Measuring Greenhouse Gas Emissions, Carbon Stocks and Stock Changes in Smallholder Farming Systems

A Training Manual

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A Training Manual: Measuring greenhouse gas emissions, carbon stocks, and stock changes in smallholder farming systems
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGB</td>
<td>Aboveground biomass</td>
</tr>
<tr>
<td>BGB</td>
<td>Belowground biomass</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CO₂-e</td>
<td>Carbon dioxide equivalent</td>
</tr>
<tr>
<td>DBH</td>
<td>Diameter at breast height</td>
</tr>
<tr>
<td>Gg</td>
<td>Gigatonne</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>IPCC</td>
<td>International panel on climate change</td>
</tr>
<tr>
<td>Mg</td>
<td>Megagrams (Ton)</td>
</tr>
<tr>
<td>KNCCAP</td>
<td>Kenya national climate change action plan</td>
</tr>
<tr>
<td>SOC</td>
<td>Soil organic carbon</td>
</tr>
<tr>
<td>SOM</td>
<td>Soil organic matter</td>
</tr>
<tr>
<td>TTB</td>
<td>Total tree biomass</td>
</tr>
</tbody>
</table>
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Preface

Agriculture is one of the most important sectors in Kenya’s economy with significant impact on the country’s greenhouse gas (GHG) budget. According to the Kenya national climate change action plan, NCCAP (2012), agriculture is the leading source of GHGs, accounting for almost a third of the country’s total emissions. Agricultural emissions are largely generated in the form of methane (CH\textsubscript{4}) and nitrous oxide (N\textsubscript{2}O) from crop and livestock production and management activities. Clearing and preparation of land for agricultural production contributes to carbon dioxide (CO\textsubscript{2}) emission from biomass and soil.

The agricultural sector can also play an important role in climate change mitigation, through carbon sequestration in trees on farms and in the soil and potential to reduce agriculture related emissions. The Government of Kenya and other stakeholders are implementing multiple interventions relevant to climate mitigation through agriculture. One notable approach is the climate-smart agriculture through technologies such as conservation agriculture, agroforestry and improved grazing.

It is important to quantify the emissions and mitigation potentials of the agricultural sector. This will enable Kenya to provide annual estimates of emissions from all important sources, including farms and capitalize on the emerging green economy. In addition, data on emissions and removals can be used by managers and policy makers to develop strategies for reducing emissions, guide in planning for low-emission development, and monitor the progress of strategies adopted. For example, full development of climate smart agriculture practices and other low carbon actions are expected to almost halve Kenya’s GHG emissions by 2030 (NCCAP 2012). In order to know that with certainty, both baseline emissions and changes will need to be measured and monitored.

Collection of data on GHG fluxes is complex and knowledge intensive. It requires knowledge of the underlying mechanisms driving emissions and sequestration as well as the basic scientific techniques to measure. Without a foundation in the practical and theoretical issues, data can be inaccurate because of the substantial impact methods on measurement.

This manual aims to bring extension staff up to date with measurement of greenhouse gases in agricultural systems in Kenya, with a focus on direct measurement of actual emissions/removals from sources and sinks within agriculture sector. It provides a snapshot of what greenhouse gases are and how they affect the climate, highlights potential ways of mitigating emissions, and describes measurement methods in easy to read step-wise guidelines.

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Head of Climate Change Research,
World Agroforestry Centre
MODULE I. INTRODUCTION TO GREENHOUSE GASES

This section introduces the greenhouse gases of greatest concern in agriculture, describes agricultural activities that emit greenhouse gases, and highlights the potential role of agriculture in helping mitigate greenhouse gas emissions. A brief description of the approaches used for quantification of greenhouse gas emissions, stocks and stock changes as well as quality control and quality assurance is presented.

Learning objectives

- To understand the causes of greenhouse gas emissions on farms
- To understand possible ways of quantifying and measuring greenhouse gas emissions

Discussion question

- What are greenhouse gases and how do they contribute to climate change?
- Where do greenhouse gases come from?

1 Greenhouse gas emissions from agriculture

1.1 What are greenhouse gases?

Gases that trap heat in the atmosphere are called greenhouse gases (GHGs). The increase of the heat trapped in the atmosphere makes the earth warmer, a phenomenon referred to as global warming. Three GHGs of major concern in agricultural systems include carbon dioxide (CO₂), nitrous oxide, and methane (CH₄). The degree to which a molecule of these gases influences global warming is affected by three factors:

1. The abundance of the gas in the atmosphere.
2. How long the gas stays in the atmosphere.
3. The global-warming potential of the gas.

Side bar 1.1 A greenhouse gas is any gas compound in the atmosphere that is capable of absorbing infrared radiation, thereby trapping and holding heat in the atmosphere.

Side bar 1.2 Global warming potential (GWP) is a relative measure of how much heat a given GHG traps in the atmosphere. Gases with higher GWP (e.g. N₂O) absorb more energy than those with lower GWP.
Figure 1.1 (a) Global greenhouse gas emissions by type. (b) Global greenhouse gas emissions by source. (International panel on climate change, IPCC 2007).

Table 1.1 A summary of greenhouse gases in agriculture sector, their global warming potential, atmospheric lifespan and activities responsible for their emission.

<table>
<thead>
<tr>
<th>Greenhouse gas</th>
<th>Global warming potential in CO₂ equivalents</th>
<th>Atmospheric lifespan in years</th>
<th>Source of greenhouse gas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>How much heat it traps</td>
<td>How long it stays in the atmosphere</td>
<td>Where does it comes from</td>
</tr>
</tbody>
</table>
| Carbon dioxide (CO₂) | 1 | About 50 to 200 | • Decomposition of biomass  
• Soil respiration  
• Combustion of fossil fuel for on-farm equipment e.g. tractors  
• Burning of wood for energy  
• Burning of crop residues |
| Nitrous oxide (N₂O) | Over 298 times more heat than the same amount of carbon dioxide | About 114 | • Soil management e.g. cultivation  
• Manure management  
• Burning of biomass |
| Methane (CH₄) | About 35 times more heat than the same amount of carbon dioxide | About 12 | • Livestock  
• Manure  
• Rice paddies  
• Burning of biomass |
1.2 Where do greenhouse gases come from?
GHGs are transferred from the biosphere into the atmosphere through natural processes such as respiration by plants and animals and through human activities. Human activity induced emissions are referred to as ‘anthropogenic’. Based on the best available science, it is now irrefutable that human activities are primarily responsible for increasing concentrations of GHGs in the atmosphere. The following are the main human activities that cause GHG emissions:

- Use of fossil fuel
- Industrial processes
- Deforestation
- Intensive livestock farming
- Use of synthetic fertilizers.

2 Kenya’s agricultural greenhouse gas emission
2.1 Agriculture is the leading emitter of greenhouse gases in Kenya
Agriculture is the largest source of GHG emissions in Kenya, accounting for one-third of the total national emissions (NCCAP, 2012). GHG emissions from agriculture mostly come from domestic livestock and manure management, flooded rice fields, burning of agricultural residues and use of nitrogenous fertilizers.

Cultivation of crops and livestock keeping contribute to emissions of GHGs in a variety of ways. For example, clearing and preparation of land for agricultural production contributes to CO₂ emission from biomass and soil. Nitrous oxide emissions mainly arise from agricultural soil management including application of fertilizer and tillage. Nitrous oxide emissions are small in Kenya due to low fertilizer use. Livestock, especially cattle, produce methane as part of their normal digestive process. Enteric fermentation is the leading source of GHG in agriculture, accounting for over 90% of methane emissions in agriculture and about 30% of the total national emissions. Management of livestock manure also contributes to higher levels of methane and nitrous oxide. Rice cultivation produce CH₄ while burning of crop residues produces CH₄ and N₂O. Table 1.1 summarizes the different sources of GHG emissions in agriculture.

![Figure 1.2](Kenya's greenhouse gas emissions in 2010: (a) by sector, and (b) by sub-sectors in agriculture (Kenya's Climate Change Action Plan, 2012)).
2.2 Agriculture has potential to mitigate greenhouse gas emissions

Emissions of CO$_2$, CH$_4$, and N$_2$O from agriculture arise from both human-induced and natural processes in the ecosystem carbon and nitrogen cycles. This means that it is not possible to completely eliminate GHG emissions due to food production. However, it is possible to lower these emissions by modifying land use and management.

Agriculture can mitigate GHG emissions in the following ways:

1. Decreasing emissions due to agriculture.
3. Provide products such as fuelwood and timber that can substitute fossil fuels and energy-intensive materials such as steel.

Detailed discussion of farming activities that can mitigate emissions or increase sequestration in different sub-sectors in agriculture are presented in modules II-V.

3 Quantification of greenhouse gases in agriculture

3.1 Approaches used to quantify greenhouse gases in agriculture

Here we will focus on two typical approaches that can be used to quantify GHG emissions/removals from agriculture:

1. Direct measurements. Measure actual GHGs in the field. Direct measurement of the actual GHG removals/emission is described in detail in modules II-V.
2. Statistical models. Estimate using available data. GHG removal/emission is quantified by multiplying emission factors with activity data.

3.2 General sources of error

There are two types of errors that contribute to uncertainty in estimates:

1. Those associated with sampling. Sampling errors result from a biased sampling procedure, and can be minimized by use of an unbiased probability sampling and by increasing the sample size.
2. Those associated with measurement. Measurement errors arise mostly from inaccurate observations and wrongly calibrated measurement instruments.

There are two aspects of measurement that inform uncertainty in estimates:

1. Accuracy - how close the estimates are to the actual true value. It is the difference between the measured and the true value.
2. Precision - the variation in a set of repeated measurements. The variation arises because of the limitations in the measurement or estimation technique, when it is used at different times and under varying circumstances, and limitations of the people taking the measurements.
3.3 Quality assurance and quality control

There are several points in data collection and processing that present opportunities for errors, which can be reduced by implementing quality assurance (QA) and quality control (QC) procedures. Quality assurance activities include a planned system of review procedures conducted by personnel not directly involved in the measurement process. Quality control activities include general methods such as accuracy checks on data acquisition and calculations and the use of approved standardized procedures for emission calculations, measurements, archiving and reporting (IPCC 1997).

3.3.1 Examples of QA/QC procedures for quantification of GHGs from existing data

- Check that source data are well documented and adopted. This includes checks for typing errors, use of the correct units and correct conversion factors
- Check that calculations have been implemented correctly
- Check that assumptions are consistent and specific parameters (e.g. activity data) are used consistently

3.3.2 Examples of QA/QC procedures for quantification of GHG from direct measurements

The first step in quality control and quality assurance for direct measurements is to create and follow standard operating procedures for field measurement, data entry and analysis. In addition, do the following during field measurements, data analysis, and data storage.

- Field measurements: Thoroughly train field staff in measurement procedures. Re-measure a proportion of plots to determine measurement error
- Data entry and analysis: Examine the data for values outside the expected range e.g. using scatter plots
- Data storage: Backup all data in alternative electronic storage and with paper copies.

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Figure 1.3 The difference between accuracy and precision of measurements. Accurate measurements hit the bull’s-eye (center) of the target. Precise measurements repeat the same estimates.
Box 1.1 IPCC Structure

The IPCC 2006 Guidelines generally advice on estimation methods at three levels of detail, that is Tier 1, Tier 2 and Tier 3.

**Tier 1** is simplest level of methods and the most commonly used
- IPCC default equations and factors
- Yield estimates with high uncertainty

**Tier 2** is the next level of methods
- IPCC default equations
- Country-specific emission factors

**Tier 3** are the most advanced methods.
- Involves modelling or measurement approaches.
- Country specific method/equations and emission factors
- Requires testing of method to demonstrate that the approach is an improvement over lower tiers.

IPCC recommends use of higher tier methods (tier 2 and tier 3) with key emission categories - those categories with the greatest contribution to the overall level of national emissions; for example, livestock emissions in Kenya – when data and expertise are available.

4 Key Messages

- The main GHGs in agriculture are CO$_2$, N$_2$O and CH$_4$.
- Accumulation of GHG in the atmosphere is responsible for global warming.
- Agriculture is the largest source of GHG emissions in Kenya, accounting for one-third of the total national emissions.
- Enteric fermentation is the leading source of GHG in agriculture, accounting for 90% of agricultural emissions.

5 Exercise

5.1 Quantifying of N$_2$O emissions from synthetic fertilizer application

Greenhouse gas emissions from synthetic fertilizers consist of direct and indirect N$_2$O emissions from nitrogen added to agricultural soils by farmers. Direct emissions are produced by nitrification and denitrification processes, while indirect emissions are produced after volatilization or re-deposition and leaching, and runoff processes. Direct emissions of N$_2$O from managed soils are estimated separately from indirect emissions.

The application of fertilizer, manure and use of leguminous plants increases the probability of N$_2$O being emitted from microbial activity in soils. However, a fraction of direct volatilization as ammonia and nitrogen oxides (NOx) has to be subtracted because this is not used by the microbes in the soil.
The amount of N\textsubscript{2}O emitted from application of artificial fertilizers is then given by equation 1.1. Default fractions of the total synthetic fertilizer nitrogen emitted to the atmosphere or leached are obtained from the 2006 IPCC Guidelines and summarized in this Table 1.2.

\begin{equation}
N\textsubscript{2}O\; emissions = N_{\text{Fert.}} \times [(1 - \text{FRAC}_{\text{atm,f}}) \times E_{\text{factor}} + (1 - \text{FRAC}_{\text{leach}}) \times EF_{\text{leach}}]
\end{equation}

Equation 1.1

\(N\textsubscript{2}O\; emissions\) = amount of N\textsubscript{2}O emissions from fertilizer use (kg N\textsubscript{2}O).

\(N_{\text{Fert.}}\) = total use of synthetic fertilizer in Kenya, (kg N/yr).

**Table 1.2** Selected emission factors and fractions for estimation of nitrous oxide emissions from fertilizer application.

<table>
<thead>
<tr>
<th>Emission factors</th>
<th>Description</th>
<th>Value</th>
<th>Source: IPCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{factor}})</td>
<td>Default emission factor for fertilizer, i.e. kg of N\textsubscript{2}O-N per kg N applied.</td>
<td>0.01</td>
<td>Tab.11.1</td>
</tr>
<tr>
<td>(EF_{\text{leach}})</td>
<td>Default emission factor from N leaching and runoff, kg N\textsubscript{2}O/kg N</td>
<td>0.0075</td>
<td>Tab.11.3</td>
</tr>
<tr>
<td>(\text{FRAC}_{\text{atm,f}})</td>
<td>Fraction of total synthetic fertilizer nitrogen that is released into the atmosphere as NH\textsubscript{3} or NO\textsubscript{x}, kg N\textsubscript{2}O/kg N</td>
<td>0.1</td>
<td>Tab.11.3</td>
</tr>
<tr>
<td>(\text{FRAC}_{\text{leach}})</td>
<td>Fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N\textsubscript{2}O/kg N</td>
<td>0.3</td>
<td>Tab.11.3</td>
</tr>
</tbody>
</table>

Estimation of nitrous oxide emission from fertilizer application in 2010 using tier 1 method can be achieved by the following steps.

**Step 1. Collect activity data**

Activity data for N fertilizer application is the amount of nitrogen consumed (kg N yr\textsuperscript{-1}), in this case estimated from data published by the FAO (Table 1.3).

**Table 1.3** Amount of different types of synthetic nitrogen fertilizer applied in Kenya in 2010. The percentage of nitrogen by mass in different fertilizers is estimated based on the chemical composition of the fertilizers. The quantities of fertilizer applied are multiplied by these percentages to determine the total synthetic nitrogen that is applied in Kenya to agricultural lands.

<table>
<thead>
<tr>
<th>Nitrogen fertilizer type</th>
<th>Quantity (tonnes)</th>
<th>Percent N</th>
<th>Total synthetic N applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium nitrate</td>
<td>3,255</td>
<td>35%</td>
<td>113,925</td>
</tr>
<tr>
<td>Ammonium sulphate</td>
<td>7,442</td>
<td>21%</td>
<td>156,282</td>
</tr>
<tr>
<td>Calcium ammonium nitrate</td>
<td>5,485</td>
<td>25%</td>
<td>137,125</td>
</tr>
<tr>
<td>Diammonium phosphate (DAP)</td>
<td>133,516</td>
<td>18%</td>
<td>2,403,288</td>
</tr>
<tr>
<td>NPK complex &gt;10kg</td>
<td>110,750</td>
<td>18%</td>
<td>1,993,500</td>
</tr>
<tr>
<td>Other nitrogen &amp; phosphates compounds</td>
<td>612</td>
<td>18%</td>
<td>11,016</td>
</tr>
<tr>
<td>Other nitrogen &amp; phosphorus compounds</td>
<td>1,046</td>
<td>18%</td>
<td>18,828</td>
</tr>
<tr>
<td>Potassium nitrate</td>
<td>5,763</td>
<td>18%</td>
<td>103,734</td>
</tr>
<tr>
<td>Urea</td>
<td>54,414</td>
<td>47%</td>
<td>2,557,458</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7,495,156</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Step 2. Estimate GHG emissions

\[ \text{N}_2\text{O Emissions} = \text{activity data} \times \text{emission factors} \]

\[ \text{N}_2\text{O Emissions} = N_{\text{Fert}} \times [(1-\text{FRAC}_{\text{Atm}}) \times \epsilon_{\text{factor}} + (1-\text{FRAC}_{\text{Leach}}) \times \epsilon_{\text{factor}} + (1-\text{FRAC}_{\text{Leach}}) x EF_{\text{Leach}}] \]

\[ = 7,495,156 \times [(1-0.1) \times 0.1 + (1-0.3) \times 0.0075] \]

\[ = 713,913.609 \text{ kg N}_2\text{O-N per year} \]

Step 3. Convert N\textsubscript{2}O-N to N\textsubscript{2}O emissions

Multiply the estimate by 44/28 to convert the emissions from kg N\textsubscript{2}O-N to kg N\textsubscript{2}O gas. 44/28 is the mass ratio of N\textsubscript{2}O and N\textsubscript{2}

\[ = 7,139,136.09 \times 44/28 \]

\[ = 1,121,864 \text{ kg N}_2\text{O per year} \]

Step 4. Convert emissions to carbon dioxide equivalent (CO\textsubscript{2}-e)

Multiply the estimate by 10\textsuperscript{-3} to convert the activity data from kg to tonnes or by 10\textsuperscript{-6} to convert the emissions from kg N\textsubscript{2}O to Gigagrams (Gg) N\textsubscript{2}O gas.

Multiply the estimate by global warming potential (GWP-N\textsubscript{2}O = 298) to convert Gg N\textsubscript{2}O to Gg CO\textsubscript{2}-e.

\[ = 1,121,864.243 \times 10^{-6} = 1.122 \text{ Gg N}_2\text{O} \]

\[ = 1.122 \times 298 = 334.316 \text{ Gg CO}_2\text{-e.} \]

Further reading


MODULE II. MEASURING CARBON IN BIOMASS

This module defines biomass carbon, presents an overview of the places where biomass carbon is stored, describes changes in carbon pool and explains how to measure the amount of biomass carbon in a given pool.

Learning objectives

- To understand the role of trees in carbon sequestration
- To understand how to measure biomass carbon stocks

Discussion question

- What causes changes in biomass carbon?
- What variables do you measure in order to estimate biomass carbon?

1 Biomass carbon

1.1 What is biomass carbon?

Biomass is defined as a mass of live or dead organic matter. It includes those parts aboveground, such as leaves, branches and stems, as well as belowground, such as roots. The amount of biomass stored by plants depends on plant size, which in turn is influenced by factors, such as local environmental conditions, species and the way the plants are managed. For example, biomass production generally increases in response to increase in rainfall and temperature unless other factors are limiting. At the same time, farmers can also change the architecture of plants and trees on their farm.

Estimates of biomass can be used to determine the amount of carbon absorbed from the atmosphere and stored in plant tissues. The amount of carbon in biomass ranges between 45 and 50%, by dry weight (Brown 1997).

Side bar 2.1 Carbon sequestration refers to the process by which atmospheric carbon is absorbed such as by biomass including trees and crops and in soils.
Box 2.1 Biomass carbon in agroforestry

Agroforestry is a term for practices where trees are combined with farming (Figure 3.1). These may include:

a. Growing trees and crops (for example Grevillea in a maize field)

b. Growing trees in pasture (for example Grevillea in a nappier grass field)

c. Growing trees with animals (for example Calliandra as fodder for livestock in a farm)

d. Growing trees with agricultural tree crops (for example Grevillea in tea plantation).

Figure 2.1 Agroforestry practices common in smallholder farming systems

Agroforestry contributes to Kenya’s agricultural GHG mitigation activities by:-

• Sequestering carbon: Agroforestry provides the following options for enhancing carbon sequestration.
  * The expansion of carbon sinks through agroforestry
  * Conversion of low-biomass land use systems (for example grasslands) to tree-based carbon-rich systems.
  * Increased carbon input in soils through conservation agriculture with trees.

• Reducing GHG emissions: Agroforestry provides the following options for reducing GHG emissions from agriculture
  * Conservation agriculture with trees reduces output of carbon from soils
  * Provision of products that would otherwise be obtained from forests protects them from over-exploitation

• Reducing reliance on fossil energy: Agroforestry provides the following options for reducing reliance on fossil energy.
  * Provides wood to substitute fossil fuels such as kerosene and natural gas.
  * Provides timber/wood to substitute energy-intensive materials such as cement and steel.
1.2 Where is biomass carbon stored?

The places where carbon is stored are generally referred to as carbon pools. There are five main carbon pools found in vegetation in a farming system (Figure 3.2):

a. Aboveground tree biomass
b. Belowground tree biomass
c. Biomass of non-tree vegetation
d. Dead wood
e. Litter

Side bar 2.2 A carbon pool refers to a reservoir of carbon. It is a system which has the capacity to accumulate or release carbon.

Figure 2.2 Carbon pools represented by biomass in (a) aboveground live trees, (b) belowground live trees, (c) non-tree vegetation, (d), dead wood and (e) litter, represented by leaves on the ground.
Table 2.1 Description of different carbon pools found in vegetation within agricultural systems and the relative proportion of the total plant biomass.

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Aboveground tree biomass</td>
<td>Carbon in all living biomass above the soil, including stem, stump, branches, bark, seeds, and tree foliage of trees.</td>
</tr>
<tr>
<td>2. Belowground tree biomass</td>
<td>Carbon in all biomass of live roots including course and fine roots, of trees and non-tree vegetation, including stumps.</td>
</tr>
<tr>
<td>4. Dead wood</td>
<td>Carbon in all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots and stumps larger than or equal to 10 cm in diameter or any other official diameter used by a country</td>
</tr>
<tr>
<td>5. Litter</td>
<td>Carbon in all non-living biomass with a diameter less than the minimum diameter for dead wood (for example 10 cm), lying dead in various states of decomposition above the mineral or organic soil.</td>
</tr>
</tbody>
</table>

1.3 What causes changes in biomass carbon?

Changes in carbon stocks within carbon pools occur due to processes that result in the amount of biomass through growth, for example photosynthesis, or losses, e.g. through human activities. Examples of activities that can change carbon stocks include planting trees (Figure 2.3a), thereby increasing the carbon stock, and harvesting trees or disturbances such as by fires or wild animals, decreasing carbon stock (Figure 2.3b).

Side bar 2.3 Carbon stock refers to the absolute quantity of carbon held within a pool at a specified time.

Figure 2.3a Planting trees and protection of existing trees lead to an increase in biomass carbon.

Figure 2.3b Harvesting trees reduces the amount of biomass carbon stored in a given place.
There are three important carbon fluxes in agricultural systems:

1. The removal of CO$_2$ from the atmosphere and storage in the structure of plants during photosynthesis.
2. The transfer of carbon from plants into the soil upon decomposition of whole or parts (such as litter, roots) of plants.
3. The release of CO$_2$ back to the atmosphere during the process of respiration and decomposition.

## 2 Overview of quantification methods

There are three methods that can be used to measure biomass carbon in agricultural systems. These include:

1. **Destructive sampling**
2. **In situ** non-destructive biomass estimations
3. **Inference** from remote sensing

These methods are classified as direct (#1) and indirect (#2 and 3) methods. Direct method is destructive and requires felling and weighing the different components of plants. This method is commonly used for estimating the biomass of non-tree living biomass. However, direct measurements are not usually permitted for rare or protected species. Indirect methods are non-destructive and rely on relationships established from direct methods to estimate biomass from easily measurable parameters such as diameter at breast height (DBH).

Much of the assessment of aboveground carbon stocks in trees usually relies on allometric equations through conversion of DBH to biomass (Figure 2.4). Remote sensing can also be used to collect inventory data. The method used depends on the available funds, desired level of accuracy and the scale of measurement. Table 2.2 highlights some of the advantages and disadvantages of these methods.

![Figure 2.4 Indirect methods of estimating biomass. Allometric equations are used to derive biomass from both ground measurements (in situ), and remotely sampled.](image-url)
### Table 2.2 Some advantages and limitations of the methods of measuring biomass.

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantage(s)</th>
<th>Limitation(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct method</td>
<td>Provides the most accurate estimate</td>
<td>Time consuming and labour intensive</td>
</tr>
<tr>
<td></td>
<td>Provides data for building and calibration of biomass estimation equations</td>
<td>Limited to small sample sizes in small areas</td>
</tr>
<tr>
<td>Field inventories</td>
<td>Provides data for calibration of remotely sensed estimates</td>
<td>Obtaining field inventories is slow and impractical in large areas</td>
</tr>
<tr>
<td>Remote sensing</td>
<td>Effective for mapping expansive and remote areas</td>
<td>Remote sensing instruments are costly to acquire and technically demanding to manage</td>
</tr>
</tbody>
</table>

### 3 Measuring biomass carbon in different pools

This module focuses on measurements for estimating stocks in woody plants, which accumulate large amounts of carbon over their lifespan. Dead wood, and in some cases litter, is often collected for firewood or consumed by fire in slash and burn agriculture. Biomass associated with non-woody plants (for example herbaceous annuals and perennials) and non-woody tissues (for example leaves and flowers) is ephemeral and generally in equilibrium with growth. Therefore the overall net carbon stocks are rather even in the long term as emissions from decay are balanced by sequestration due to re-growth.

#### 3.1 Measuring aboveground biomass of living trees

Estimation of aboveground biomass carbon in a given area requires information on the size of trees, which can be obtained by measuring DBH. Additional information can be gained based upon the tree species and any management practices applied. A detailed description of the plot location such as administrative location and owner’s details is helpful for follow up measurements, especially where Global Positioning System (GPS) coordinates are not available.

The following tools are required when taking measurements to estimate aboveground biomass:

- Caliper for measuring DBH for small-diameter (e.g. <10 cm) trees
- Diameter (or regular) tape for measuring DBH or Girth
- Wooden stick, 1.3 m long for quick location of DBH
- Knife for clearing trees of debris etc.
- Fifty metre long measuring tape for measuring distances when establishing plots
- GPS devise for locating pre-determined sample points or marking plots
- Compass for orientation and directions
- Plot center markers (PVC tubing) for marking the centre of the plot
- Bright colored ropes and pegs for setting up the plots
- Crayons/marker pens/labeling cards for marking trees measured
- Clipboard/datasheet/pens for recording data.
The **procedure** below is followed when taking field data for estimation of aboveground biomass:

1. Locate the plot and draw out plot boundaries with a measuring tape and compass.
2. Mark, for example with a PVC tubing or record the GPS coordinates of the centre of the plot for follow-up measurement.
3. Describe the (administrative) location and owners (name and contacts) details on the datasheet.
4. Identify all trees eligible for measurement within the plot.
5. Measure the DBH of each tree within the plot at 1.3 m above the soil surface (Figure 2.5), noting irregularities.
6. Determine and record the botanical or local name of the tree. A labeled sample can be retained for identification of trees whose name could not be established in the farm. A tree identification book or local (para-taxonomists) guides can be helpful.

---

**Figure 2.5 How to measure DBH correctly.** Wrap a diameter tape around the tree at 1.3 m, ensuring that the tape measure is horizontal and tight to the tree.
Box 2.2 Measuring diameter at breast height (DBH)

A. Why use DBH as a predictor for biomass
Diameter at breast height is preferred because of the following attributes:
* It can easily be measured with relatively high accuracy
* It is highly correlated with biomass, and other structural parameters such as height

B. Where to measure on the stem
Diameter is measured outside the bark, at breast height - defined as 1.3 m above the ground on the uphill side of the tree. This is a standardized height established to avoid bias in measuring tree diameter because stems are wider at the base and narrows along the axis towards the tip (West 2009).

C. How to measure DBH
Diameter can be measured using a diameter tape or regular tape as follows:
1. Clear the trunk (using the knife) of protruding dead wood, or dirt that would distort the measurement.
2. Stand next to the trunk of the tree and wrap the tape around the trunk at 1.3 m above the ground.
3. Read the diameter where the tape overlaps with the zero mark.
4. Record the DBH or girth measurement, in cm.

It is advisable to measure large diameters (>10 cm) with diameter tape or regular tape. Smaller diameters (<10 cm) should be measured with a caliper. The datasheet should also clearly state whether diameter was measured directly or the readings correspond the circumference/girth. Measurements of circumference can be transformed into DBH by dividing the girth by pi ($\pi = 3.14$).

When using a caliper, measure the diameter twice, cross-wise and average. The caliper should be held at horizontal level. Avoid taking measurements with caliper slanting/diagonal to the tree axis.
3.1.1 Measuring DBH of trees with anomalies

Agricultural landscapes abound with management practices and other factors that introduce anomalies in tree form, such that measuring diameter at exactly 1.3 m can introduce errors. For trees with irregularities at breast height, their DBH is taken at a point where the deformity does not affect the value. The aim is to obtain the estimate that would be closest to the expected DBH if the irregularities were not present. A tree has abnormal diameter if the diameter measured at 1.3 m above the ground varies more than 10 percent from the average of the diameters measured directly below and directly above the abnormality. Independent trees that grow together should be treated as two separate trees.

The following five special situations prevent conventional measurements of DBH at exactly 1.3 m above the ground. Always document the anomaly and the height at which diameter was measured in the comment section of the datasheet.

1. Irregularities at breast height (1.3 m) include swelling, protruding knot or ring of knots, bumps, depressions and branches. Measure DBH immediately above the irregularity at the place it ceases to affect normal stem form.
2. The DBH of tree forks below 1.3 m or near 1.3 m are measured at the narrowest part of the main stem below the fork.
3. Vertically growing trees on a slope are measured at 1.3 m from the ground along the stem on the uphill side of the tree.
4. Leaning trees are measured at 1.3 m on the under-face of the stem i.e. in the direction of the lean.
5. Multi-stemmed trees are those that split into several trunks close to ground level. Measure the diameter of each trunk separately, using the concepts illustrated in 1-4, then determine the DBH of the tree as the square root of the sum of individual DBHs squared.

3.2 Measuring belowground biomass of living trees

Belowground biomass is an important carbon pool, accounting for about 26% of the total biomass. However the relative proportion changes based on environmental and management factors. Belowground biomass is difficult and time-consuming to measure and methods are usually not standardized. Live and dead roots are generally not distinguished and therefore root biomass is reported as total live and dead roots.

The main methods to measure belowground biomass directly are:

1. Excavation of roots for tree vegetation (Figure 2.6)
2. Soil core or pit for non-tree vegetation
Figure 2.6  Excavation method for measuring belowground biomass:  

a) The stump together with the roots are excavated within a radius of about two metres from the stem and a depth of about 1.5 metres. 
b) They are weighed in the field to determine their fresh weight.  
c) A subsample is taken and later oven-dried and its dry weight determined. The ratio of the dry weight to the fresh weight is multiplied by the total fresh weight to estimate belowground biomass of the tree.

Since measurements in the field are very costly and labour-intensive, belowground biomass is estimated using the ratio of belowground biomass to aboveground biomass (root-to-shoot ratio) or allometric equations. The IPCC provides default root-shoot ratios for estimating belowground biomass as a function of aboveground biomass.

3.3 Measuring aboveground biomass of non-tree vegetation

Non-tree vegetation may include herbaceous plants, grasses, shrubs and small trees that do not meet the lower DBH threshold set for trees, for example <2.5 cm. The lower DBH threshold used in a study is determined based upon the dominant tree sizes in the study area. Herbaceous plants can be measured by simple harvesting techniques in small subplots, defined by a sampling frame measuring 0.5 m x 0.5 m for example. About two to three subplots per tree plot are recommended. The material inside the frame is cut to ground level, pooled by plot area to give a composite sample and weighed. Well-mixed sub-samples are oven-dried to determine the ratio of the dry weight to fresh weight. The biomass of the entire sample is obtained by multiplying the ratio of dry to fresh weight by the total fresh weight. A similar approach can be used for larger shrubs using sub-plots measuring 0.5 x 0.5 m to 2 m x 2 m, depending on the size of the vegetation.

The following tools are needed to sample non-tree vegetation:

- Measuring tape for setting transects/measuring distances
- Sampling frame for encompassing about 0.25 m2
- Knife or scissors for cutting the vegetation
- Weighing scales, e.g. 3 kg and 10 kg for determining fresh weights in the field
- Marker pens for labeling samples
- Sample bags for collection of samples
- Clipboard/datasheet/pens for recording data
The **procedure** below is followed when sampling non-tree vegetation (Hairiah et al. 2011):

1. Draw a transect, for example 5 m x 30 m within the plot used for aboveground biomass.
2. Place sampling frame about 8 m from the start of the transect, and then every 6 m along the centerline of the transect.
3. Cut all vegetation in the sampling frame and place it in a plastic bag.
4. Weigh directly to get fresh weight in the field (g/0.25 m²).
5. Chop all samples and mix them well before taking subsamples.
6. Weigh about 100 g as a subsample and place it in a labelled paper bag.
7. Place subsample in an oven and dry to a constant weight, for example at 85 °C for 48 hours.
8. Weigh oven-dried sample to get its dry weight.
9. Determine the total dry weight of the vegetation sampled in 0.25 m² as:

\[
\text{Total dry weight} = \frac{\text{subsample dry weight}}{\text{subsample fresh weight}} \times \text{total fresh weight}
\]  

**Equation 2.1**

10. Determine the total dry weight per meter squared by multiplying the estimated biomass by 1 m²/0.25 m².

### 4 Estimating biomass carbon stocks

Once field data has been collected, the following steps are used to calculate biomass carbon for individual trees or trees within a defined area:

1. Transfer the data from the field data collection forms and combine them in an excel spreadsheet for cleaning and storage.
2. Apply allometric equations to the DBH data to calculate aboveground biomass of individual trees, in kilogrammes per tree.
3. Apply allometric equation or root-to-shoot ratio to aboveground biomass to determine belowground biomass of individual trees, in kg per tree.
4. Multiply biomass estimate by the percent carbon in plant tissues to calculate biomass carbon. The value of carbon is generally estimated to be 45-50% of the plant biomass. However, there exists slight variability of carbon concentration in tissues of different species or tree compartments. Projects may use the IPCC default value of 47% (IPCC 2006) for aboveground biomass in tropical trees or may choose to determine the actual carbon fraction in their samples by element analysis.
5. Divide biomass estimate by the age of the tree to calculate the average annual rate of carbon sequestration. For individual trees, age can be obtained from farm records. Alternatively, cores can be taken from a subset of trees and their age determined using dendrochronology protocols.
6. Sum all the biomass sequestered by individual trees within the plot and divide the estimate by the plot area to obtain carbon sequestered or stock per unit area.
7. Calculate and report the mean biomass carbon stocks at 95% confidence intervals.
Box 2.3 Allometric equations

Allometric equations are used to estimate biomass of trees without cutting them down. A variety of these equations is available in literature, developed for individual species (species specific) or for a group of species (mixed species).

The majority of the equations are in the form $Y = aX^b$, where $Y$ is the oven dry weight of the tree, $X$ is the predictor variable such as DBH (in cm), and $a$ and $b$ are allometric coefficients. This form of equation is preferred because it is simple – requiring only DBH as predictor variable, hence less expensive to develop and use compared to those including additional predictors such as height.

The quality of the allometric equation depends on the empirical data used. Choose an equation that matches your area in terms of climatic and edaphic conditions, species mix, and land cover type. The maximum diameters should not greatly exceed the maximum diameter of trees used to develop the equation. Allometric equations developed from a small sample size, of say less than 30 trees, are likely to miss out on large diameter trees, or only capture few species of interest.

Table 2.3 Examples of allometric equations for estimating aboveground biomass.

<table>
<thead>
<tr>
<th>Allometric equation</th>
<th>No of trees</th>
<th>DBH range</th>
<th>Scope</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AGB = 0.091 \times (\text{dbh})^{2.475}$</td>
<td>72</td>
<td>2.5–102</td>
<td>Agroforestry systems of western Kenya</td>
<td>Kuyah et al. 2012</td>
</tr>
<tr>
<td>$AGB = 0.136 \times (\text{dbh})^{2.32}$</td>
<td>28</td>
<td>5–40</td>
<td>Mixed species (global dry forests)</td>
<td>Brown 1997</td>
</tr>
</tbody>
</table>

Table 2.4 Examples of allometric equations and root-to-shoot ratios for estimating belowground biomass.

<table>
<thead>
<tr>
<th>Method</th>
<th>Example</th>
<th>Scope</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allometric equation</td>
<td>$BGB = 0.489 \times AGB^{0.890}$</td>
<td>Tropical forests</td>
<td>Mokany et al 2006</td>
</tr>
<tr>
<td>Root-to-shoot ratio</td>
<td>0.26</td>
<td>Tropical forests</td>
<td>Cairns et al 1997</td>
</tr>
<tr>
<td></td>
<td>0.26</td>
<td>Agroforestry systems (Western Kenya)</td>
<td>Kuyah et al 2012</td>
</tr>
</tbody>
</table>
Carbon emission data are expressed as CO\textsubscript{2}-e. Emissions and removals are converted in Gg of CO\textsubscript{2}-e to make these comparable with the GHG fluxes of other sectors. The index 3.67 (44/12) is the conversion factor from carbon to CO\textsubscript{2}-e.

5 Key messages

• The amount of biomass carbon stored by plants depends on their size, and varies between species, climatic conditions and how the plants are managed.
• Aboveground biomass is the most significant and typically the most commonly measured biomass carbon pool in farming systems.
• Biomass carbon is typically calculated by applying measurements of diameter at breast height in allometric equations.

6 Exercises

6.1 Estimation of total tree biomass

Calculate the aboveground biomass (AGB), belowground biomass (BGB), total tree biomass (TTB), and biomass carbon of the following ten trees whose diameters were inventoried in a 30 m x 30 m plot. Assume the general equation (AGB = 0.0136 x DBH\textsuperscript{2.32}) by Brown (1997) and the default root-to-shoot ratio (0.26) by Cairns et al. (1997) best describes the vegetation.

<table>
<thead>
<tr>
<th>Tree No</th>
<th>DBH (cm)</th>
<th>Scientific name</th>
<th>AGB, kg/tree (0.0136 x DBH\textsuperscript{2.32})</th>
<th>BGB, kg/tree (0.26 x AGB)</th>
<th>TTB, kg/tree (AGB + BGB)</th>
<th>Biomass carbon, kg/tree (TTB x 0.47)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.7</td>
<td>Faiderbia albida</td>
<td>11.2</td>
<td>2.9</td>
<td>14.1</td>
<td>6.6</td>
</tr>
<tr>
<td>2</td>
<td>8.5</td>
<td>Cassia spectabilis</td>
<td>19.5</td>
<td>5.1</td>
<td>24.5</td>
<td>11.5</td>
</tr>
<tr>
<td>3</td>
<td>8.9</td>
<td>Faiderbia albida</td>
<td>21.7</td>
<td>5.6</td>
<td>27.3</td>
<td>12.8</td>
</tr>
<tr>
<td>4</td>
<td>9.2</td>
<td>Mangifera indica</td>
<td>23.4</td>
<td>6.1</td>
<td>29.5</td>
<td>13.9</td>
</tr>
<tr>
<td>5</td>
<td>11.1</td>
<td>Mangifera indica</td>
<td>36.2</td>
<td>9.4</td>
<td>45.6</td>
<td>21.4</td>
</tr>
<tr>
<td>6</td>
<td>13.0</td>
<td>Cassia spectabilis</td>
<td>52.2</td>
<td>13.6</td>
<td>65.8</td>
<td>30.9</td>
</tr>
<tr>
<td>7</td>
<td>16.2</td>
<td>Faiderbia albida</td>
<td>87.0</td>
<td>22.6</td>
<td>109.6</td>
<td>51.5</td>
</tr>
<tr>
<td>8</td>
<td>19.5</td>
<td>Cassia spectabilis</td>
<td>133.7</td>
<td>34.8</td>
<td>168.4</td>
<td>79.2</td>
</tr>
<tr>
<td>9</td>
<td>29.3</td>
<td>Faiderbia albida</td>
<td>343.8</td>
<td>89.4</td>
<td>432.2</td>
<td>203.6</td>
</tr>
<tr>
<td>10</td>
<td>39.8</td>
<td>Faiderbia albida</td>
<td>699.8</td>
<td>181.9</td>
<td>881.7</td>
<td>414.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total in kg/30 m x 30 m</td>
<td>1428.4</td>
<td>371.4</td>
<td>1799.7</td>
<td>845.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total in kg/ha</td>
<td>15870.6</td>
<td>4126.4</td>
<td>19997.0</td>
<td>9398.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total in Mg/ha</td>
<td>15.9</td>
<td>4.1</td>
<td>20.0</td>
<td>9.4</td>
</tr>
</tbody>
</table>
6.2 Estimation of biomass within herbaceous vegetation

Determine the biomass for herbaceous vegetation collected using a 0.5 m x 0.5 m sampling frame. Assume the total fresh weight was 1000 g, and that a subsample weighing 400 g was oven-dried to a constant weight of 250 g.

Total weight per (0.5 x 0.5 m) 0.25 m$^2$

$$\frac{250}{400} \times 1000 = 625 \text{ g}$$

Total dry weight per m$^2$

$$625 \text{ g} \times \frac{1 \text{ m}^2}{0.25 \text{ m}^2} = 2.5 \text{ kg m}^2; \quad 25 \text{ Mg ha}^{-1}$$

Further reading

MODULE III. MEASURING SOIL CARBON

This module presents an overview of carbon in agricultural landscapes and how to collect soil samples for determination of carbon concentration and bulk density. The section also presents the calculations required to estimate the soil organic carbon at a defined depth of soil over a given area.

Learning objectives
- To understand carbon sequestration in agricultural soils
- To understand how to measure soil carbon stocks in conservation agriculture

Discussion questions
- What activities are most responsible for increasing or reducing soil carbon?
- What variables do you measure to estimate soil carbon?

1 Soil carbon

1.1 What is soil carbon?

Soil carbon is carbon stored within the soil. Carbon in the soil exists in two forms, organic and inorganic carbon. Organic carbon includes decaying plant material, soil organisms and microbes. Inorganic carbon is derived from bedrock or formed when CO₂ is trapped in mineral form e.g. calcium carbonate. Inorganic carbon is not strongly influenced by land management practices, although it can be dissolved under acidic conditions. Organic carbon on the other hand can be greatly affected; both increased or reduced, through farming activities.

Side bar 3.1 Soil organic carbon (SOC) is the carbon associated with soil organic matter (SOM). Carbon forms about 58% of SOM, by weight.

Side bar 3.2 Soil organic matter is the organic matter component of soil, consisting of plant and animal material at various stages of decomposition.

1.2 Importance of soil organic carbon: (a) in agriculture

Soil organic carbon improves overall soil productivity by improving:

- Nutrient availability. Decomposition of soil organic matter releases nitrogen, phosphorus and a range of other nutrients essential for plant growth.

- Soil structure and soil physical properties. SOC promotes a healthy soil structure by aggregating the soil particles together which improves soil physical properties such as water holding capacity, water infiltration, gas exchange, root growth and ease of cultivation.

- Soil biodiversity. SOC is a source of energy and nutrient for soil organisms and hence influences the number and diversity of soil inhabitants.
1.2 Importance of soil carbon: (b) in climate change

Agricultural soils are both a source and sink for carbon. In addition to carbon storage, agricultural soils emit carbon to the atmosphere, increasing atmospheric GHG concentration. The amount of carbon stored in the soil is influenced by:

- Changes in vegetation cover and plant growth.
- Removal of biomass by harvest.
- Mechanical soil disturbance such as tillage.

Box 3.1 Soil carbon in conservation agriculture

Conservation agriculture is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment.

Three guiding principles of conservation agriculture are:

1. Minimum soil disturbance, with no-till or minimum tillage.
2. Maximum soil surface cover, with cover crops (Figure 3.1) and/or crop residues.
3. Species diversification through crop associations and rotations, with annual and/or perennial crops including trees (Corsi et al 2012).

Conservation agriculture practices have the potential to increase SOC level through reduced loss of carbon as well as increase carbon sequestered in soil as organic matter. In addition, conservation agriculture provides many other benefits such as build soil fertility, protect soil from compaction, and nurture soil biodiversity.

Figure 3.1 Intercropping with cover crops keep the soil covered. Soil cover can also be maintained by returning crop residues in the soil instead of burning or intercropping with perennials such as trees. Keeping the soil cover reduces soil erosion and also accumulates organic matter in the soil.
1.3 Changes in soil organic carbon

Changes in soil organic carbon are brought about by inputs from photosynthesis and losses by decomposition. Photosynthesis fixes atmospheric carbon into plant biomass, which is eventually added to the soil when plants die and decompose. Decomposition of soil organic matter releases carbon into the atmosphere.

A carbon sink refers to anything that absorbs more carbon than it releases.

A carbon source refers to anything that releases more carbon than it absorbs.

Soil carbon sequestration is the process by which CO$_2$ is removed from the atmosphere and stored in the soil carbon pool, in a form that is not immediately re-emitted.

Figure 3.2 Agricultural practices control the balance of carbon stored in the soil and carbon that moves out of the soil. Practices that maximize carbon inputs and minimize carbon outputs increase soil organic carbon.

1.3.1 Activities that increase soil carbon

There are various practices that can be carried out to improve soil organic carbon. These practices are broadly grouped into two categories:

1. Management practices that reduce losses of existing soil carbon by comparison to conventional practices.
2. Management practices that increase the amount of carbon in soils, a practice particularly effective in degraded agricultural soils.

Table 3.1 Examples of practices that reduce loss of carbon and those that increase the levels of carbon in conservation agriculture

<table>
<thead>
<tr>
<th>Practices that reduce loss of carbon</th>
<th>Practices that increase levels of carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reduced till options (e.g. minimum tillage)</td>
<td>• Adding compost manures</td>
</tr>
<tr>
<td>• Planting cover crops</td>
<td>• Returning crops residues</td>
</tr>
<tr>
<td>• Maintaining cover by residues</td>
<td>• Green manures</td>
</tr>
<tr>
<td>• Controlling soil erosion</td>
<td>• Adding animal (poultry, pig, cattle) waste</td>
</tr>
<tr>
<td>• Controlling soil erosion</td>
<td>• Crop rotation</td>
</tr>
<tr>
<td>• Maintaining cover by residues</td>
<td>• Application of biochar</td>
</tr>
<tr>
<td>• Controlling soil erosion</td>
<td>• Growing of nitrogen fixing plants</td>
</tr>
</tbody>
</table>
1.3.2 Activities that reduce soil carbon

Agricultural practices reduce the amount of carbon in the soil by accelerating losses via decomposition, erosion, or by leaching of dissolved carbon through the soil into groundwater (Figures 3.3a-d).

a. Intensive cultivation. Tillage increases the aeration of the soil and causes a flush of microbial action that speeds up the decomposition of organic matter. When soil microbes decompose organic matter, some carbon is mineralized rapidly to CO₂ and is lost from the soil.

b. Soil erosion. Soil erosion removes the part of the soil which is usually richest in plant nutrients. Removed soil is often deposited in low laying areas, resulting in increased SOC relative to upslope areas.

c. Burning or removal of residues. Removal of crop residues for fodder or fuelwood decreases the amount of plant material that could potentially add carbon to the soil.

d. Overgrazing. Overgrazing reduces biodiversity, soil cover and increases erosion.
2 Overview of measurement methods

Soil organic carbon stocks can be quantified by either direct measurements using soil sampling protocols and chemical analysis, or indirect estimation using models. Direct methods estimate soil carbon from sampling soils at the field followed by laboratory analysis. Estimation of soil carbon requires information on concentrations of organic carbon within the sample, soil bulk density and soil depth.

The concentration of carbon in soil samples is determined in the laboratory by conventional methods such as dry combustion and wet oxidation (Walkley-Black) method, instrumental methods such as CN analyzer or spectral analysis technologies (e.g. Mid InfraRed Spectroscopy).

The following steps are followed when measuring soil organic carbon.

1. Define the sampling strategy. Select the sample points and sampling depth/layer(s) within a defined plot. The default sampling depth is 0-30 cm.
2. Sample collection. Collect samples for determination of carbon concentration, sample for determination of bulk density, and measure the depth sampled.
3. Sample preparation. Air-dry the sample, clearly label, and package
4. Laboratory analysis. Determine carbon concentration within the sample, bulk density, and the percentage of coarse fragments (stone and gravel) in the sample.
5. Estimate carbon stocks. Multiply the carbon content for a given depth with the bulk density. Correct for the amount of stones/gravels in the sample.
6. Calculate and report the mean carbon stocks at 95% confidence interval.

3 Measuring soil organic carbon

3.1 Sample collection

Two samples are collected in the field: (1) a sample for determination of carbon concentration often collected by an auger or core sampler; and (2) a sample for determination of bulk density often collected by a bulk density ring.

The following tools are required for sampling soil for determination of carbon concentration.

- Measuring tape for laying out plots and fixing location
- Soil auger for extracting soil
- Knife for removing soils from auger, cutting roots
- Machete for clearing vegetation
- Bulk density ring for collecting soil core for bulk density
- Large plastic bucket for collecting and mixing soil in the field
- Mixing trowel for mixing soil
- Sample bags for storing samples
- GPS devise for mapping plots

Side bar 3.6 Bulk density is the dry weight of soil per unit volume of soil, including pore spaces.
Compass for laying out plots
Coloured ribbon for marking plot center
Permanent marker for labeling sample bags
Rubber mallet for driving in the auger when there is resistance
Clipboard and data forms for recording data
Metal sampling plate for stabilizing soil while sampling

3.1.1 Composite sampling

A composite sample consists of three to four sub-samples that are thoroughly mixed together to create one sample for analysis. The objective of composite soil sampling is to provide a sample that represents the average conditions in the sampled soil. A composite sample should be selected from a uniform field area that has a similar crop and fertilizer history for at least the last two years. Soil characteristics such as color, slope, texture, drainage and degree of erosion from a uniform field area tend to appear similar.

The following procedure is followed when collecting samples for determination of carbon concentration (modified from Hairiah et al. 2011).

1. Randomly choose three sampling points within a plot from where soil samples will be taken at predetermined depths such as 0-10, 10-20 and 20-30 cm depths following the steps below. Dry soils are difficult to auger and collect all of the soil from the depth increment. Sampling points should be away (at least 1 m distance) from tree stems and should avoid disturbances like trails, animal holes, termite hills etc.

2. Remove litter cover and small plants from soil surface at each of the sampling point.

3. Place the auger vertically over the soil and turn it clockwise until its base penetrates the soil to 10 cm depth. Augering should be done straight down in order to obtain accurate measurement of depth (Figure 3.4a).

4. Pull the auger out gently by slightly turning it counter clockwise. Some soil can stick to the corer, while some drop back in the bore hole. Soil left in the hole can be recovered using a long-handled spoon.

5. Transfer the sample to a bucket marked “0-10 cm”. Break up the large clods of soil by hand.

6. Continue sampling the 10-20 cm layer and then the 20-30 cm layer with the same procedure, transferring the samples to the buckets marked “10-20 cm” and “20-30 cm”, respectively.

7. Move to the next sampling point and repeat step 2 to 6, taking samples by layers.

8. Transfer each sample from the same depth into the respective buckets until all of the predetermined number of samples within the plot has been collected.

9. Mix the samples in each bucket thoroughly.

10. For each bucket, transfer about 500 g of soil to a plastic bag for chemical analysis and another 500 g into a sample bag for archiving; discard the remainder. Place each plastic bag into a second plastic bag to prevent any breakage and sample loss during transportation.

11. Using a permanent marker, clearly label each sample bag with the sampling date, sample depth, and location.
12. Record other relevant observations such as presence of stones, coarse materials etc. during sampling.

3.1.2 Bulk density sampling

Bulk density of a soil is the ratio of the mass of oven-dried soil to its bulk volume either at time of sampling or at specified moisture content. It is usually expressed in terms of grams per cubic centimeter (g cm\(^{-3}\)) or mega gram per cubic meter. Bulk density is altered by cultivation, compression by animals and machinery, weather, and loss of organic matter. It generally increases with depth in the soil profile and normally varies from 1.0 to 1.8 g cm\(^{-3}\).

\[
\text{Bulk density (g cm}^{-3}\text{)} = \frac{\text{oven dry weight of soil (g)}}{\text{volume of soil (m}^{-3}\text{)}}
\]  

Equation 3.1

Bulk density samples should be taken at the same time as soil carbon samples. Since bulk density is less variable than carbon concentration, only one sample can be taken at the center of the plot.

The following procedure is followed when collecting samples for determination of bulk density (modified from Hairiah et al 2011).

1. Clean soil surface of litter and vegetation. Surface litter can be considered part of the soil when it is difficult to separate the dead surface litter from the mineral soil. However, fresh organic material such as crop residues, roots and manure are generally avoided at sampling because they are not technically part of soil organic carbon because most of the carbon they contain is readily lost as CO\(_2\) during decomposition.
2. Place the sample ring on the soil surface and push it into the ground using a wooden block and a rubber mallet. Do not compress the soil when pushing in a soil core.

3. Cut excess soil carefully from the top of the ring until the soil is level with the top of the ring and then put a lid on the top of the ring.

4. Using a machete, dig the soil around the place where the ring is placed; drive the machete at the bottom of the ring to lift the ring and the soil.

5. Cut excess soil carefully from the bottom of the ring until the soil is level with the bottom of the ring and then put a lid on the bottom of the ring.

6. Label the sample with information on depth, the date of sampling and the location (including GPS position) of the soil sampling.

7. Send the samples in the box to a certified soil physics laboratory.

3.2 Preparation of samples

The following guidelines refer to preparation of samples that are to be taken to another laboratory for analysis.

1. Samples should be air-dried immediately after field sampling to minimize oxidation of soil carbon. Open the sample bags in a room that is well ventilated and free from dust and draughts. Do not expose samples to sunlight.

2. Break up any clay clods, crush soil lumps and remove any gravel, roots and large organic residues.

3. Transfer the samples into clean labelled sampling bag or paper boxes. The samples can be placed in into a second bag to prevent any breakage and sample loss during transportation.

4. Send the soil samples to a certified laboratory for carbon content analysis. Depending on the need, other chemical analyses could also be requested using the same samples.

Further processing of samples happens at the laboratory. Laboratories have standard operating procedure for soil processing. At the laboratory, sample preparation steps include air-drying, weighing, crushing, sieving, mixing and sub-sampling cores or composites. We refer you to Aynekulu et al. (2011) for details on laboratory analysis.
4 Estimating soil carbon stocks

Calculation of soil carbon stocks of a site requires determination of SOC concentrations, bulk density, soil depth and coarse fragments. The following steps are followed:

1. Calculate carbon stocks for each layer.
2. Sum the layers to obtain carbon stocks within the 0-30 soil layer.
3. Calculate the mean carbon stocks at 95% confidence interval.

The laboratory analysis will present the soil carbon content in terms of percentage by weight or in terms of g kg⁻¹, where 1% by weight = 1 g carbon per 100 g soil = 10 g carbon per kg soil = 0.01 kg carbon per kg soil = 0.01 Mg carbon per Mg soil.

The amount of soil carbon stock per unit area is given by the following equation.

\[ \text{SOC} = C \times \text{bulk density} \times \text{depth} \times 100 \times \% \text{ coarse fragments} \]  
Equation 3.2

- \( \text{SOC} \) = is the soil organic carbon stock (Mg ha⁻¹)
- \( C \) = is the soil organic carbon concentration, determined in the laboratory (%).
- 100 is used to convert the estimate to per hectare.

5 Key messages

- Soil is both a sink and a source of carbon.
- SOC levels are influenced by management practices.
- Estimation of soil carbon requires information on carbon concentration, bulk density and the sampling depth.

6 Exercises

6.1 Determination of bulk density

Calculate the bulk density of a soil sample collected from a 10 cm deep hole using an auger with diameter of 7.6 cm. The oven-dry weight of the sample is 450 g.

\[
\text{volume} = \pi \times \text{radius}^2 \times \text{height}
\]

\[
\text{volume} = 3.14 \times 3.8^2 \times 10 = 453.6 \text{ cm}^3
\]

\[
\text{Bulk density} = \frac{450}{453.6} = 0.99 \text{ g cm}^{-3}
\]  
Equation 3.3
6.2 Quantification of soil organic carbon when given in soils with stones

How much carbon stock (Mg ha\(^{-1}\)) is in the soil layer sampled at 10 cm depth, if the soil bulk density is 0.99 g cm\(^{-3}\) and the concentration of organic carbon in the soil is 1.5%?

\[
SOC = \frac{0.99 \times 10 \times 100}{100} = 14.9 \text{ Mg ha}^{-1}
\]

Laboratory analyses of soil organic carbon are generally done on sieved soil samples. Sieving soil samples excludes all materials larger than 2 mm in size. To reflect the original composition of the soil sample, laboratory results are corrected for stone/gravel using the proportion of stone/gravel in the original sample. For example in worked exercise 6.2, if 10% of the original sample volume was gravel or stone, then the actual soil organic content of that soil is 13.4 Mg ha\(^{-1}\) (i.e. 90% of 14.9%).

6.3 Quantification of soil organic carbon at different layers

How much carbon stock (Mg ha\(^{-1}\)) is in each of the 0-10, 10-20 and 20-30 cm soil layers if the soil bulk density of the three respective layers is 0.9, 1.1 and 1.2 g cm\(^{-3}\) and the soil organic carbon content is 3, 2 and 2%, respectively?

<table>
<thead>
<tr>
<th>Soil layer (cm)</th>
<th>Bulk density (g/cm(^3))</th>
<th>Carbon content (%)</th>
<th>Calculations</th>
<th>Carbon stock (Mg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10 layer</td>
<td>0.9</td>
<td>3</td>
<td>[SOC = \frac{0.9 \times 10 \times 100}{100}]</td>
<td>27</td>
</tr>
<tr>
<td>10-20 layer</td>
<td>1.1</td>
<td>2</td>
<td>[SOC = \frac{1.1 \times 10 \times 100}{100}]</td>
<td>22</td>
</tr>
<tr>
<td>2-30 layer</td>
<td>1.2</td>
<td>2</td>
<td>[SOC = \frac{1.2 \times 10 \times 100}{100}]</td>
<td>24</td>
</tr>
<tr>
<td>Total SOC for the 0-30 layer</td>
<td></td>
<td></td>
<td></td>
<td>73</td>
</tr>
</tbody>
</table>

Further reading

MODULE IV. MEASURING SOIL GREENHOUSE GAS EMISSIONS

This module provides a summary of the methods for quantification of greenhouse gas emissions from the soil, and outlines step-by-step procedures for field measurements, laboratory analyses and calculation of greenhouse gas fluxes.

Learning objectives

• To understand what causes greenhouse gas fluxes from soils
• To understand how to measure greenhouse gas fluxes from soils

Discussion question

• What greenhouse gases are emitted from agricultural soils?
• What factors influence greenhouse gas emissions from soils?

1 Greenhouse gas emissions from agricultural soils

Agricultural activities contribute directly to emissions of CO$_2$, N$_2$O and CH$_4$ gases from the soil through a variety of microbial-mediated processes. Emissions of these gases vary greatly from time to time and from place to place because of different environmental conditions such as rainfall and temperature, and the impact of management activities such as tillage, application of fertilizers etc.

1.2 Carbon dioxide emissions from soil

Soil contributes about 20% of the total CO$_2$ emissions to the atmosphere through soil respiration. In addition to increasing atmospheric CO$_2$ concentrations, soil CO$_2$ emissions result in reduction of soil organic carbon pool, reducing soil fertility and overall productivity.

Carbon dioxide is released from the soil through soil respiration. Soil respiration comprises gas flux of soil organisms and plant roots (IPCC 2006). The source of carbon for microbial respiration in the soil is applied manures, crop residues, litter fall, and death and decay of roots. The source of carbon for root respiration comes from photosynthesis. Unlike decomposition of soil organic matter, CO$_2$ emissions resulting from plant roots are sometimes offset by increase in rates of photosynthesis, and therefore may not result in net increase in atmospheric CO$_2$.

1.3 Nitrous oxide

Agriculture, specifically cropping and grazing lands, are a significant source of N$_2$O emissions in Kenya. N$_2$O emissions from agricultural soils are broadly classified into two groups:

1. Direct emissions which are emissions arising directly from the soils to which nitrogen is added or released due to application of animal manure, fertilizer nitrogen, and crop residues left in the field.
2. Indirect emissions which refer to emissions resulting from the leaching and runoff of nitrate from managed soils to ground water and surface water, and deposition of volatized ammonia and nitrogen oxide gases (IPCC 2006).

Nitrous oxide (N\textsubscript{2}O) emissions from the soil occur as a result of soil microbial activity. There are two processes that produce N\textsubscript{2}O emissions. The first is nitrification, which occurs in the presence of oxygen, and converts ammonium into nitrate (NO\textsubscript{3}\textsuperscript{-}) following two steps where ammonium is first oxidized to nitrite, and nitrite is then converted to nitrate. N\textsubscript{2}O can be a by-product of this process. The second process is denitrification, which occurs in the absence of oxygen and converts nitrate to nitrogen gas (N\textsubscript{2}). Nitrous oxide is produced as an intermediate product, when reduction of nitrate to nitrogen is incomplete. Nitrification and denitrification are microbial processes that occur in the soil naturally. However, their rates are often increased by certain agricultural practices that increase available mineral nitrogen in the soil.

The following agricultural practices increase mineral nitrogen in the soil (Figure 4.1a-d).

a. Application of \textit{inorganic fertilizers} such as calcium ammonium nitrate and urea in excess of plant needs directly increases soil nitrogen availability.

b. Application of \textit{animal waste} (dung and urine) deposited to the soil by grazing animals to improve nitrogen content in crop and grazing fields.

c. Incorporation of \textit{crop residues} into the soil rather than burning or removing them from the field. This is particularly the case of residues which contain nitrogen.

d. Growing \textit{leguminous crops}. Leguminous plants fix atmospheric nitrogen from the air through biological nitrogen fixation.

e. Application of \textit{organic materials} such as compost (IPCC 2006).

\textbf{Figure 4.1a Urea, an example of an inorganic fertilizer (photo: http://www.me.a.co.ke/Straight).}
1.4 Methane

Methane is produced naturally in oxygen free environments, such as those found in flooded soils e.g. rice paddies, wetlands and landfills. Much of CH$_4$ emission from agricultural soils is restricted to soils with standing water e.g. those under rice cultivation (Figure 4.2). Standing water creates oxygen-free (anaerobic) conditions that allow growth of bacteria (methanogen) which decompose organic matter, producing methane, which escapes to the atmosphere.

There are three processes by which CH$_4$ is released to the atmosphere from rice fields.

1. Methane loss as bubbles (ebullition) emitted through the water. Methane loss as bubbles is a major release mechanism during land preparation and initial growth of rice, especially if the soil texture is not clayey.

2. Methane transport through rice plants. The majority of methane emission during cropping season occurs through rice plants; the air spaces (aerenchyma) in the rice plants conduct methane from the soil into the atmosphere.

3. Diffusion of CH$_4$ across the water surface, considered as the least significant process.
In addition to emissions, natural processes in soil and chemical reactions in the atmosphere help remove CH\textsubscript{4} from the atmosphere. In the presence of oxygen, some bacteria utilize CH\textsubscript{4}, oxidizing it to CO\textsubscript{2}. Utilization of CH\textsubscript{4} occurs mainly in undisturbed non-flooded soils, which remove some of the gas from the atmosphere. Disturbance of soils through tillage and increase in soil ammonium content from ammonium-based nitrogen fertilization reduce the role of the soils as a sink for CH\textsubscript{4}.

### 1.5 Factors that influence GHG emissions from soils

The production and emission of GHGs from the soil is influenced by climatic conditions, soil characteristics, type of crop, and management activities (Table 4.1).

**Table 4.1 Factors that influence greenhouse gas emission from soils (Butterbach-Bahl et al 2015; IPCC 2006)**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2}, N\textsubscript{2}O, CH\textsubscript{4}</td>
<td>Temperature</td>
<td>Soil temperature affects the activity of soil microorganisms. Increase in temperature increase the rate at which microbes break down soil organic matter and the diffusion of GHGs to the atmosphere.</td>
</tr>
<tr>
<td></td>
<td>Soil moisture</td>
<td>Soil moisture affects aeration and regulates oxygen availability to microorganisms. Increase in soil moisture increases activity of microorganisms.</td>
</tr>
<tr>
<td></td>
<td>Soil texture</td>
<td>Soil texture affects the spread and the growth of microbes through the supply of air and moisture, as well gas diffusion rates. Emissions are greater from clay loam soil than sandy soil.</td>
</tr>
<tr>
<td></td>
<td>pH</td>
<td>Soil pH affects the growth and proliferation of soil microbes. Low pH (acidic soils) can reduce soil microbial activity. Excess amounts of salt affect carbon and nitrogen mineralization, and enzyme activities, which are crucial for decomposition of organic matter.</td>
</tr>
<tr>
<td></td>
<td>Carbon source</td>
<td>Organic matter provides a carbon source for the microorganisms. Agricultural practices that increase the amount of organic matter in the soil have potential to increase GHG emissions because of increased soil carbon content.</td>
</tr>
<tr>
<td>CO\textsubscript{2}, N\textsubscript{2}O</td>
<td>Tillage</td>
<td>Tillage improves soil aeration and accelerates mineralization of soil organic carbon.</td>
</tr>
<tr>
<td></td>
<td>Nitrogen inputs</td>
<td>An increase in mineral nitrogen in the soil increase N\textsubscript{2}O emissions. Application of nitrogenous fertilizer affects CO\textsubscript{2} emissions directly by providing nitrogen to microorganisms and indirectly by changing soil pH.</td>
</tr>
<tr>
<td>CH\textsubscript{4}</td>
<td>Plants</td>
<td>Plants provide carbon substrate for the bacteria, and transport methane internally from the root zone to the atmosphere. Emissions are low during the early growth stages of rice plants, and maxima during the reproductive and ripening stages. Plants can reduce emissions by causing aerobic conditions around the root zone.</td>
</tr>
</tbody>
</table>

### 2 Overview of measurement techniques

The rate of emissions of GHGs from the soils can be quantified directly through measurement of gas fluxes. Direct methods have the advantage of providing data that can be used to develop, calibrate or validate empirical and process-based models. The methods for direct measurements of GHG emissions from the soil are broadly classified into two categories: (1) micro-meteorological methods and (2) chamber methods.

#### 2.1 Micro-meteorological techniques

Micro-meteorological techniques measure the movement of gases from the ground surface to the lower atmosphere. The most common approaches employ tower-based equipment such as eddy covariance or aircraft-mounted equipment. Micro-meteorological methods are able to measure gas fluxes over a larger area than is possible with chamber method, with the added advantage of minimum
disturbance of the soil and hence the measurements do not interfere with natural processes. They also provide almost continuous sampling through time. However, several limitations (listed below) restrict the utility of the method.

- Costs
- Sophisticated instrumentation
- Require relatively level homogenous terrain
- Complexity in calculations
- Cannot distinguish among emissions sources
- Sensitive to wind velocity.

Figure 4.3 Flux tower that measures emissions by the Eddy Covariance method ([http://www.isws.illinois.edu/atmos/boundary.asp](http://www.isws.illinois.edu/atmos/boundary.asp)).

2.2 Chamber method

The chamber method is the most commonly used and typically the most suitable sampling method for smallholder systems. Chambers are placed over the surface of the soil at predetermined points and times, and gas within the chamber headspace manually extracted, stored in air-tight vials, and sent to a laboratory for analysis. The majority of chambers are operated manually. Table 4.2 highlights some of the advantages and limitations of chamber method.

Table 4.2 Some of the advantages and limitations of the chamber method

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Chambers allow measurements at small scales (&lt;1 m²) making them appropriate for smallholder, plot level studies</td>
<td>• Labor-intensive because of the need to install several chambers and make repeated measurements.</td>
</tr>
<tr>
<td>• Chambers are relatively cheap to purchase, install, maintain and use, and can be readily moved around the study area</td>
<td>• The use of chambers is restricted to bare soils or to soil with small-sized vegetation</td>
</tr>
<tr>
<td>• Chambers can be adapted to a wide range of field conditions and experimental objectives.</td>
<td>• It is difficult to interpret soil CO₂ flux data in the context of net GHG flux when measurements are taken in the presence of plants.</td>
</tr>
<tr>
<td>• Chambers allow collection and storage of gas samples for later analysis</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.3 Flux tower that measures emissions by the Eddy Covariance method ([http://www.isws.illinois.edu/atmos/boundary.asp](http://www.isws.illinois.edu/atmos/boundary.asp)).
Chamber methods disturb the environment, which may affect gas diffusion and hence soil fluxes; first through insertion of the chamber and then subsequently by changing conditions inside the chamber when taking measurements. To overcome some of the potential sources of errors encountered with chamber based measurements, Table 4.3 gives a list of critical consideration when taking measurements.

**Table 4.3** Potential sources of errors associated with chamber-based flux measurement techniques and how to overcome them

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Description</th>
<th>Corrective measure(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil disturbance</td>
<td>Short term disturbance can occur upon installation of the anchor used to support the chamber.</td>
<td>Install permanent chamber anchors at least 24 hours prior to gas sampling</td>
</tr>
<tr>
<td>Temperature perturbations</td>
<td>Shading alters temperature regimes within the chamber. Temperature changes affect microbial activity, cause expansion and contraction of gases and affect absorption or dissolution of dissolved soil gases.</td>
<td>Minimize anchor or collar height to reduce micro environment perturbations. Alternatively, use insulated chambers to help maintain a constant temperature regime during deployment. Keep chamber deployment time as short as possible without sacrificing detection sensitivity.</td>
</tr>
<tr>
<td>Pressure perturbations</td>
<td>Wind passing over the chamber anchor may cause pressure-induced mass flow of gas into or out of the soil.</td>
<td>Use a properly vented chamber</td>
</tr>
<tr>
<td>Humidity perturbations</td>
<td>Humidity increase inside a chamber will affect trace gas concentrations due to dilution by water vapor and effect on microbial activity.</td>
<td>Keep chamber deployment short. Estimate relative humidity changes inside chamber to potentially correct for dilution and/or gas solubility effects.</td>
</tr>
<tr>
<td>Gas mixing</td>
<td>Gas mixing is likely to occur if large amounts of vegetation are present or the chamber volume to surface area ratio is large.</td>
<td>A small fan can be placed within the chamber to help mix the gases if vegetation is present or if the chamber is large</td>
</tr>
</tbody>
</table>

There are usually two types of chambers: and static chambers - changes (increase/decrease) in gas concentration over time are monitored, which are then used for calculation of flux rates (Figure 4.4a); dynamic chambers - air is circulated between the chamber and the analyzer, and data saved in a data logger (Figure 4.4b). The change in gas concentration with time is considered as emission or consumption in soil (Figure 4.5).
Box 4.1 Important consideration of the chamber method (Butterbach-Bahl et al. 2015)

Chamber design and size

The design of the chambers for smallholder systems is determined by factors such as vegetation type and planting patterns or simply the treatment under investigation. These factors influence the shape of the chamber (whether round or rectangular), its size, and the cost of construction.

The size of the chamber determines the volume of space inside the chamber headspace, the appropriate surface area covered and whether the chamber can accommodate plants of a given size.

Smaller chambers are cheaper, easy to transport; preferred for short-term trials and where soil is cultivated and more homogenous, allowing the chambers to be placed between rows. However, many small chambers may be required to obtain representative samples. Smaller chambers also greatly influence the microclimate due to shading of the soil within the chamber and the larger edge effects associated with the area of soil disturbed around the edge of the chamber. Larger chambers on the other hand are preferred for longer-term trials where microclimate may influence emissions.

Analytical instruments used for chamber measurements

The concentration of GHGs in the sample air can be determined directly in the field by some instruments, e.g. using Licor CO₂ or photoacoustic spectroscopy analyzers, or in the laboratory following storage of gas samples in vials using gas chromatography. Gas chromatography is the most commonly used instrument for analyzing gas measurements from the static chamber method.
Box 4.2 Designing a gas sampling program

The sampling program should account for temporal and spatial variability of GHGs emission, and use our existing understanding of the processes producing agricultural fluxes to help design an experimental procedure and reduce as much as possible uncertainties in the flux estimates. In addition to selecting an appropriate size and number of chambers, it is important to install chambers at the right place, collect gas samples at the right time of the day, and ensure adequate sampling frequency.

Where to sample

- Samples should be taken from the interior of the plots to minimize edge effects from surrounding areas. Care should be taken not to walk on, or interfere with, the identified future sampling sites within a site of interest.
- Avoid evident disturbance like foot path, rain water path, uneven ground like animal burrows and ant hills.

When to sample

The sampling frequency is determined by the design of the experiment and available funds. The time of the day to collect samples from the headspace depends on the objective of the research. Samples can be taken when the emission is expected to be at peak, or at the time of day when the flux is believed to equal its daily mean. The sampling program should ensure that:

- Samples are also collected when the processes that give rise to emissions are known to be most active, e.g. shortly after application of fertilizers, sowing, irrigation and rainfall events.
- Samples are also collected when the emissions profile is expected to change e.g. during periods of active plant growth, establishment of a cover crop or bare soil.

How to sample

Sampling can be achieved using conventional approach or gas pooling technique. It is good practice to:

- Use a greater number of sampling points where emissions are expected to be very low, in order to detect differences between treatments
- Use weighted sampling, e.g. by installing two or more additional chambers at each sampling point in areas known to have differences in soil properties, topography and field preparations.
- Take samples sequentially across the site, rather than per treatment and control area to minimize potential sampling bias associated with climatic conditions. Vary the order of sampling from one sampling round to the next.
- Plan sampling of sites with management actions to occur at the same time of day for each sampling round, and at the time that best represents the average daily, for example between 10.00 am and 12.00 pm in Kenya.
- Over-pressurize pre-evacuated glass vials (i.e. inject a slightly greater volume of gas sample into the vials about 20% more than the volume of the vial) to minimize sample dilution and reduce risk of contamination (if leakage occurs during transfer and storage).
3 Measuring soil emissions using chamber method

The following tools are required for collecting gas samples and monitoring auxiliary measurements.

- Static chamber and accessories
- Glass sampling vials
- Plastic syringes (60 ml)
- Gas sampling syringes (0.6 x 25 mm) with aluer lock
- Double ended syringes (vacutainer)
- Vacuum pump for evacuating gas vials
- Zip lock bags for packing samples
- Digital manometer for measure pressure inside the vial
- GPS device for measure ambient pressure and elevation
- Thermometers for measure soil and air temperatures
- Stop watch/altimeter wrist watch for timing and scheduling sampling intervals
- Measuring ruler (30 cm) for measuring chamber height
- Clipboard/data recording form/pens for recording the measurement
- Rubber bands for tying the glass vials together
- Marker pens for Labeling samples
- A pair of scissors for clipping vegetation inside the chamber
Box 4.3 Evacuating the vials

Evacuation is the process of cleaning vials before introducing new gas samples. It is recommended to change the rubber septum of the vial after two samplings in the field or more frequently, before evacuating. Two approaches can be used, (1) in the lab using a vacuum pump, and (2) in the field by flushing out gas using excess gas sample in the syringe.

1. Evacuating using a vacuum pump
   1. Connect the silicone tubing to the vacuum pump and cap the end of tube.
   2. Turn on the vacuum pump and pierce the shorter end of the double ended needle to the tube.
   3. Connect the glass vial on the longer end of the needle by piercing through the rubber septa and evacuate for about 10 minutes.
   4. Remove the vial from the silicone tube and check the inside pressure using a manometer.

![Figure 4.6 Evacuating vials using a vacuum pump. Several vials can be evacuated simultaneously depending on the length of the tubing and the power of the pump. The display on the manometer should read a value below negative 550 mm Hg (negative pressure).]

2. Evacuation done in the field by flushing out gas using excess gas sample in the syringe
   1. Fill a 60 ml syringe with gas sample
   2. Insert a needle into the vial
   3. Transfer gas from the syringe into the vial while flushing out gas through the needle until the 20 ml mark on the syringe (i.e. 40 ml of the gas).
   4. Remove the needle from the vial and force the remaining 20 ml into a 10 ml vial creating an over pressure

![Figure 4.7 Flushing out old gas and introducing new gas into the vial.]
3.1 Chamber installation

The chamber described here has two parts: (1) a base which is driven into the soil and (2) a removable lid containing the vent tube and sampling port. The base of a two piece chamber should be driven into the soil at least 24 hours before the start of sampling but preferably longer, and left permanently throughout the sampling season.

The following procedure is followed when deploying chambers.

1. Identify the sampling point to place the chamber bases.
2. Clear vegetation (without disturbing the root system) at the spot where the chamber base will be placed.
3. Push the sharp end of the base into the ground, about 10 cm deep. Ensure that no air seeps from under and outside the base, especially because of uneven ground.
4. Record the height of the base above ground for use when calculating chamber volume. This should be taken from all sides, approximately at the center of each side; and needs to happen at each sampling period due to changes because of weather/rain.

Note: Check the condition of the base, correct or change where there is need and note any incidents in the data sheet. Check the chamber lids to ensure that the sealing material, the septum in the sampling port and fan wires are in good condition. These are possible areas for loose connections that may lead to leakage of gas and cause contamination in the sample.

3.2 Gas sampling

Gas sampling involves physical removal of gas sample from the chamber headspace for analysis in the laboratory. Gas samples are withdrawn at regular intervals during the chamber deployment to monitor changes in fluxes in time. Gas sampling is performed by inserting a syringe into the chamber septa and slowly removing a gas sample. The gas sample is then transferred to a previously evacuated glass vial sealed with butyl rubber septum for storage. Gas samples are stored in a cool place, away from the sun. They are packaged and transferred to a laboratory for analysis.

3.2.1 Conventional gas sampling procedure

The following procedure is followed for collecting gas using conventional sampling approach.

1. Start the timer (e.g., stop watch) and record the initial time i.e. T1 (0 min) and immediately close the first chamber, clamp each side of the base and the lid to make the chamber air tight.
2. Insert the needle into the chamber through the septum of the sampling port. In cases when an internal fan is not being used, extract gas with syringe and then expel gas without removing the syringe from the chamber to mix the gas in the chamber.
3. Remove gas filling up the syringe (preferably 60 ml), close the luer lock.
4. Repeat step 2 and 3 for all the chambers while recording the chamber temperature before taking the sample. Take the shortest time possible.
5. Record the time you finish sampling T1 of the last chamber for example 3.30 minutes.
6. Transfer the gas from the syringes to the vials.
7. Ten minutes from the time you started the timer, start the second round of sampling for T2 vials in the same sequence you sampled for T1 vials. Record temperature for each chamber and the finishing time of the last chamber, for example 13.00 minutes.
8. Twenty minutes after start of timer, sample for T3 vials in the same sequence as for vial T1 and vial T2 for all chambers and record the finish time.

9. Repeat for vial T4 after exactly 30 minutes on your timer for vial T4 and ensure you record the finish time.

10. Using a rubber band tie together four vials T1-T4 from each chamber.

11. Pack all vials in well labeled zip lock bag then carefully remove the cables, thermometers and clamps and open the chambers.

3.2.2 Gas pooling method

The principle idea of gas pooling method is to composite gas sample from all the chambers headspace (i.e. for T1) using a single syringe and storing in one vial. This method allows for installation of many chambers and reduces on the number of samples to analyze. The following procedure is followed collecting gas using gas pooling method for a site with four chambers.

1. Start the stop watch timer and record the initial time for example T1 (0 min) and immediately close the first chamber.

2. Record chamber temperature then insert the needle into the chamber through the septum of the sampling port.

3. Take gas up to the 15 ml mark of the syringe (60 ml syringe), close the luer lock.

4. Go to the second chamber, close the chamber and record the chamber temperature.

5. Insert the needle into the chamber through the septum of the sampling port, open the luer lock and take gas up to the 30 ml mark, then close the luer lock.

6. Go to chamber three repeat step 2, using the same syringe take gas up to the 45 ml mark.

7. Go to chamber four and repeat step 2, then fill up the syringe (60 ml) and record the time on the time for example [3.30 minutes].

8. Mix the gas in the syringe then transfer the gas into the well labeled vial for T1 samples.

9. Immediately after ten minutes on your timer, start the second round of sampling for T2 samples.

10. Repeat step 2, 3, 5, 6, 7 and 8 while recording chamber temperature before taking the gas.

11. Do the same for T3 and T4 (i.e. exactly after 20 minutes and 30 minutes on the timer).

12. Pack all vials (4 in total) in well labelled zip lock bag. Carefully remove the cables, thermometers and clamps and open the chambers.

Note: It is good practice to ensure that gas samples collected are labelled and stored in a manner that will prevent contamination and maintain the identity and condition of each sample. The method used should be easily understood by the lab technician analyzing the sample.

3.3 Taking auxiliary measurements

There are a range of properties that influence the generation and emission of CH$_4$, N$_2$O and CO$_2$ from the soil (Table 4.4). Auxiliary measurements should be monitored at the same time of gas sampling in order to account for their variability and resultant impact on gas fluxes (Sapkota et al. 2014).
Table 4.4 Auxiliary measurements

<table>
<thead>
<tr>
<th>Period</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluxes measurement</td>
<td>• Chamber temperature</td>
</tr>
<tr>
<td></td>
<td>• Soil temperature (7 cm)</td>
</tr>
<tr>
<td></td>
<td>• Soil water content (0-10 cm)</td>
</tr>
<tr>
<td></td>
<td>• Atmospheric pressure</td>
</tr>
<tr>
<td>Chamber installation</td>
<td>• Chamber base height above the soil</td>
</tr>
<tr>
<td></td>
<td>• Bulk density</td>
</tr>
<tr>
<td></td>
<td>• Soil texture</td>
</tr>
<tr>
<td></td>
<td>• Organic carbon and nitrogen</td>
</tr>
<tr>
<td></td>
<td>• pH</td>
</tr>
<tr>
<td></td>
<td>• Soil nitrate and ammonium (0-10 cm)</td>
</tr>
<tr>
<td>Throughout sampling season</td>
<td>• Daily rainfall</td>
</tr>
<tr>
<td></td>
<td>• Air temperature</td>
</tr>
<tr>
<td></td>
<td>• Relative humidity</td>
</tr>
</tbody>
</table>

The following **procedure** is used to collect data on physical and chemical properties of the site and management influence.

1. Insert the thermometer 7 cm into the soil under shade. Wait for the reading to stabilize then record soil temperature displayed.

2. Record the ambient pressure in millibars, which can be done using a GPS or barometer.

3. Hang the thermometer under a shade at the site of sampling and record the ambient air temperature.

4. Record all incidents that occur during the sampling process to provide more information during analysis of samples in the laboratory and flux calculations.

### 4 Estimating greenhouse gases from chamber measurements

#### 4.1 Laboratory analysis

Analysis of gas samples can be undertaken at any laboratory with a gas chromatograph (Figure 4.8), following appropriate management and calibration procedures. Samples received from the fields are checked for their appropriateness for analysis. Samples with wrong documentation such as those wrongly packaged, incorrectly labelled/unlabeled, and those in broken glass vials are rejected. Sample details are filed and later entered into excel spreadsheets. It is recommended to analyze the samples within two weeks of sampling to minimize potential for contamination with ambient air.
Once samples have been analyzed, outputs from the gas chromatograph can be used to calculate fluxes. This is done by expressing the increase in gas concentration within the known volume of chamber over the closure time, as a function of the cross-sectional area of soil within the chamber. This is then expressed in the units of micro grams for $\mu$Mol m$^{-2}$ h$^{-1}$ for N$_2$O, mg m$^{-2}$ h$^{-1}$ for CH$_4$. Means and standard errors can be calculated and statistical tests (e.g. analysis of variance) performed to determine the significance of differences between treatments and controls.

Figure 4.8 Gas chromatograph that is used to measure concentration of molecules in a gas sample.

Box 4.4 Analysis of gas samples

Analysis of a gas sample follows a three-step procedure.

1. **Sample injection.** The sample from the vial is injected into gas chromatograph through a sample injection valve which then enters into gas chromatograph column; this can be done manually or by having an automated system. Samples are analyzed in a systematic manner: according to the site, treatment and chamber they were sampled from, also the time sequences the sampling was done i.e. T1 representing sampling at zero minutes, T2 (10 minute) up to T4 (30 minutes), rather than segregating all the samples by time (analyzing zero time samples from all chambers together). Calibration standards (gas of known concentration) are included in the analysis to compute actual sample concentrations.

2. **Sample separation.** The analytical column (3 mtr. Hayesep D, 80 to 100 mesh) is where separation of gas mixture takes place based on molecular weight of each analyte. The gas chromatograph is equipped with a standard back-flush system where moisture is removed from the sample.

3. **Sample detection.** A gas chromatograph is equipped with two detectors i.e. electron capture detector (ECD) for N$_2$O detection and flame ionization detector (FID) for analysis of compounds containing carbon such as CO$_2$, and CH$_4$. Detailed description of the ECD and FID are contained in separate protocols available upon request from ICRAF and other laboratories.
4.2 Estimating GHG emissions from chamber measurements

Concentration of gases can be calculated through peak area of sample in relation to the peak area of the respective standard gas of known concentration.

Fluxes are determined by calculating the rate of change of trace gas concentration in the chamber headspace. The following field conditions are also included in calculation of fluxes:

- Ambient air pressure
- Chamber area and volume
- Temperature inside the chamber

This manual adopts the formula described by Butterbach-Bahl et al. (2011):

\[
F = \frac{b \times M_w \times V_{ch} \times 60 \times 10^6}{A_{ch} \times V_m \times 10^9}
\]

- \( b \) = slope of increase or decrease in concentration (ppb min\(^{-1}\))
- \( M_w \) = molecular weight of component of the compound (g mol\(^{-1}\))
- \( V_{ch} \) = chamber volume (m\(^3\))
- \( A_{ch} \) = chamber area (m\(^2\))
- \( V_m \) = corrected standard gaseous molar volume (m\(^3\) mol\(^{-1}\))
- \( V_m = 22.4 \times 10^{-3} \text{ m}^3 \text{ mol}^{-1} \times ((273.15+\text{Temp})/273.15) \times (1013/\text{air pressure}) \)

Gas fluxes in the N and C cycle are generally reported in terms of N and C rather than in terms of the compound i.e. N\(_2\)O, and CO\(_2\) and CH\(_4\), respectively.

5 Key message

- Agricultural activities contribute directly to emissions of CO\(_2\), N\(_2\)O and CH\(_4\) gases from the soil.
- The chamber method is typically the most common and suitable for small holder systems.
- Environmental and soil conditions affect greenhouse gas emissions and hence auxiliary measurements of these factors should be measured during sampling.
6  Exercise

6.1  Calculation of CO₂ and N₂O fluxes

Calculate the fluxes of CO₂ and N₂O using the following data from GC and field measurements.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>CO₂ Peak areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard gas</td>
<td>4000.00</td>
</tr>
<tr>
<td>Sample T1</td>
<td>4180.89</td>
</tr>
<tr>
<td>Sample T2</td>
<td>6185.97</td>
</tr>
<tr>
<td>Sample T3</td>
<td>8182.36</td>
</tr>
<tr>
<td>Sample T4</td>
<td>10458.34</td>
</tr>
</tbody>
</table>

Field conditions at time of sampling

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Temperature</td>
<td>35°C</td>
</tr>
<tr>
<td>Ambient pressure</td>
<td>810 mb</td>
</tr>
<tr>
<td>Chamber volume (m³)</td>
<td>0.0154</td>
</tr>
<tr>
<td>Chamber area (m²)</td>
<td>0.0905</td>
</tr>
<tr>
<td>Molecular weights</td>
<td>C=12</td>
</tr>
<tr>
<td>CO₂ concentration</td>
<td>400.00 ppm</td>
</tr>
</tbody>
</table>

**Step 1.** Calculate the concentrations of CO₂

\[
\text{CO}_2 \text{ concentration } = \frac{\text{Peak area}}{\text{CO}_2 \text{ concentration in standard gas}}
\]

<table>
<thead>
<tr>
<th>Sample</th>
<th>CO₂ concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>418.09 ppm</td>
</tr>
<tr>
<td>T2</td>
<td>618.60 ppm</td>
</tr>
<tr>
<td>T3</td>
<td>818.24 ppm</td>
</tr>
<tr>
<td>T4</td>
<td>1045.83 ppm</td>
</tr>
</tbody>
</table>

**Step 2.** Calculate CO₂ fluxes using the parameters below

\[
b = 20.829 \\
M_w = 12 \\
V_{cm} = 0.0154 \\
A_{cm} = 0.0905 \\
V_m = 0.0316
\]

\[
V_m = 22.4 \times 10^{-3} \times \frac{273.15 \times 35}{273.15 \times (810/1013)}
\]

\[
F(\text{CO}_2 - C) = \frac{20.829 \times 12 \times 0.0154 \times 10^3}{0.0905 \times 0.0316 \times 10^3} = 80.76 \text{ mg m}^2 \text{ h}^{-1} \text{; \ milligrams of C per square metre per hour}
\]
6.1 Calculation of average CO\textsubscript{2} in a farm

Calculate the mean flux of CO\textsubscript{2} from a tea farm installed with five chambers:

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Peak Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chamber 1</td>
</tr>
<tr>
<td>Standard gas</td>
<td>4000.00</td>
</tr>
<tr>
<td>T1</td>
<td>5277.47</td>
</tr>
<tr>
<td>T2</td>
<td>7956.78</td>
</tr>
<tr>
<td>T3</td>
<td>10377.26</td>
</tr>
<tr>
<td>T4</td>
<td>12993.87</td>
</tr>
</tbody>
</table>

Field conditions at time of sampling

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Chamber Temperatures</td>
<td>35, 34.5, 37, 40, 36.8\textdegree C</td>
</tr>
<tr>
<td>Ambient pressure</td>
<td>810 mb</td>
</tr>
<tr>
<td>Chamber volume (m\textsuperscript{3})</td>
<td>0.0154</td>
</tr>
<tr>
<td>Chamber area (m\textsuperscript{2})</td>
<td>0.0905</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>C=12</td>
</tr>
</tbody>
</table>

Calculate CO\textsubscript{2} concentrations using the standard gas concentration (400 ppm).

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chamber 1</td>
</tr>
<tr>
<td>Standard gas</td>
<td>400.00</td>
</tr>
<tr>
<td>T1</td>
<td>527.75</td>
</tr>
<tr>
<td>T2</td>
<td>795.68</td>
</tr>
<tr>
<td>T3</td>
<td>1037.73</td>
</tr>
<tr>
<td>T4</td>
<td>1299.39</td>
</tr>
</tbody>
</table>

Slopes: CH1 = 25.57 CH2 = 25.21 CH3 = 28.11 CH4 = 33.42 CH5 = 28.54

\[
V_{ch} = 0.0154 \\
A_{ch} = 0.905 \\
V_{m, CH 1} = (22.4 \times 10^{-3} \times (273.15+35) / (273.15 \times 810/1013) = 0.03160 \\
V_{m, CH 2} = (22.4 \times 10^{-3} \times (273.15+34.5) / (273.15 \times 810/1013) = 0.03155 \\
V_{m, CH 3} = (22.4 \times 10^{-3} \times (273.15+37) / (273.15 \times 810/1013) = 0.03181 \\
V_{m, CH 4} = (22.4 \times 10^{-3} \times (273.15+40) / (273.15 \times 810/1013) = 0.03212 \\
V_{m, CH 5} = (22.4 \times 10^{-3} \times (273.15+36.8) / (273.15 \times 810/1013) = 0.03179 \\

\[
F(Ch1) = \frac{25.57 \times 12 \times 60 \times 0.0154 \times 10^{6}}{0.0905 \times 0.03160 \times 10^{6}} = 99.129 \text{ mg m}^{-2} \text{ h}^{-1}
\]
The average emission on the farm at this time period is:

\[
\frac{(99.13 + 97.89 + 108.26 + 127.48 + 110.01)}{5} = 108.55 \text{ mg m}^{-2} \text{ h}^{-1}
\]

Further reading


MODULE V. MEASURING METHANE EMISSIONS IN LIVESTOCK PRACTICES

This module provides an overview of methane emissions from animal production. A summary of methods available for measurement of methane from enteric fermentation is presented.

Learning objectives

- To understand greenhouse gas emissions from enteric fermentation
- To understand how to estimate greenhouse gas emissions from enteric fermentation

Discussion question

- What greenhouse gases are associated with livestock production?
- What data are required for estimation of greenhouse gas emissions from livestock?

1 Greenhouse gas emissions from livestock

Livestock production is associated with production of CH₄ emissions from enteric fermentation, and CH₄ and N₂O emissions from livestock manure management systems (IPCC 2006).

1.1 Methane emission from enteric fermentation

CH₄ is produced as part of the normal digestive process in animals. During digestion, microbes that live in the digestive system of animals ferment food consumed by the animal in a process referred to as enteric fermentation (IPCC 2006). CH₄ is produced as a byproduct and primarily emitted through an animal’s mouth as burps.

Figure 5.1 Enteric methane is a by-product of the digestive process in ruminant animals such as cattle, goats, sheep, camels etc.

Side bar 5.1 Enteric fermentation refers to the digestive process in animals in which microbes ferment food consumed by the animals. Methane is a natural by-product of enteric fermentation.
Factors that influence CH$_4$ emission from enteric fermentation

The amount of CH$_4$ produced by an individual animal depends primarily upon two factors:

a. Animal’s digestive system. Livestock are classified in two groups according to the digestive systems: (1) ruminant animals e.g. cattle and (2) non-ruminant animals e.g. pigs.

b. Amount and type of feed consumed by the animal. Feed quality and quantity affect the amount of CH$_4$ emitted by providing additional substrate. Lower quality feed increases CH$_4$ emissions; higher quantity of feed increases CH$_4$ emissions (Figure 5.2). Feed intake is positively related to the animal size, growth rate, and production level e.g. milk production, pregnancy etc.

1.2 Methane and nitrous oxide from livestock manure

CH$_4$ and N$_2$O are the main greenhouse gases emitted from decomposition of manure (IPCC 1997). CH$_4$ is produced during the decomposition of livestock manure by bacteria in the absence of oxygen, for example when animal waste accumulates in piles. N$_2$O is produced during storage of manure by the same microbial processes (nitrification and denitrification) responsible for generating N$_2$O from the soil (Module III).

Factors that influence methane emission from manure

The amount of methane produced from manure depends on:

- Quantity of manure produced. Manure production varies by animal type and is proportional to the animals’ weight, number of animals, and amount of feed consumed.

- Manure characteristics. Emissions are dependent on the manure composition which is effected by feed type and the animal’s digestive system. Feed that is easier to digest leads to manure that produces lower methane emissions.

Figure 5.2 Animals fed on Napier grass may produce more methane than those fed on diets with greater quantity of legumes.

Side bar 5.2 Denitrification is a process by which soil organisms convert nitrate to nitrogen, which is then lost to the atmosphere.

Side bar 5.3 Nitrification is a process by which soil organisms use oxygen to convert ammonium ions to nitrite ions and nitrite ions to nitrate ions.
• Manure handling. The way manure is stored determines the portion of the manure that decomposes anaerobically or aerobically. Manure tends to decompose anaerobically when stored as liquid or slurry, producing significant quantity of CH\textsubscript{4}. Manure tends to decompose aerobically when handled as a solid and little or no CH\textsubscript{4} is produced (Figure 5.3a).

• Environmental conditions. Manure decomposes more rapidly when temperature and moisture conditions encourage bacterial growth or activity.

1.3 Reducing CH\textsubscript{4} and N\textsubscript{2}O emissions from livestock production

Enteric CH\textsubscript{4} production represents a loss of feed energy; therefore reducing enteric CH\textsubscript{4} will improve livestock productivity. The following are potential options for reducing the amount of CH\textsubscript{4} and N\textsubscript{2}O emissions per unit of product from ruminant livestock (IPCC 2006).

a. Change the way manure is stored. Manure stored as liquid produces significant quantity of CH\textsubscript{4} while manure stored as solid produces little or no CH\textsubscript{4} (Figure 5.3a).

b. Reduce stock numbers. CH\textsubscript{4} emissions are correlated with the total population of ruminant animals. Less CH\textsubscript{4} is produced when a small number of animals that produce highly are kept compared to keeping a larger herd of animals that, especially if the animals are less productive (Figure 5.3b).

c. Remove production impediments such as improving animal health. Best management practice such as eliminating parasites and nutrient deficiencies help animals maximize feed energy (Figure 5.3c).

d. Improve animal diets by things such as graze on younger grasses or supplement diets with concentrates or high protein forage. Grasses in the earlier growth phase are more digestible than mature or senescing plants. Animals fed on legumes or diets rich in cereal grains such as barley, maize or wheat yield less CH\textsubscript{4} than animals grazed on pasture. Legumes and cereals create conditions for lower CH\textsubscript{4} emissions compared to grass due to their lower fiber concentration (Figure 5.2b)

Figure 5.3a Manure stored in solid as piles (i) and manure treated in liquid (ii).
Overview of measurement techniques

There are several direct and indirect methods that can be used to measure CH$_4$ emissions from enteric livestock (Table 5.1). These methods measure CH$_4$ at scales ranging from laboratory incubation studies to individual animals, herd/farm measurements. Some techniques require enclosure of animals while others can be used on free animals. Enclosure techniques are most precise but require trained animals, specialized facilities and limit animal movement reducing the number of places such measurements can be undertaken.

Key challenges to measuring enteric methane production in smallholder production systems include:

- Variability in production systems.
- Variability in feeds.
- Seasonality in feed supply and quality.
- Costs.

2.1 Direct measurement of methane

A common technique for directly measuring methane in the exhaled gas from ruminants involves placing the animal into some form of enclosed space (chamber) and measuring the change in atmospheric composition within the chamber. These chambers may be fully sealed with CH$_4$ measured...
either as it accumulates over time or, alternatively, in a continuous flow-through gas stream extracted from the chamber. The animals are trained, and the conditions within the chambers kept as normal as possible to minimize the potential of animals becoming stressed and altering their respiratory or digestive behavior which may affect the amount of CH$_4$ they produce.

A range of other techniques have been developed that do not require whole animal enclosure. Most of these techniques are not used in developing countries due to the specialist nature of the required equipment, its limited availability and the high level of expertise required to set up, calibrate and maintain such measurement systems. An overview of the measurement techniques, and their respective advantages and disadvantages are briefly given in Table 5.1.

**Table 5.1 Techniques for estimation of methane emission from livestock**

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lab-based incubation</td>
<td>Feed substrate is incubated in air-tight bottles/bags to allow gas accumulation, and then gas samples analyzed for CH$_4$ concentrations.</td>
<td>Less expensive Controlled conditions</td>
<td>May not represent environmental conditions well</td>
</tr>
<tr>
<td>2. Prediction equations</td>
<td>Models based on relationships developed using feed characteristics, such as dry matter intake.</td>
<td>Inexpensive to use once developed. Applicable in cases where measurements are not possible.</td>
<td>The assumptions and conditions that must be met for each equation limit their ability to accurately predict methane production</td>
</tr>
<tr>
<td>3. Open circuit respiration chambers</td>
<td>Measures methane concentration within exhaled breath while the animal is in an enclosed chamber.</td>
<td>Provides accurate and precise measurements of emissions including CH$_4$ from ruminal and hindgut fermentations</td>
<td>It is expensive to construct and operate. Their use is technically demanding. Restricts normal animal behavior and movement.</td>
</tr>
<tr>
<td>4. Ventilated hood</td>
<td>An airtight box is placed to surround the animal’s head. Gas exchange is measured only from the head rather than the whole body</td>
<td>Relatively low-cost compared to whole animal chamber</td>
<td>Requires training to allow the test animals to become accustomed to the hood apparatus It does not measure hindgut CH$_4$</td>
</tr>
<tr>
<td>5. SF$_6$ tracer technique</td>
<td>A small permeation tube containing SF$_6$ is placed in the cow’s rumen, and SF$_6$ and CH$_4$ concentrations are measured near the mouth and nostrils of the cow.</td>
<td>Allows the animal to move about and graze. Can be used to measure large numbers of individual animals.</td>
<td>It is necessary to train the animal to wear a halter and collection yoke SF$_6$ is a greenhouse gas itself.</td>
</tr>
</tbody>
</table>
### Method Description

**6. Polyethylene tunnel**

- **Description:** Are large inflatable or tent type tunnel made of heavy duty polyethylene fitted with end walls and large diameter ports. The concentrations of air between the incoming and outgoing air are continuously monitored.
- **Advantage:** It is portable, hence adaptable to different feeding systems such as grazing animals. Can be used for individual or small group of animals under semi-normal conditions.
- **Disadvantage:** There is difficulty in controlling the tunnel’s temperature and humidity. The method is not suited for evaluating differences between imposed experimental treatments.

**7. Open-path laser**

- **Description:** This technique uses lasers and wireless sensor networks to send beams of light across paddocks containing grazing animals and then analyze the reflected light for greenhouse gas concentrations.
- **Advantage:** Measure CH\(_4\) emissions from herds of animals and facilitates whole-farm methane measurements across a number of pastures.
- **Disadvantage:** It requires expensive instrumentation and is technically demanding. No source attribution.

### Notes:

- In vitro incubation and estimation from direct are indirect methods.
- Indirect methods such as SF\(_6\) tracer technique, poly tunnel and open-path laser techniques can be used to perform measurements under natural grazing conditions.

### 2.2 Indirect estimates of methane

#### 2.2.1 Methane prediction equations

Indirect methods are used to calculate methane emissions where it is impractical or too expensive for direct measurements to be undertaken and include; for example, where facilities are not available or when estimating methane emissions over a large geographic area. Prediction equations are therefore used to estimate methane emissions (Hristov et al. 2013).

Prediction equations are based on data derived from experiments conducted with cattle in respiration chambers, and recently SF\(_6\) techniques. These equations utilize dry matter intake (DMI) and gross energy intake (GE). Some equations are designed specifically to predict CH\(_4\) emissions from animals. Other equations are modified to estimate CH\(_4\) emission from rumen fermentation (e.g. feed intake). Depending on the model selected, methane emission can be quantified at different scales; farm, county, nationally.

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**Side bar 5.4** Dry matter intake is the amount of feed an animal consumes per day (in kg) on a moisture free basis.
3 Estimating methane emissions from livestock populations

Oftentimes it is not possible to directly measure emissions or estimate them based on predictive equations based on energy or dry matter intake. Another option is to estimate the emissions based on the size of the livestock population (e.g., the number of each type of animal). The population can then be multiplied by default emissions factors, which are available for each animal type and typically for each region globally. This method is useful for estimating changes in emissions only for inventories and mitigative actions that affect animal numbers (e.g., reducing stocks). It cannot differentiate changes in emissions from actions that affect emissions rates from individuals (e.g., feed supplements or other dietary changes).

Methane emissions from livestock can be estimated by using the following steps:

- Dividing animals into animal groups and collecting population data
- Estimating methane emission using appropriate emission factors
- Multiplying the population by 'estimate methane' for each animal group
- Summing emissions across animal groups

**Key message**

- Enteric fermentation from livestock is the main source of agricultural emissions in Kenya
- Methane emissions are increased when cows are fed on poor quality diets, by keeping many low producing cows, or by storing manure in liquid form
- Methane emissions can be estimated using prediction equations that utilize dry matter intake or gross energy intake or more commonly, just by the population size.

4 Exercises

4.1 Quantification of methane from enteric fermentation and manure management

The amount of methane emitted by a population of animals is calculated by multiplying the emission rate per animal by the number of animals (equation 1.2). Methane emissions are separately calculated for sub-categories of cattle, sheep, goats, pigs and poultry.

\[
\text{CH}_4 \text{ emissions} = \text{Emission factor} \times \text{Livestock population} \quad \text{Equation 1.2}
\]

- Emissions \( \text{CH}_4 \) = methane emissions (kg GHG)
- Livestock population = total population of each type of livestock

Emission factor = default emission factors from 2006 IPCC Guidelines that are specific to climate region for the livestock in question

\( \text{CH}_4 \) emissions can be estimated from enteric fermentation and manure management using the following three steps. It is recommended to use Tier 2 to estimate emission from cattle in Kenya because cattle are such a large share of the total GHG budget. However, as noted in Module V, Tier II requires additional information, e.g., on feed intake and characterization that is rarely available. This example illustrates emission calculation using tier 1.
Step 1. Collect activity data for livestock population groups and subgroups.

Activity data include data on livestock population and manure management system usage. The Tier 1 methodology for methane emissions requires only data on livestock population by livestock group (Table 1.4 A). Activity data should represent an average estimate for the entire year. The following information is collected.

- Livestock species and categories. Generate a complete list of all relevant livestock populations that have default emission factor values.
- Average annual population. Obtain data from official national statistics. FAO data can be used if national data are unavailable.
- Climate data. Describe livestock populations in terms of warm or cool temperature climates for purposes of estimating livestock manure emissions. Data on the annual average temperature of the regions where livestock are managed should be used as follows: Cool (<15 °C), Temperate (15 °C to 25 °C) and Warm (>25 °C). The climate data collected as part of the activity data is used to select the appropriate emission factors.

Step 2. Estimate emissions factors for each subgroup or use default emission factors. To reflect the variation in emission rates among animal types, the population of animals is divided into subgroups, and an emission rate per animal is determined for each subgroup. Some default values relevant for Kenya for emission from enteric fermentation and manure management are summarized in Table 1.4 B, C.

Step 3. Multiply the subgroup emission factors by the subgroup populations to estimate subgroup emission, and sum across the subgroups to estimate total emission (Table 1.4 D, E).

Step 4. Sum emission estimates from enteric fermentation and manure management to obtain total emissions due to livestock production.

Estimation of methane emissions from enteric fermentation and manure management using IPCC default emission factor (taken from the 2006 IPCC guidelines and are based on regional defaults for Africa and developing countries) and livestock population (head of livestock) in Kenya in 2010. Livestock populations were obtained from the Ministry of Livestock and are summarized the NCCAP 2012.

<table>
<thead>
<tr>
<th>Livestock type</th>
<th>No of animals</th>
<th>EF for enteric fermentation</th>
<th>EF for manure management</th>
<th>Emissions from enteric fermentation</th>
<th>Emissions from manure management</th>
<th>Total annual emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D=A x B</td>
<td>E = A x C</td>
<td>F = (D+E)/10^6</td>
</tr>
<tr>
<td>Cattle</td>
<td>17,862,852</td>
<td>40</td>
<td>1</td>
<td>7,145,140.800</td>
<td>178,628.52</td>
<td>7.324</td>
</tr>
<tr>
<td>Sheep</td>
<td>17,562,105</td>
<td>5</td>
<td>0.15</td>
<td>878,105.250</td>
<td>26,343.157</td>
<td>0.904</td>
</tr>
<tr>
<td>Goats</td>
<td>28,174,158</td>
<td>5</td>
<td>0.17</td>
<td>1,408,707.900</td>
<td>47,896.0686</td>
<td>1.457</td>
</tr>
<tr>
<td>Pigs</td>
<td>347,413</td>
<td>1</td>
<td>1</td>
<td>3,474,130</td>
<td>3,474.13</td>
<td>0.007</td>
</tr>
<tr>
<td>Chicken</td>
<td>30,398,033</td>
<td>0</td>
<td>0.02</td>
<td>0.000</td>
<td>6,079.6066</td>
<td>0.006</td>
</tr>
<tr>
<td>Sub-total s</td>
<td></td>
<td></td>
<td></td>
<td>9,435,428.08</td>
<td>262,421.482</td>
<td>9.697</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Further reading


Glossary of terms

**Aerobic conditions**: conditions with oxygen present

**Activity data**: data on the magnitude of human activity resulting in emissions or removals taking place during a given period of time

**Allometric equation**: an equation that predicts tree biomass on the basis of easily measurable parameters such as diameter at breast height

**Ammonia volatilization**: the loss of nitrogen as ammonia gas from the soil surface following application of manures and urea fertilizers. The reaction is driven by the urease enzyme

**Anaerobic conditions**: conditions with low levels of (or no) oxygen

**Biomass**: the total weight of living material in plants expressed as oven-dry weight per unit area

**Bulk density**: the dry weight of soil per unit volume of soil, including pore spaces

**Carbon dioxide equivalent or “CO$_2$-e”**: is a term for describing different greenhouse gases in a common unit. A quantity of GHG can be expressed as CO$_2$e by multiplying the amount of the GHG by its global warming potential

**Carbon dioxide**: a greenhouse gas produced by burning carbon and organic compounds and by respiration

**Carbon flux**: the process by which carbon moves from one pool to another. For example, carbon moves from the atmosphere to plants through photosynthesis and it can move back from plants to the atmosphere through plant or soil respiration during decomposition or when fire burns the plants

**Carbon pool**: any place where carbon can be found, such as plants, the atmosphere, or soil. A carbon pool has capacity to accumulate or release carbon

**Carbon stock**: the amount of carbon held within a pool at a specified time

**Climate change mitigation**: activities aimed at reducing greenhouse gas emissions and/or removal of CO$_2$ from the atmosphere

**Climate smart agriculture**: agricultural practices that sustainably increase productivity and system resilience while reducing greenhouse gas emissions

**Denitrification**: process by which soil organisms convert nitrate to nitrous oxide and nitrogen, which is then lost to the atmosphere. It occurs predominantly in water logged soils

**Emission factor**: the average emission rate of a given GHG for a given source, relative to units of activity

**Enteric fermentation**: microbial processes occurring in the rumen to convert feed carbohydrate to useable forms, mainly volatile fatty acids, with methane produced as a bi-product

**Global warming potential**: the relative global warming effect of a unit mass of gas compared with the same mass of carbon dioxide over a specified period. Multiplying the actual amount (in grams) of gas emitted by its global warming potential gives the emissions in terms of carbon dioxide equivalence

**Greenhouse gas**: any gas compound in the atmosphere that is capable of absorbing infrared radiation, thereby trapping and holding heat in the atmosphere
**Methane**: a greenhouse gas produced from enteric fermentation and manure management

**Methanogenesis**: the formation of methane by microbes known as methanogens. It takes place in the absence of oxygen

**Nitrification**: processes by which soil organisms use oxygen to convert ammonium ions to nitrite ions and nitrite ions to nitrate ions

**Nitrous oxide**: a greenhouse gas largely produced by fertilizer use, land clearing, burning of biomass, and some industrial processes

**Root-to-shoot ratio**: the dry weight of root biomass divided by dry weight of shoot biomass.

**Ruminant**: Herbivore with an expanded foregut consisting of several stomach compartments before the intestine. Sheep and cattle have a four-component stomach; the first is termed the rumen

**Sequestration**: the process of removing carbon from the atmosphere and storing it in a reservoir e.g. into other pools, such as plant biomass via photosynthesis or into soils from decaying plant and animal matter. It can also be termed as removal of CO₂

**Sink**: a process or mechanism which removes a greenhouse gas from the atmosphere. A given pool (reservoir) can be a sink for atmospheric carbon if, during a given time interval, more carbon is flowing into it than is flowing out

**Soil carbon**: carbon stored within the soil. It is also known as soil organic carbon. Soil carbon is the largest terrestrial pool of carbon

**Source**: any process or activity that releases a GHG (such as CO₂ and CH₄) into the atmosphere. A carbon pool can be a source of carbon to the atmosphere if less carbon is flowing into it than is flowing out of it