recorded.
- After three weeks, a 50-mL syringe is used to sample the total gas from the gas collection chambers, and the collected volume is recorded.

Advantages

- The sensor precisely measures the size of individual bubbles up to a volume of 1 ml and offers comprehensive data on the precise time of bubble release.
- The bubble size sensor can be easily adjusted due to the removable design of both the gas collection chamber and the extension funnel.
- The sensor is inexpensive to manufacture, consumes relatively little power, and can accurately measure bubble size over long periods of time.

Disadvantages

- Only one bubble passed through the glass tube at a time in these controlled experiments.
- Under real conditions, a wide range of flow velocities is to be expected, which increases the probability of errors due to coalescence of bubbles.

Indirect measurements of CH_4 that rises to the surface through ebullition can be done in the following ways:

2.2.2.3 Acoustic measurements

When CH_4 bubbles rise to the surface, they can be detected and measured using acoustic techniques (Hilgert et al. 2019). This method is mostly used in detecting intensity, occurrence, and dynamics of CH_4 ebullition from sediments in lakes or waters bodies. There are several acoustic measurements are available:

- Sonar imaging techniques that use sound waves to create images of the seafloor or water column, allowing researchers to identify gas plumes or bubbles rising from sediments.
- Acoustic doppler current profiler that measures water currents can also be used to measure methane ebullition. This technique uses Doppler effect to measure the velocity of water particles in a water column which often changes due to occurrence and intensity of methane ebullition events.
- Acoustic gas flux meters are specialized instruments that directly measure the rate of gas bubble release from sediments or water bodies on real time basis
- Echosounders are also used to estimate the depth, size, and distribution of methane ebullition events.
- Hydrophone arrays are underwater microphones that can detect and record underwater sounds, including methane ebullition bubbles.

2.2.2.4 Geostatistical modelling

This technique uses geostatistical models to calculate the geographic and temporal variability of ebullition rates based on environmental variables such as water depth, temperature, and soil type.

2.2.3 Measurement of methane released by diffusion

Diffusion of CH_4 in soils or water can be measured by several methods, including:

2.2.3.1 Flux chambers

The CH_4 flux between the water or soil surface and the atmosphere can be measured using flux chambers. Using Fick's first law of diffusion, the diffusion flux can be calculated by observing the CH_4 concentration inside the chamber over time.

2.2.3.2 Tracer release method

- In the tracer release method, a tracer gas is released in a known amount at a location that is coincident with the CH_4 emission being identified, but the source is unknown (Yver Kwok et al. 2015).
- A mobile instrument is used to measure the concentrations of the target gas and the tracer in the co-propagating plumes.
- The emission rate is proportional to the ratio of the areas of the two plume signals.
- Calculation of the CH_4 emission rate requires knowledge of the emission rate of the emitted gas and the concentrations of both gases.

$$F_{CH_4} = F_{tg} \frac{A_{CH_4}}{A_{tg}} \frac{M_{CH_4}}{M_{tg}}$$

Where, F_{CH4} are the emissions of CH_4 (kg h^{-1})

F_{tg} is the emission of tracer gas at a known rate

$\frac{A_{CH_4}}{A_{tg}}$ is the ratio of the areas under the signals of CH_4 and known tracer gas.

$\frac{M_{CH_4}}{M_{tg}}$ is the ratio of the molar masses of CH_4 and known tracer gas.

2.2.3.3 Water-atmosphere methane exchange method

- The method for measuring CH_4 exchange in the water-atmosphere interphase in mangrove and coastal ecosystems is well established (Bhattacharyya et al. 2020).
- To assess CH_4 transfers in the interphase, surface water is sampled from standing waters both during and after the flood.
- This method considers the dissolved CH_4 concentration in the water, its partial concentration, and wind speed.
- From each container, 50 ml of the obtained sample is replaced with nitrogen.
- The remaining water sample containers are then shaken for 10 minutes and subjected to GC analysis.

$$F = k.K_0.(P_{water} - P_{air})$$

Where, F is the exchange of GHGs in the water-atmosphere interphase

k is the gas transfer velocity in cm h^{-1}

K_0 is the solubility coefficient of GHGs in mol L Pa^{-1}

P_{water} is the GHGs partial pressure in water (mol/mol)/ (v/v)

P_{air} is the GHGs partial pressure in atmosphere (mol/mol)/ (v/v)

2.2.3.4 Gradient method

The gradient method uses sensors or gas samplers to measure the amount of CH_4 at different depths in the soil. Calculating the diffusion flux of CH_4 requires measuring the diffusion coefficient and plotting the concentration gradient with depth.

2.2.3.5 Stable isotope tracing

In this technique, CH_4 is labelled with stable isotopes and a mass spectrometer is used to track the movement of the labelled CH_4 in the soil or sediment. In this way, the direction and rate of CH_4 diffusion can be measured.

2.2.3.6 Microsensors

Microsensors can be used to measure CH_4 concentration in soil with high spatial resolution. Methane diffusion flux can be determined by combining these observations with measurements of soil parameters such as permeability and porosity.

2.3 Measurements of N_2O

According to estimates, N_2O accounts for roughly 6% of the GHG-induced global warming. The single most significant ozone-depleting emission in the 21st century is likewise anticipated to be N_2O. Nitrous oxide measurement has come a long way, but sensors that can map the spatial fluctuation of N_2O emissions over a large region are urgently needed. Developments in sensitive analytical techniques for N_2O measurement are briefly outlined here, and several exciting new technologies are discussed with an aim to enlighten people creating new analytical techniques as well as those just starting out in N_2O measurement so they may choose the technology that is most appropriate for their situation. We give a quick overview of some of the current sampling procedures in order to help the reader comprehend the analytical methods used to assess N_2O.

2.3.1 Chamber method

This method has been discussed thoroughly in 2.1.1

2.3.2 Micrometeorological methods

This is the scale at which traditional micrometeorological approaches can be used. In addition, concentrations likely change vertically but not horizontally, and fluxes are nearly constant with height. Many ground-level sources upwind contribute to fluxes at a given altitude. Footprint analyses, which use atmospheric dispersion theories to predict the paths of wind-moving air parcels, can be used to estimate the contributions from sources located at various distances from the sensor. The footprint is strongly influenced by surface roughness and thermal stability. Gas fluxes over a large area (1-10 km^2) have been measured using micrometeorological techniques (Dalal et al. 2003). Gas sensors are installed on towers to measure gas concentration, temperature, and wind at one or more locations above the ground or vegetation (Philips et al. 2007).

2.3.2.1 Flux-gradient methods

This method simplifies the measurements required to calculate vertical flux by recording gas concentrations at two or more different altitudes and recording horizontal wind speed instead of horizontal and vertical wind speeds. The turbulent diffusivity calculated from wind speed and turbulence measurements is multiplied by the vertical concentration gradient calculated from two different altitudes or from surface energy exchange measurements and vertical concentrations of gas, humidity and air temperature (Harper et al. 2011). When using flux-gradient methods, it is critical for accuracy to use standard instruments to measure gas concentrations at different altitudes (Denmead, 2008).

2.3.2.2 Integrated horizontal flux (IHF)

This method works effectively in tiny, well-defined shape regions (less than 1 ha). Profiles of horizontal wind speed and gas concentrations are established at the centre of the test site. This method allows measurement of horizontal gas fluxes at altitudes up to the top of the emitted gas plume, assuming that the gas is generated at the surface and that the horizontal fluxes can be integrated with respect to altitude to obtain the vertical flux. IHF techniques bridge the gap between chamber methods and traditional micrometeorological approaches by eliminating the need for fast-response gas analyzers (Denmead, 2008).

2.3.2.3 Backward Lagrangian stochastic (bLs) dispersion technique

This method employs observations of the downstream gas concentration, wind direction and speed to determine surface fluxes from the location, making it suited for small, well-defined source areas (Flesch, 1995). This method is suitable for monitoring emissions from treated fields and it can measure concentrations at both point and line-averaged levels (Denmead, 2008).

2.3.2.4 Moving platforms

Movable platforms like trains, planes, and ships are helpful in atmospheric investigations (Griffith et al. 2011). High spatial and temporal resolution measurements in both vertical and horizontal directions are possible because of the moving platforms.

3. Ecosystem level measurements of GHG

Measurements of GHGs at the ecosystem level are usually made with a number of methods, including direct and indirect methods. While indirect methods make estimates of GHG fluxes based on associated variables or processes, direct methods involve measuring GHG fluxes at the ecosystem level. Direct methods involve eddy covariance measurements of GHG fluxes and measuring ecosystem respirations. Modelling approaches, such as ecosystem process models or remote sensing, which use satellite data to anticipate GHG fluxes based on ecosystem characteristics including temperature, vegetation cover, and moisture, are a few examples of indirect methods for estimating ecosystem-level GHG fluxes.

For an understanding of the carbon and nitrogen cycles, as well as how ecosystems either contribute or mitigate climate change, ecosystem-level measurements of GHGs are essential. They offer useful information for determining policy, assessing the success of climate mitigation measures, and guiding ecosystem management practices to lower GHG emissions and increase climate resilience.

3.1 Eddy covariance techniques

The Eddy Covariance (EC) method is a sensor-based, real-time system for measuring heat fluxes (energy exchange) and GHGs (mass exchange) (Chatterjee et al. 2019a, 2019b, 2020a, 2020b, 2021; Swain et al. 2018a, 2028b, 2018c). This technique is used for determining the exchange of energy and GHGs between ecosystems (surface) and the atmosphere. It is one of the most precise and reliable methods for determining gas fluxes and tracking GHG releases from vast areas, helping measurements in large plots. The EC technique employs fast, direct measurements of gas transport using 3-D wind speed in situ and calculates turbulent fluxes within the atmospheric boundary layer. This technique has the potential to be extensively used in areas outside of micrometeorology, such as ecology, hydrology, environmental surveillance, and industrial monitoring, in combination with modern tools and software. However, for non-experts, the main challenge is the complex design of the system and the processing of large volumes of data.

Purpose

The flux in EC system is measured as the covariance of a GHG concentration or amount of heat and the vertical wind velocity component (Uz). Sensors are positioned at a suitable height in the large field above the crop which has uniform growth. The data recorder records high-frequency (10-Hz) data. All high-frequency data are accumulated on a half-hourly basis, assuming perfect turbulent mixing, to compute water, carbon, and heat exchanges and balances from diurnal, seasonal to annual time scales. The flux values are also reported directly.

Principle

The principle behind EC measurement is to record the variations in vertical wind speed and the concentration of gases (like CO_2, CH_4, water vapour) or heat at high frequency in order to determine the exchange of gases and energy between the surface (like vegetation or soil) and the atmosphere. Principally the measurement of eddy covariance relies on turbulence, which describes the chaotic and random fluctuations in wind speed and gas concentrations that occur in the atmosphere naturally. A

horizontal movement of several rotating eddies has three components of horizontal (u), lateral (v), and vertical (w) velocity can be used to describe an eddy. According to Burba (2013), vertical flux in a turbulent flow can be presented as:

$$F = \overline{\rho_a ws}$$

Where ρ_a is the density of air and s is the dry mole fraction of the measured gas.

After splitting above equation into its mean and deviation using Reynold's decomposition and removing the terms which are negligible (~0), this can be rewritten as:

$$F = \overline{\bar{\rho}_a w's'}$$

The different fluxes are measured based on the aforementioned principle. As a covariance between variations in w (w') and the CO_2 mixing ratio (C_{CO2}´) on a half-hourly basis, the mean vertical CO_2 flux density (F_{CO2}) is obtained:

$$F_{CO2} = \overline{\rho_a w' c'_{CO2}}$$

In the equation, ρ_a represents the air density, the overbars refer to the time average, and primes denote the fluctuations about mean. Similarly, the following fluxes are measured:

$$F_{CH4} = \overline{\rho_a w' c'_{CH4}}$$

$$F_{H2O} = \overline{\rho_a w' q'}$$

$$H = \rho_a C_p \overline{w'T'}$$

$$LE = \lambda \frac{M_w/M_a}{P} \rho_a \overline{w'e'}$$

F_{CH4} and F_{H2O} are flux density of CH_4 and water vapour, respectively, while C_{CH4}´is the CH_4 mixing ratio and q' is the fluctuation in specific humidity. C_p stands for specific heat capacity of air at constant pressure, T refers to air temperature, λ is the psychrometric constant, M_w/M_a stands for the ratio of molecular weight of wet to dry air, e indicates vapour pressure, P stands for air pressure.

Assumptions

- The terrain is horizontal and uniform.
- Fetch need to be sufficient and adequate in the dominant wind direction.
- Flux measurements are confined to the boundary layer of interest.
- Measurements represent an upwind area.
- The flux needs to be fully turbulent and eddies cause the vertical transfer of the gas in question.
- Highly sensitivity of instruments that can detect minute changes at high frequencies.

Materials

Both the open path and closed path EC system consists of several sensors that measure the concentration and flux components. Various components of the eddy covariance system include sensors, data loggers, power supply system mounted in and around a tripod (**Figure 2**):

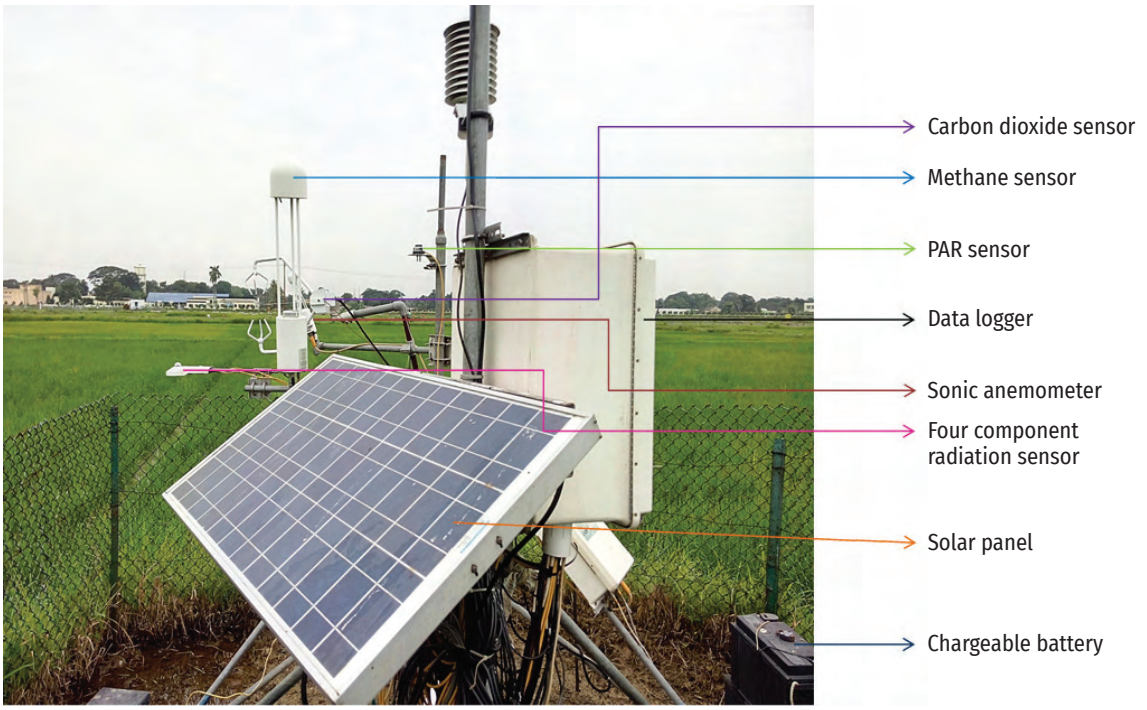


Figure 2 Different sensors of open path eddy covariance system installed at ICAR-NRRI

- Sonic anemometer: It monitors three-dimensional wind speed, sonic temperature, and wind direction. The sonic anemometer measures the speed of sound in the air, which is conveyed through a transducer. The sound reflections are collected by another transducer. The difference in duration between transmission and reception is used to calculate wind speed. CSAT3, RM Young, R3-50, HS-50 are the commonly used sonic anemometer in EC system.
- CO_2/water vapour sensor: An open path infrared gas analyzer (LI -7500A) is used to measure the variations of CO_2 and water vapour density. To minimize interference from raindrops, the head of the LI -7500A is tilted at 15°. EC155 model is a closed-path analyzer for CO_2 and water vapour.
- CH_4 sensor: an open-path infrared CH_4 gas analyzer (LI7700)
- A 4-component radiation sensor: It is used to measure net radiation (NR), shortwave upward radiation (SU), shortwave downward radiation (SD), longwave upward radiation (LU), and longwave downward radiation (LD).
- Air temperature relative humidity (ATRH) sensor: It measures air temperature (Ta) and relative humidity (RH).
- Photo synthetically active radiation (PAR) sensor: It measured using silicon photodiode quantum sensor.
- Soil heat flux plates: HFT3-L is used for measuring soil heat flux at 3 depths (5, 15, and 30-cm).
- The soil temperature probe: monitors soil temperature (Tg) at three different depths. (5, 15, and 30-cm).

- Datalogger: All data (10-Hz) is saved in a memory card connected to a data logger (e.g. CR3000, CR1000X). This datalogger's characteristics include real-time and rapid integration, data recording, and storage.
- Power supply: The EC system uses solar panel, sunsaver and batteries (12 V) to supply power to run its component sensors.

Methods

- Select a flat, homogeneous region that represents the same ecosystem.
- Position the sensor about 0.5-2 times higher than the surface roughness preferably in a constant flux layer. Maintain an adequate fetch (100 times the sensor's height) in the dominant wind direction.
- Record the data at different stages of crop growth and fallows. Periodically clean the sensors and solar panels carefully with a soft cloth to avoid scratch.
- The real-time data (10 Hz) is saved on a compact flash card (2 GB) in TOA3 format (about 1.94 GB).
- Generate TOA5 (ASCII) file to get half an hour data of all radiation and temperature
- Raw datasets changed into TOB1 file (binary format, Ts file) with help of LoggerNet software. Further, the binary data (TOB1) are converted to flux using softwares (e.g., EddyPro, TK3, EdiRe, etc.).
- Several corrections are done while processing the flux data for WPL corrections, coordinate rotation, despiking, detrending and U star etc.
- The data after correction is gap-filled (post processing) and finally represented as half-hourly flux.
- Further, diurnal, annual and interannual variations are calculated.

Calculation of flux

The flux of a gas or heat between a surface and the atmosphere using measurements of the fluctuating vertical wind velocity and the concentration of the gas or heat. Detailed equations are mentioned in "Principle" section. The flux can also be partitioned into its components using additional measurements and equations.

Correction of flux data

It is essential to correct for different sources of measurement error in order to obtain precise estimates of gas and heat fluxes using EC measurements. Here are some corrections methods for EC flux data:

- Instrumental corrections: This may include correcting for sensor drift, calibration errors, or contamination of gas samples. Instrumental corrections can be made by comparing measurements from the EC system with other independent measurements or through regular calibration and maintenance of the sensors.
- Coordinate rotation: This correction accounts for any misalignment between the EC system and the standard coordinate system and can be important for accurately calculating the fluxes.
- WPL (Webb-Pearman-Leuning) correction: This correction accounts for any water vapor density fluctuations due to temperature fluctuations in the air.
- Time lag corrections: In EC, the measured concentration of a gas or heat lags behind changes in wind velocity due to the time it takes for air to move between the source and the sensor.
- Despiking: It may be caused by internal instrument malfunctions or by outside factors such as bird droppings, dirt, precipitation, cyclones, car movement, extreme events, etc. Outlier values in the time

series are found and removed during the despiking process.

- Detrending: It is used to reduce random or systematic errors in flux estimations caused by low-frequency bias in turbulent time series.
- U star correction: U* is calculated using the lower threshold limit of night-time air velocity, below which fluxes can be discarded.

Errors

Eddy covariance measurements are subject to a number of errors, which can result in inconsistencies in the computed fluxes.:

- Instrumental errors: This category covers problems with sensors that are used to detect gas concentrations and wind speed, such as drift, noise, and calibration errors. Through routine sensor calibration and maintenance, instrument errors can be reduced.
- Non-stationarity: While EC measurements presume that fluxes are constant over the duration of the measurement, in practice, they may fluctuate over time due to changes in environmental conditions. (e.g., humidity, temperature, wind speed). Using shorter averaging intervals or filtering the data to remove non-stationary fluctuations are two ways to deal with non-stationarity.
- Spatial representativeness: EC measurements are made at a single point or tower, which may not be representative of the entire ecosystem being studied.
- Spectral losses: The sensor and measurement setup attenuate the high-frequency changes in wind velocity and gas concentrations, which can cause the fluxes to be underestimated. Spectral losses can be reduced by making use of the right filters and frequency of sampling.
- Environmental errors: Measurement errors due to cloudy day and addition of fresh rainwater from rainfall causes errors in energy balance measurements. Thus, imperfect closures of energy balance are obtained in rainy season.
- Anthropogenic errors: Caused by farm activities, presence of farm buildings, farm roads or trees in the fetch area may cause errors in the flux measurements.

Advantages

- Continuous in-situ data for an ecosystem covering large area
- Accounts small-scale variability of fluxes
- Continuous measurements with better temporal resolution than the chamber
- Flux measurement does not interfere the surface/crop
- Capture real time data
- Highly precise, verifiable and reliable data

Disadvantages

- Need turbulence
- Random measurement errors and noisy data
- Gap filling issues
- Relatively expensive
- Open-path sensors

- Homogenous vegetation and flat terrain required.
- Unsuccessful to explain fluxes in mixed ecosystem
- Mathematically complex and required trained staff for maintenance

3.2 Eddy accumulation

A conditional sampling approach called eddy accumulation collects air from updrafts and downdrafts into two distinct containers at a rate proportionate to the vertical wind speed (Brut et al. 2004). A fast-responding solenoid valve is used in eddy-accumulation techniques, allowing air to be sampled without the use of a gas analyzer (Denmead, 2008). Relaxed eddy accumulation (REA) is a type of eddy accumulation in which the direction of the wind (up or down) determines which bins the air is channeled into (Denmead, 2008).

Principle

In flux measurements using the true eddy accumulation method, the flow rate of the atmospheric air sample is adjusted to the magnitude of the vertical wind speed. During a given period, air samples are collected in two reservoirs: one for positive (w+) and one for negative (w-) wind speeds [m s^{-1}]. Using this method, the time-averaged concentration of the target trace gas, ρg [mg m^{-3}], can be calculated. The use of syringes coupled to a high-speed pulse motor synchronised with a pulse generator is proposed as a true eddy accumulation method (Komori et al. 2004). In the relaxed eddy accumulation approach, the vertical flux of a trace gas, Fg [mg m^{-2} s^{-1}], is expressed as follows.

$$F_g = b.\sigma_w.\Delta\rho_g$$

Where $\Delta\rho g$ is the average concentration difference of an atmospheric trace gas between the two measurement reservoirs and σw is the standard deviation of w over a given time period. One of the other variables that can be used to derive the variable b, an empirical coefficient, is the sensible heat flux, which can be measured by the eddy covariance method. Assuming that the value of b for an atmospheric trace gas flux is equal to that of the sensible heat flux, the sensible heat flux and the coefficient b have the following relationship:

$$w'T' = b\sigma_w(T^+ + T^-)$$

where the left and right sides of the equation represent the sensible heat flux of the Eddy covariance method and the sensible heat flux of the REA method, respectively. The variables T^+ and T^- represent the average air temperatures [K] at times when w is positive and negative, respectively.

Materials

The main components of the atmospheric trace gas collection system are a ultrasonic anemometer thermometer (SAT), pumps, solenoid valves, air sample containers, a mass flow controller, a programmable recorder such as a CR1000 (Campbell Scientific, Inc., US), and a computer.

Methods

- The air sample collected near SAT is sorted into the appropriate reservoir according to the sign (positive or negative) of the vertical wind velocity, w. A solenoid valve that is operated at fast speed is used to sort the air sample. The time-averaged value of w is calculated after w is observed using a SAT.

- A mass flow controller regulates the flow rate of the air that is being sampled in order to keep it constant. To make sure that the sample rate does not exceed the sampling tube's capacity, the flow rate must be kept low (0.2 L min^{-1}) at all times. In addition, the air intake rate must be kept constant (4 L min^{-1} or greater) and a bypass must be built into the measurement system in order to eliminate the effects of changing wind velocity.
- The system also has a three-way solenoid valve installed for the purpose of maintaining system pressure during solenoid valve switching. In place of the sampled air, VOC-free air that has been filtered by activated carbon is provided to the gas sampling tube when the sampling air input is closed.
- The sign of w is identified, the solenoid valves are switched, and the sign is then recorded. A programmed data logger such as the CR1000 is used to control the solenoid valves, record temperature and wind speed, and determine the sign (positive or negative) of w using the moving average of w.
- Air sampling reservoirs are exchanged automatically.
- The air sample reservoirs must be returned to a lab if on-site automatic analysis is not carried out. The air samples are evaluated after the analysis apparatus has been calibrated using a calibration gas, and the difference in trace gas concentrations between times with positive w values and times with negative w values is calculated.
- The value of b is calculated with the use of the sensible heat flux.

An REA system's air inlet should be placed as close to the SAT as is practical, but not so close that it affects the vertical wind. Additionally, the solenoid valves and their switching mechanism should be installed right after the air inlet to reduce the measurement time delay caused by the switching of flow channels. Moreover, a sufficiently strong suction force is required to prevent changes in wind velocity from having an impact on the rate of air input at the time of suction. A mass flow controller is employed to keep the flow rate consistent for this purpose. Finally, care must be taken to prevent water from getting inside the analyzer and water vapour from condensing there.

Advantages

- Real-time flux measurements
- High precision and accuracy

Disadvantages

- Complex setup and maintenance
- Sensitivity to measurement conditions
- Uncertainties in flux estimation

3.3 Microbial molecular techniques

Microbes play an essential role in GHG emissions. Microbes are found in a variety of environments, including the soil, water, and they are involved in the production and consumption of GHGs. In soil environments, microbial activity contributes to the release of CO_2 through the decomposition of organic matter. Methanogenic microbes produce CH_4 during the breakdown of organic matter in wetland soils, and rice paddies, while methane-oxidizing microbes consume CH_4 in soil and aquatic environments. N_2O is a by-product of the microbial processes that convert nitrogen in soil and water into forms that are available

for plant uptake. Due to excess nitrogen application N_2O emissions increased, which can contribute to climate change. Understanding the microbial processes involved in GHG emissions is essential for developing strategies to reduce these emissions (Singh et al. 2010). There are several microbial molecular techniques that can be used to study greenhouse gas emissions. We have discussed here the major microbial techniques with their purposes, principles, materials and methods, analysis, advantages and disadvantages for GHG emission research.

3.3.1 Microbial DNA sequencing

This technique can be used to identify and quantify the microbial communities that are responsible for greenhouse gas production in soil or other environments (Morant et al. 2020). By analysing the DNA of these microbes, one can gain a better understanding of how they contribute to greenhouse gas emissions. DNA sequencing can also be used to investigate the genetic basis of traits related to GHG emissions, such as the ability of microbes to degrade organic matter and produce CH_4 or N_2O (Xu et al. 2013). By understanding the genes and metabolic pathways involved in these processes, researchers can develop more effective strategies for mitigating GHG emissions.

Purpose

DNA sequencing can be used to identify the microorganisms present in a given environment and to analyze their functional capabilities, such as their ability to produce or consume GHGs. In addition to studying microbial communities, DNA sequencing can also be used to investigate the genetics of plants and other organisms involved in the carbon cycle. For example, by analyzing the genetic basis of plant traits related to carbon uptake and storage, researchers can identify ways to enhance carbon sequestration in forests and other ecosystems (Jiang et al. 2021).

Principle

The principle of DNA sequencing is to determine the order of nucleotides (A, C, G, and T) in a DNA molecule. There are several methods for DNA sequencing, but they all involve the same basic steps, such as DNA isolation from the biological sample, DNA amplification using polymerase chain reaction (PCR), DNA fragmentation into smaller pieces of varying lengths, DNA sequencing using a variety of methods, such as Sanger sequencing, next-generation sequencing (NGS), and single-molecule sequencing. Once the DNA sequence has been determined, it can be used for a variety of applications, including studying genetic variation, identifying disease-causing mutations, and investigating the genetics of complex traits such as GHG emissions.

Materials

Sanger sequencing

- DNA template, primers
- DNA polymerase
- deoxynucleotides (dNTPs),
- dideoxynucleotides (ddNTPs)
- gel electrophoresis apparatus

Illumina sequencing:

- DNA template, adapters
- polymerase, deoxynucleotides (dNTPs)

- reagents for bridge amplification
- flow cell
- sequencing machine

Nanopore sequencing:

- DNA template
- nanopore sequencing device
- polymerase
- salt buffer
- deoxynucleotides (dNTPs)

Methods

Sanger sequencing

- The Sanger sequencing method uses a chain-terminating nucleotide method to sequence DNA.
- The DNA template is amplified using PCR, and then a specific primer is used to initiate sequencing.
- The reaction mixture contains all four deoxynucleotides (dNTPs) as well as a small amount of one of the four dideoxynucleotides (ddNTPs), which lacks the 3' hydroxyl group needed for DNA chain elongation.
- As the polymerase extends the new DNA strand, if it incorporates a ddNTP instead of a dNTP, the elongation is terminated, resulting in a series of DNA fragments of different lengths that can be separated by gel electrophoresis.

Illumina sequencing:

- Illumina sequencing is a highly parallel sequencing method that uses reversible terminator-based chemistry.
- The DNA template is fragmented, and adapters are added to each end. These adapters have complementary sequences to the oligonucleotide-coated flow cell that is used in the sequencing machine.
- The flow cell is used for bridge amplification, where the DNA fragments are amplified, and complementary strands are synthesized. Each fragment generates millions of identical copies, which form clusters on the flow cell.
- The sequencing reaction is initiated by the addition of the first nucleotide and polymerase. Each fluorescently-labelled nucleotide base is then sequentially added to the flow cell, and the resulting signals are recorded by the sequencing machine.

Nanopore sequencing:

- Nanopore sequencing uses a single-molecule approach to sequence DNA.
- A single-stranded DNA molecule is threaded through a protein nanopore, and as each nucleotide passes through the nanopore, it causes a characteristic change in the electrical current flowing through the nanopore.
- These changes are detected by a sensor and are used to identify the specific nucleotide.
- The sequencing reaction is performed in a salt buffer and involves the addition of deoxynucleotides (dNTPs) and a polymerase.

Analysis

- The first step in data analysis is to assess the quality of the raw sequencing data by filtering out low-quality reads and trimming reads to remove adapter sequences and low-quality bases.
- Then, the filtered and trimmed reads are aligned to a reference genome or assembled de novo to generate a consensus sequence.
- It is followed by variant calling which involves comparing the sequence data to a reference genome to identify mutations, SNPs, and indels, which may have an impact on biological function, including GHG emissions.
- Then functional information is added to the DNA sequence data, such as identifying the location of genes, introns, and exons, as well as other functional elements such as enhancers and promoters, which is known as annotation.
- The final step in DNA sequencing analysis is interpretation of the data by comparing the sequence data to other data sets, such as gene expression data or metabolic pathway analysis, to identify relationships between the sequence data and biological function.

Advantages

- High accuracy
- High throughput
- Non-destructive
- Unbiased

Disadvantages

- DNA sequencing can be expensive
- Technical complexity
- Limited information as it does not provide direct information on the actual GHG emissions themselves.
- It generates large amounts of data, which can be difficult and time-consuming to analyze and interpret.

3.3.2 Metagenomics

Targeted metagenomics is another technique which can be used to study the microbial communities involved in GHG emissions (Kumar et al. 2020). These techniques involve sequencing and analysing specific genes or gene clusters that are known to be involved in the production or consumption of GHGs. Some of the key genes involved in methanogenesis include the methyl-coenzyme M reductase (mcr) gene, which catalyzes the final step in the methane production pathway, and the genes encoding the enzymes involved in the Wood-Ljungdahl pathway, which is an alternative pathway for methanogenesis from CO_2 and H_2 (Zhang et al. 2020). Metagenomics can be a powerful tool for studying the genes and metabolic pathways involved in microbial CO_2 fixation. Some of the key genes involved in CO_2 fixation include the ribulose bisphosphate carboxylase/oxygenase (Rubisco) gene, which is the primary enzyme involved in the Besides, some of the key genes involved in N_2O production include the nitrous oxide reductase (nosZ) gene, which encodes the enzyme that converts N_2O to N_2, and the nitric oxide reductase (nor) gene, which encodes the enzyme that converts NO to N_2O (Orellana et al. 2014).

Purpose

The purpose of microbial targeted metagenomics for GHG emissions is to identify and characterize the microorganisms and genes that are responsible for GHG production and consumption in different environments. By analyzing the DNA or RNA extracted from microbial communities, researchers can identify the functional genes and metabolic pathways that are involved in GHG emissions, and they can also quantify the abundance and diversity of the microbial communities that are contributing to these emissions.

Principle

The principle of microbial targeted metagenomics for GHG emissions is to use high-throughput DNA sequencing technologies to study the genes and metabolic pathways of microorganisms in their natural environments, with a focus on those that are involved in GHG emissions. This approach involves extracting DNA or RNA from microbial communities and sequencing the genetic material to identify the functional genes and metabolic pathways that are involved in GHG emissions.

Materials

- DNA extraction kits
- Illumina, PacBio, or Nanopore
- Suitable software and databases

Methods

- DNA is extracted from the microbial communities present in the samples using commercially available kits.
- DNA libraries are prepared by fragmenting the DNA, adding adapters, and amplifying the fragments using PCR using commercial kits.
- The DNA libraries are sequenced using high-throughput sequencing platforms, such as Illumina, PacBio, or Nanopore.

Analysis

The raw sequencing data is processed using bioinformatics tools to filter, trim, and quality control the reads. The identified genes are annotated based on their putative functions and metabolic pathways, using bioinformatics tools and databases such as KEGG or COG. The abundance and diversity of these genes are quantified across different environmental samples. The data is interpreted in the context of the environmental conditions and biotic factors that may be influencing GHG emissions, using statistical analysis and visualization tools.

Advantages

- Unbiased and comprehensive analysis
- Identification of novel genes
- High-throughput and scalability
- Identification of functional genes involved in GHG emissions
- Non-invasive sampling that minimizes disturbance to the environment

Disadvantages

- Data analysis complexity
- Sample variability
- Suffer from bias and noise due to DNA extraction methods, sequencing platforms, and bioinformatics pipelines.
- Limited taxonomic resolution

3.3.3 Quantitative PCR (q-PCR)

Quantitative Polymerase Chain Reaction (q-PCR) is a powerful molecular biology technique used to quantify the abundance of specific microbial taxa or functional genes involved in GHG emissions (Kolton et al. 2019). q-PCR involves amplifying a target gene using specific primers and a fluorescent probe, and measuring the increase in fluorescence as the gene is amplified. The amount of fluorescence is directly proportional to the amount of DNA present in the sample, allowing for the quantification of specific microbial taxa or genes (Kumar et al. 2019). The genes mentioned for targeted metagenomics can also be validated in q-PCR metods.

Purpose

The q-PCR quantify the abundance of specific microbial groups or functional genes involved in GHG emissions

Principle

The q-PCR process involves the use of specific primers and a fluorescent probe that bind to the target DNA sequence of interest. During the PCR amplification process, the primers bind to the target DNA, and the probe hybridizes to the DNA between the primers. Once the target DNA is amplified, the probe is cleaved by the Taq polymerase enzyme, releasing the fluorescent dye. The fluorescence produced during the q-PCR reaction is measured in real-time using a fluorescence detector. As the amount of amplified DNA increases, so does the amount of fluorescence, allowing for the quantification of the target DNA in the sample. The amount of target DNA in the sample is determined by comparing the fluorescence signal to a standard curve generated from known quantities of a synthetic DNA template containing the target sequence of interest.

Materials

- DNA extraction kits
- Primers
- Suitable software and databases

Methods

- The first step in q-PCR analysis involves the extraction of DNA from the samples.
- Specific primers to the target gene or group of interest are to be selected and a fluorescent reaction probe to be detected during the q-PCR .
- Then the PCR amplification is performed using a thermal cycler that allows for the repeated cycling of the reaction mixture through different temperature regimes. The PCR reaction mixture typically contains DNA template, primers, fluorescent probe, Taq polymerase enzyme, and buffer components. The cycling conditions involve an initial denaturation step at a high temperature, followed by a series

of denaturation, annealing, and extension steps that amplify the target DNA.

- Real-time PCR technology is used to quantify the amount of target DNA in the sample. The fluorescence signal produced during the q-PCR reaction is measured at every cycle, and the amount of target DNA is calculated based on a standard curve generated from known concentrations of a synthetic DNA template containing the target sequence of interest.
- The q-PCR analysis can be performed using a variety of instruments, including the Applied Biosystems QuantStudio, Bio-Rad CFX96, and Roche LightCycler. The data analysis involves the calculation of the threshold cycle (Ct) value, which represents the cycle number at which the fluorescence signal reaches a threshold level. The Ct value is used to calculate the amount of target DNA in the sample based on the standard curve.

Analysis

The analysis of q-PCR techniques involves the calculation of the target DNA quantity in the environmental sample based on the Ct values generated during the q-PCR reaction (Kumar et al. 2019). The Ct value represents the cycle number at which the fluorescence signal of the target DNA reaches a threshold level. The q-PCR data analysis can be performed using different software packages, such as Applied Biosystems QuantStudio, Bio-Rad CFX Manager, and Roche LightCycler software.

Advantages

- High sensitivity and specificity
- Rapid and cost-effective
- Accurate and reproducible
- Easy to use

Disadvantages

- Limited taxonomic resolution
- Lack of functional information

There are several other techniques of microbial molecular approaches for GHG emission quantification, including transcriptomics, proteomics, stable isotope probing, microbial community profiling etc. Each of these molecular techniques has its advantages and limitations, and the choice of technique depends on the research question, the environmental sample, and the available resources. A combination of these techniques can provide a comprehensive understanding of the microbial ecology and metabolic pathways involved in GHG emissions in different environmental systems.

4. Regional level measurements of GHG

There are several regional-level measurements of greenhouse gas (GHG) emissions from agriculture, which can vary depending on factors such as climate, land use, and agricultural practices. The development and improvement of a globally accepted methodology and software for the computation and reporting of national greenhouse gas (GHG) emissions and removals is the responsibility of the IPCC's Task Force on National Greenhouse Gas Inventories (TFI). The methodologies and software developed by the TFI are used by member countries to prepare their national GHG inventories, which are submitted to the UNFCCC (United Nations Framework Convention on Climate Change) as part of their reporting obligations under the Paris Agreement. The TFI also provides capacity building and training to help countries improve their

inventory reporting and meet their climate commitments. It is important to note that these measurements are based on estimates and can vary depending on the specific region and the methods used to calculate emissions. Life cycle assessment, carbon footprint analysis, and several broadly predefined steps are involved in regional level measurements of GHGs (**Figure 3**).

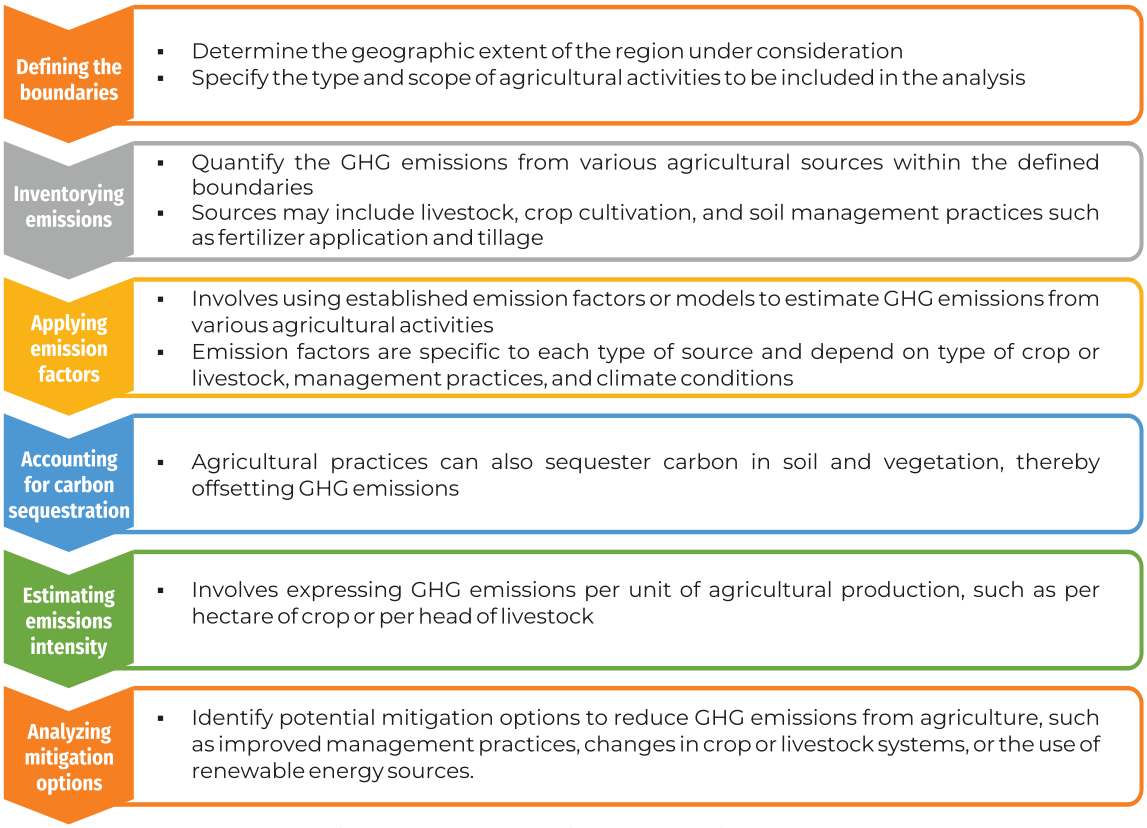


Figure 3 Steps of measuring GHGs at regional level

4.1 Life cycle assessment (LCA)

This is a more comprehensive method that takes into account all the stages of a product's life cycle, from production to disposal. LCA can provide a detailed breakdown of the emissions associated with specific inputs and processes, and can help identify areas where emissions reductions can be made. It is a comprehensive assessment method used to evaluate the environmental impact of a product or service throughout its entire life cycle, from raw material extraction to disposal (Fava et al. 2014). The LCA of GHG emissions in agriculture involves assessing the entire life cycle of agricultural products, including the cultivation of crops, the raising of livestock, and the production of food and fiber products. The assessment includes measuring the emissions of GHGs such as carbon dioxide, methane, and nitrous oxide from all stages of the agricultural life cycle. This approach provides a comprehensive assessment of the environmental impacts of agricultural products and helps identify areas where emissions can be reduced. This information can be used to make informed decisions about the production and consumption of agricultural products, and to develop policies and programs to reduce GHG emissions from the agricultural sector.

In LCA, system boundaries are an essential aspect of the methodology (cradle-to-grave, cradle-to-gate, gate-to-gate). System boundaries define the scope of the assessment, which includes the processes and activities that are included in the analysis and those that are excluded. The boundaries help ensure that all the relevant inputs and outputs associated with the life cycle of a product are accounted for in the assessment. For example, in an LCA of a crop production system, the system boundaries may include the inputs used in crop production such as fertilizers, pesticides, and irrigation water, as well as the energy used to power machinery and equipment. The boundaries may also extend to include the transportation of the harvested crop to processing and packaging facilities, as well as the emissions associated with these activities. It is important to define the system boundaries correctly to ensure that the assessment accurately reflects the environmental impact of the product or system being analyzed. If the boundaries are too narrow, important inputs and emissions may be excluded, leading to an underestimation of the environmental impact. On the other hand, if the boundaries are too broad, irrelevant inputs and emissions may be included, leading to an overestimation of the environmental impact. Input-related emissions, often known as "indirect" emissions, have typically been relatively well accounted for. Indicators for the majority of manufactured inputs used in agricultural production are available in the literature. Using the default data for energy usage for field operations translated to CO_2 equivalents (CO_2e) emissions for on-farm activities may be computed.

4.2 Carbon footprint

This measures the total amount of greenhouse gases emitted during the production of a crop or livestock product. It can be expressed in CO_2 equivalents per unit of produce (kg CO_2e per kg), or as a total amount per region (metric tons of CO_2e per year for a region). As compared to LCA methods, carbon footprint is much simpler, while LCA provides a more comprehensive picture of the environmental impact of agricultural activities and help to identify opportunities for improvement across the entire supply chain, such as reducing waste or increasing efficiency (Finkbeiner and König, 2013). Carbon footprint measures the direct emissions of a product or service, while LCA takes a holistic approach by considering both direct and indirect emissions throughout the entire life cycle.

4.3 National GHG inventories

Many countries have established national greenhouse gas inventories that include emissions from agriculture at the regional level. These inventories typically use a combination of methods, including direct measurements, modelling, and data from surveys and other sources. For example, Holos is a software model developed by Agriculture and Agri-Food Canada that is designed to calculate greenhouse gas (GHG) emissions from both on-farm and off-farm processes in dairy systems. The model takes into account various factors such as animal feed, manure management, energy use, and transportation in order to estimate GHG emissions from a dairy farm. Using Holos, farmers and other stakeholders can gain a better understanding of the GHG emissions associated with their dairy operations, and identify opportunities to reduce emissions through changes in management practices or the adoption of new technologies. This can help to support sustainable dairy production and reduce the environmental impact of the industry.

4.4 IPCC factors

The IPCC provides guidelines for calculating GHG emissions from various sectors, including agriculture. These guidelines include a set of factors that are used to estimate emissions based on activity data and emission factors. The IPCC factors for greenhouse gas emissions from agriculture provide a framework for estimating emissions and identifying opportunities for mitigation. By understanding the factors that

contribute to emissions, farmers and policymakers can take steps to reduce their environmental impact and help mitigate climate change. The IPCC provides a set of emission factors for enteric fermentation, manure management, synthetic fertilizers, crop residue burning, rice cultivation, land use change etc. The IPCC factors for GHG emissions from agriculture are expressed in terms of global warming potential (GWP), which is a measure of how much a given amount of a GHG will contribute to global warming over a specified time horizon (usually 100 years). The factors for CO_2, CH_4, and N_2O are expressed relative to CO_2, which is assigned a GWP of 1.

The IPCC factor for CH_4 emissions from enteric fermentation is 25, which means that 1 kg of CH_4 emitted is equivalent to 25 kg of CO_2 in terms of GWP. Similarly, decomposition of livestock manure also produces CH_4, as well as N_2O. The IPCC factor for CH_4 emissions from manure management is 25, while the factor for N_2O emissions is 298. The production and use of fertilizers can also contribute to GHG emissions, primarily through N_2O emissions from soil. The IPCC factor for N_2O emissions from fertilizer use varies depending on the type of fertilizer and the method of application, but can range from 0.01 to 0.6. This means that 1 kg of N_2O emitted from fertilizer use is equivalent to 0.01 to 0.6 kg of CO_2 in terms of GWP. It is important to note that these emission factors are not one-size-fits-all, and may vary depending on local conditions and practices. Therefore, it is recommended to use region-specific emission factors when available.

The IPCC provides guidelines and methodologies for estimating GHG emissions and removals. There are three tiers (Tier 1, 2 and 3) for estimation of emission factors depending on increasing precision and accuracy of measurement and lowering of uncertainty. Tier 1 includes IPCC default factors, while Tier 2 includes country specific data for key factors. Tier 3 method includes detailed national inventory through repeated or detailed inventory measurement and use of model. These guidelines include default emission factors that serve as reference values for various emission sources and activities. However, countries may also develop their own country-specific emission factors (**Table 2**) based on their specific data and circumstances. In India (Sinha et al. 2020), the Ministry of Environment, Forests and Climate Change (MoEFCC) is responsible for developing and updating the national GHG inventory, including country-specific emission factors. The MoEFCC's Environmental Information System (ENVIS) portal and the Indian Network for Climate Change Assessment (INCCA) are reliable sources for obtaining the most up-to-date emission factors for India. In addition, the Indian government can submit its national GHG inventory to the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC's national communications and GHG inventory reports may contain country-specific emission factors for India.

Table 2. Country specific IPCC emission factors for India

Agricultural Activity/Practice	Emission Factor	Reference
Enteric Fermentation (Livestock)		
Dairy cows	25-30 kg CH_4 animal^{-1} yr^{-1}	Swamy and Bhattacharya, 2006
Beef cattle	15-20 kg CH_4 animal^{-1} yr^{-1}	
Sheep and goats	4-10 kg CH_4 animal^{-1} yr^{-1}	
Pigs	6-12 kg CH_4 animal^{-1} yr^{-1}	
Poultry	0.1-0.5 kg CH_4 animal^{-1} yr^{-1}	
Manure Management		

CH_4 from storage facilities	10-100 kg CH_4 animal unit*$^{-1}$ yr^{-1}	Gupta et al. 2009
CH_4 from open lot systems	15-70 kg CH_4 animal unit $^{-1}$ yr^{-1}	
CH_4 from solid storage systems	30-100 kg CH_4 animal unit^{-1} yr^{-1}	
CH_4 from liquid storage systems	15-50 kg CH_4 animal unit^{-1} yr^{-1}	
Crop Cultivation		
Rice cultivation under continuous flood in irrigated condition	1.0 kg CH_4 ha^{-1} d^{-1}	Sinha et al. 2020
Rice cultivation under multiple drainage period in irrigated condition	0.55 kg CH_4 ha^{-1} d^{-1}	
Rice cultivation under single drainage period in irrigated condition	0.6 kg CH_4 ha^{-1} d^{-1}	
Rice cultivation under seasonally integrated for continuously flooded fields	0.85 kg CH_4 ha^{-1} d^{-1}	
Rice cultivation under deepwater in irrigated condition	0.06 kg CH_4 ha^{-1} d^{-1}	
Rice cultivation under deepwater in rainfed condition	0.8 kg CH_4 ha^{-1} d^{-1}	
Rice cultivation under drought prone in rainfed condition	0.16 kg CH_4 ha^{-1} d^{-1}	
Methane from flooded rice	25-90 kg CH_4 ha^{-1} yr^{-1}	IPCC, 2006
Irrigated maize	0.3 kg CH_4 ha^{-1} yr^{-1}	
N_2O emission from direct from soil under different crop cultivation		
Sugarcane cultivation	0.2-1 kg N_2O-N ha^{-1} yr^{-1}	Hergoualc'h et al. 2021
Cotton cultivation	0.1-0.5 kg N_2O-N ha^{-1} yr^{-1}	
Oilseed cultivation	0.1-0.5 kg N_2O-N ha^{-1} yr^{-1}	
Pulses cultivation	0.1-0.5 kg N_2O-N ha^{-1} yr^{-1}	
Rice cultivation	0.5-3 kg N_2O-N ha^{-1} yr^{-1}	
Maize cultivation	0.2-1 kg N_2O-N ha^{-1} yr^{-1}	
Wheat cultivation	0.2-1 kg N_2O-N ha^{-1} yr^{-1}	
Synthetic fertilizers and manure management		
N_2O from manure	0.5-5 kg N animal unit^{-1} yr^{-1}	IPCC, 2006
N_2O from applied N fertilizers	0.7-3%	
N_2O from volatilized N from manure and fertilizer	0.5%	Sinha et al. 2020
N_2O from applied fertilizer	0.7%	
N_2O from runoff and leached from manure and fertilizer	0.5%	
Gas loss through volatilization from inorganic fertilizer	15%	
Gas loss through volatilization from organic manure	15%	
Leaching from applied N fertilizer and manure	10%	

**Animal Unit represents the feed intake and waste production of a mature cow weighing approximately 1,000 pounds (450 kilograms). Other livestock species are converted into Animal Units based on their relative size and feed requirements compared to a mature cow*

However, there are also limitations to using these factors. One limitation is that the factors are based on average values and may not accurately reflect the emissions associated with specific agricultural practices or conditions. For example, the N_2O emissions from fertilizer use can vary widely depending on factors such as soil type, climate, and management practices.

5. Global level measurements of GHG

5.1 Aerial platform

GHG emissions are usually measured using specialized equipment and sensors mounted on mobile platforms such as aircraft, unmanned aerial vehicles (drones), or satellites. There are numerous tools available for measuring GHG through the aerial platform. These can include ground-based devices, aeroplane instrumentation, and satellites that track total atmospheric GHG from low-earth orbit (Klausner et al. 2020; Lorente et al. 2021). Broadly two types of aerial platforms are available. Geospatially flexible measurement platforms, such as those in moving vehicles, and geospatially stationary, like towers or long-term permanent monitoring sites (Knox et al. 2019). A mobile measurement platform is one that is fixed in one location for an extended period of time but is mobile enough to be moved elsewhere to take measurements. These platforms are used to gather data on GHGs in the atmosphere, such as CO_2, CH_4, and NO_2. Data on GHG concentrations in the atmosphere can be collected by aircraft and drones fitted with sensors such as spectrometers or infrared cameras. The spatial and temporal distribution of GHGs is then determined using this data. Satellites can also be used to collect data on GHG emissions from space. Satellites equipped with instruments such as spectrometers or microwave radiometers can detect and measure GHGs in the earth's atmosphere.

The popularity of airborne measurements has been particularly high (Fried et al. 2008). These platforms have made it possible to research how N_2O moves through the troposphere and into the stratosphere (Fried et al. 2008). A rapid gas analyzer can be used to monitor samples in situ or the collected samples can be preserved for subsequent laboratory analysis. Because wind components are measured in real time on the moving platform, the "actual" vertical wind velocity must be corrected for platform motion (Brut et al. 2004). Measurements on moving platforms require instruments that are resistant to vibration and changing environmental factors such as pressure, temperature, and humidity (Fried et al. 2008).

Materials

- Sensors are a key component of any GHG measurement system. Laser-based sensors are used for CH_4, while infrared sensors are used for CO_2 detection.
- Instrumentation such as spectrometers, radiometers, or other specialized equipment mounted on the aerial platform.
- Communication systems are used to transmit data from the aerial platform to the ground-based data processing centre through satellite links or wireless communication technologies.
- Power systems provided by batteries or solar panels or fuel cells.
- Data processing systems using specialized software or data analysis tools.
- Platform structure based on payload capacity and endurance.

Methods

- The aerial platform needs to be equipped with appropriate sensors.
- To make sure that all areas of interest are covered, the flight path needs to be meticulously planned.

In order to do this, it may be necessary to plan out the area to be surveyed and choose the right altitude and speed for the aerial platform.

- During the flight, the instruments on board the aerial platform will record data on the concentration of GHGs in the atmosphere (Chang et al. 2020). The samples are either collected in-situ and measured immediately using sensors, or the air samples are brought to the ground station for measuring in a highly specific laboratory facility (Brosy et al. 2017). In the first instance the measurements are real-time.
- The amount of GHGs in the atmosphere is calculated using the data gathered during the flight. In order to do this, it may be necessary to compare the results to background levels or to earlier measurements made at the same site.
- The amount of GHGs emitted per unit of time or per unit of area is usually used to be reported. This information can be used to inform policy decisions, identify sources of emissions, or track progress towards emissions reduction goals.

Advantages and disadvantages

To better comprehend how GHGs are distributed in the atmosphere and how they are affecting the earth's climate, data from aerial platforms is often utilized. This data can be used to improve climate models and guide policy choices aimed at lowering GHG emissions. Additionally, these tools are capable of measuring GHGs in inaccessible or isolated locations, which is highly useful information for climate change research.

One disadvantage of this system is the issue of a sampling gap between the earth and up to certain heights above the ground, where mobile platforms cannot function.

5.2 Modelling GHG emission

Estimates of GHG emissions from different cropping systems remain highly imprecise and expensive due to large geographic and temporal differences in soil properties and cropping practises (Smith et al. 2004). Use of simulation models at both regional and field scales has been used by several researchers to measure GHG emissions under different agricultural systems (Tripathi et al. 2021). Models such as CENTURY, DNDC, DayCent, DSSAT, TechnoGAS, ECOSSE, EPIC are widely used and validated globally (**Table 3**).

Table 3. Different models of GHGs emission

Model name	Type of model	Features	References
Denitrification Decomposition (DNDC)	Process-based	➢ It was initially developed to estimate GHG emissions from agricultural soils and has since been extended to model the dynamics of SOC, which is influenced by a range of soil and environmental processes. ➢ The DNDC model has been used to compare long-term experiments for agricultural cropland with SOC variations over time.	Yin et al. 2020; Tripathi et al. 2021
IPCC Tier 1	Empirical	➢ Method for evaluating changes in GHG emissions of soil. ➢ Using medium and long-term information, a relationship was found between the application of compost and manure and GHG emission.	Smith et al. 1997

CENTURY	Process-based	➢ It is advantageous if ecosystem models are able to predict GHG emission in both aerobic and anaerobic soils. ➢ This model is suitable for predicting the long-term dynamics of GHG emission in rotations with lowland rice grown once every three years, but it may be less suitable for predicting dynamic behaviour in rotations that are flooded annually.	Milne et al. 2008
Daily Century (DayCent)	Process-based	➢ In this model, CENTURY is extended to a daily time frame to more accurately predict crop development and the effects of soil activity on GHG emission. ➢ DayCent has studied how changes in SOC, GHG emissions, and yields are affected by different cropping practices.	Necpálová et al. 2015
Decision support system for agrotechnology transfer (DSSAT)	Process-based	➢ A wide range of on-farm and precision management, regional studies of climate variability and change impacts, water use, GHG emissions and soil C-balances are just a few examples of the many uses at different temporal and geographic scales. ➢ Since the CENTURY-based soil model was incorporated into DSSAT, the model has improved the accuracy of modelling long-term changes in upscaling of GHGs emission.	Attia et al. 2021
Technical coefficient generator for mitigation technologies of greenhouse gas emissions from agricultural sectors (TechnoGAS)	Process-based	➢ Inputs and outputs were calculated for different crops, units of area, and production methods ➢ For a single crop, inputs and outputs are calculated on a seasonal basis.	Pathak and Wassmann, 2007
Estimate Carbon in Organic Soil sequestration and Emissions (ECOSSE)	Process-based	➢ Updated and applied to assess the GHG emissions of different agricultural systems and soils in Europe. ➢ In the Mediterranean pedoclimatic zones, there is limited experience with the use of ECOSSE to simulate the potential for sequestration of SOC on cropland with different crops and agricultural management systems.	Dondini et al. 2015
Environmental Policy Integrated Climate (EPIC)	Process-based	➢ Operated on a daily time basis and was capable of simulating vast regions over a long period of time, up to 100 hectares. ➢ The EPIC model was used to study the modeling of the GHG emission under different irrigation, fertilization, and tillage conditions.	Zhao et al. 2013

Over many years, numerous researchers from around the world have evaluated and validated the DNDC model using information from various field studies (Yin et al. 2020; Tripathi et al. 2021). The model is composed of two parts. The first model component consists of sub models for climate, soil, plant growth, and degradation; the second consists of sub models for nitrification, denitrification, and fermentation.

The first component simulates soil moisture, temperature, redox potential (Eh), pH, and substrate concentration profiles, while the second component simulates agroecosystem emissions of CH_4, N_2O, and nitric oxide (NO), dinitrogen (N_2), CO_2, and ammonia (NH_3) (Giltrap et al. 2010). It is observed that the DNDC model accurately represents the basic trends of CH_4, N_2O, NO, and NH_3 fluxes. Tripathi et al. (2021) conducted a study with the objective of applying the DNDC model to simulate N_2O and CH_4 emissions from paddy fields in eastern India regionally, using satellite data and information on cultivation and land management. In this study, Landsat-8 data from the flowering stage of the crop were used to estimate rice grain yield. In addition, the DNDC model was used to simulate N_2O and CH_4 emissions in the rice-dominated Khordha block in eastern India using cropping practises, soil maps, weather data, and crop yields as model inputs **(Figure 4).**

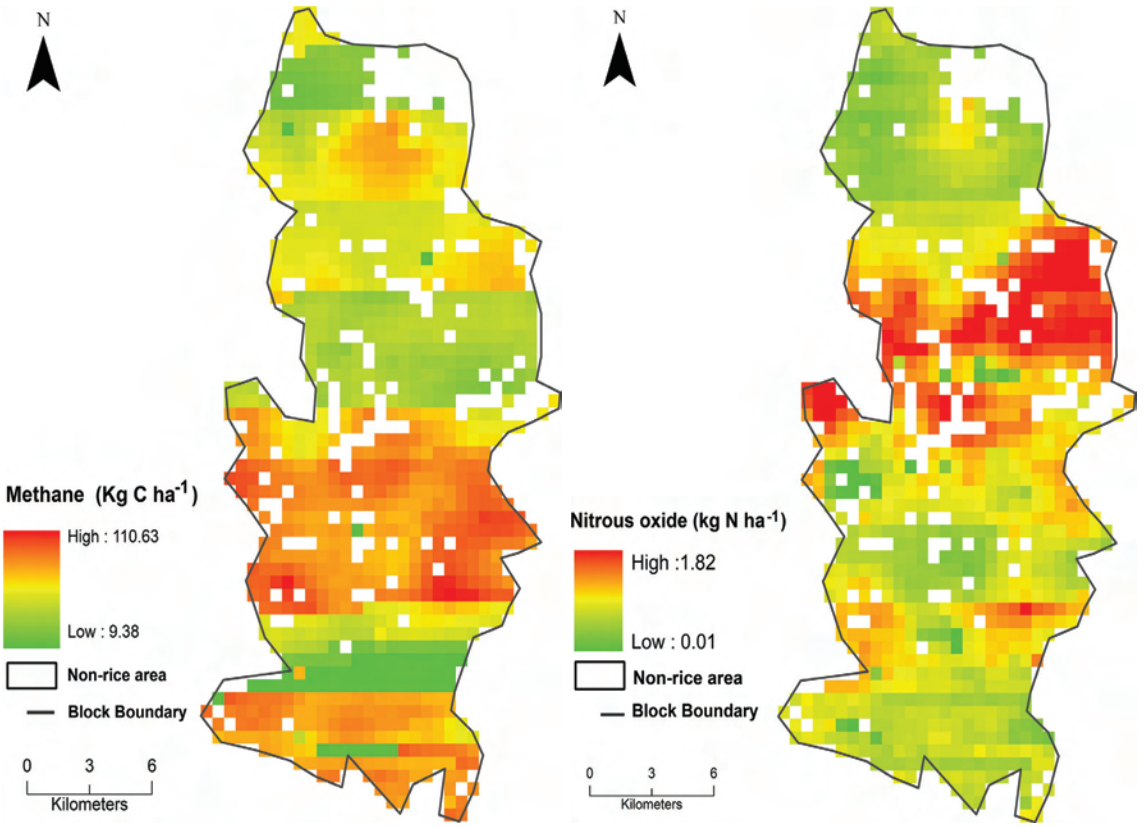


Figure 4 Spatial distribution of CH_4 and N_2O emission from Khordha as simulated by DNDC

According to the observations, the model can be used to simulate GHG emissions in rice agroecosystems. The results showed that the DNDC model accurately predicted the trend of N_2O and CH_4 emissions from paddy fields under various management practises, but the simulated emissions were higher than the measured values. Methane and N_2O emissions in the study region varied greatly due to differences in soil properties and cultivation practises. CH_4 emissions were high due to the flooded rice fields created by

group rice cultivation. The model was not able to accurately capture N_2O emissions during the final stages of rice harvesting. This finding has the potential to significantly improve the performance of the DNDC biogeochemical model and validate it for additional areas, which is critical for accurate GHG emissions calculations.

5.3 Satellite-based earth observations

Satellite has the ability to measure GHGs from the surface level to the upper atmosphere, which enables us to understand the nature of GHGs and their interactions with the atmosphere. The concentrations of GHGs are determined by examining the spectral properties of the reflected or emitted light which is impacted by the presence of GHGs in the atmosphere. Satellite-based GHG measurements are used to track changes in GHG concentrations over time, record and monitor sources of GHG emission like fossil fuel combustion, deforestation, and agriculture, and track changes in GHG concentrations over time. However, satellite-based GHG measurements have some drawbacks, such as measurement uncertainties, difficulties attributing emissions to particular sources, and limitations on spatial and temporal resolution.

Satellite-based Earth observations such as MODIS (Moderate Resolution Imaging Spectroradiometer) and Landsat are rapid, non-invasive, and completely free, and can monitor changes in the carbon balance of individual farms as a result of land use and management changes (Weiss et al. 2020). While MODIS data have low spatial resolution (250-1000 m), Landsat imagery has higher resolution (30 x 30 m) and can better resolve the field sizes of typical farms. In agroecosystems, remote sensing data have accurately predicted aboveground biomass with relatively low uncertainty (Wiesner et al. 2020).

6. Conclusion

Several analytical methods are available to measure GHGs at field, ecosystem, regional and global levels. Due to temporal and spatial variations in GHG concentrations measurement are always complicated and difficult. However, each technique has its own pros and cons, and the best technique to utilize ultimately relies on the needs of the user. Recent years have seen significant progress in the study of GHG emissions as it has become possible to quantify extremely low amounts of GHGs very quickly. In order to accurately detect GHGs, a low-cost, easily deployable sensor that can gather emission data over a large region is essential. Instead of relying on a small number of isolated investigations, such a sensor would allow for a more precise knowledge of GHG emissions across large areas.

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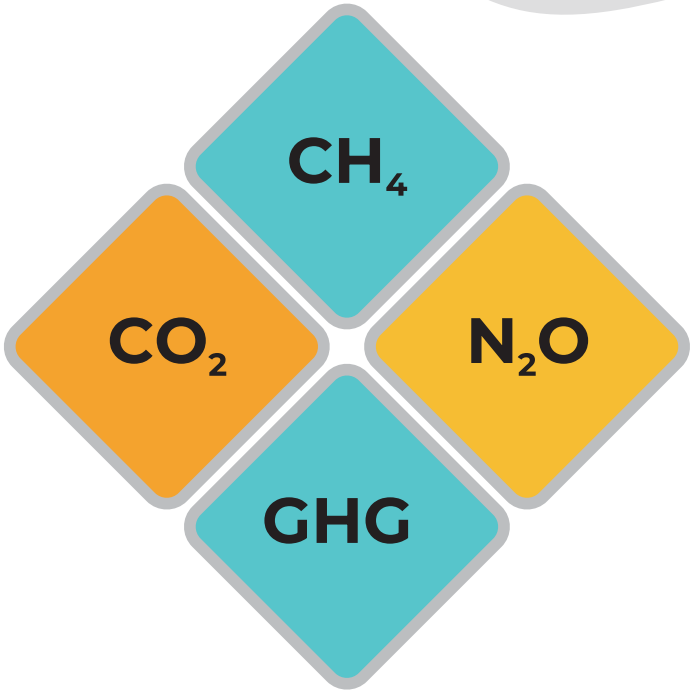

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