Chapter 2
Considerations When Estimating Greenhouse Gas Fluxes in Agriculture and Forestry

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Acronyms, Chemical Formulae, and Units

CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalents
CrIS	Cross-track Infrared Sounder
FIA	Forest Inventory and Analysis
FTIR	Fourier transform infrared
GHG	greenhouse gas
GWP	global warming potential
HMTLS	handheld mobile terrestrial laser scanning
HWP	harvested wood products
IPCC	Intergovernmental Panel on Climate Change
LiDAR	light detection and ranging
N_2O	nitrous oxide
NAIP	National Agriculture Imagery Program
NH_3	ammonia
NO	nitric oxide
OpTIS	Operation Tillage Information System
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PDF	probability density function
SF_6	sulfur hexafluoride
STLS	static terrestrial laser scanning
sUAS	small unmanned aerial system
TDL	tunable-diode laser
TROPOMI	TROPOspheric Monitoring Instrument
UAS	unmanned aerial system
USDA	U.S. Department of Agriculture

2. Considerations When Estimating Greenhouse Gas Fluxes in Agriculture and Forestry

The methods provided in this report depend on standard definitions and common estimation elements for all emission sectors. This standardization ensures that landowners or managers can accurately inventory their direct greenhouse gas (GHG) emissions and removals and make comparisons across years; management practices; or farms, ranches, or forests. This chapter provides standard definitions, explains the steps in the estimation process, and provides other information to help landowners and managers understand the estimation elements to include and the methods to use.

2.1 Standard Definitions

2.1.1 Entity

The methods in this report allow GHG source and sink quantification at an entity scale. For this report, an entity is defined as all activities occurring on all tracts of land under the ownership and or management control—now and for the foreseeable future—of a farm, ranch, forest landowner or manager.

This is not a policy or regulatory definition; it is provided to help the landowners and managers determine what practices they should include in their GHG estimations. The definition is intentionally broad and will depend on the landowner's input data for the estimation methodologies. Any policy, registry, or market will provide its own, narrower definition.

2.1.2 Emissions and Sinks

This report uses "emissions," and some related terms, as follows:

- **Emissions:** The calculated total mass of GHG released over a specified period. Emissions can be direct or indirect. Direct emissions are caused by an entity's activities—for example, manure managed in solid storage stacks produces direct nitrous oxide emissions. Indirect emissions are caused by the activity but removed by space or time—for example, nitrogen volatilization and subsequent deposition, or leaching and runoff of manure, produces indirect nitrous oxide emissions.
- **Carbon dioxide (CO_2) equivalents:** GHG emissions are often presented in units of CO_2 equivalents (CO_2-eq), calculated by multiplying the amount of a GHG by its global warming potential (see section 2.2.4.1).
- **GHG sequestration, sinks, and removals:** Sequestration is the process of removing GHG from the atmosphere through capture and storage. For this report, GHG removals are the calculated total mass of GHG removed from the atmosphere. (In the context of forest management, "removals" can also refer to the volume of trees felled or removed from the forest during a timber harvest or treatment, but for this report refers to the mass of GHG removed from the system in question.)
- **Flux:** The change in GHG mass within system boundaries (see section 2.2). GHG flux is normally reported for discrete time steps—such as annually, daily, or hourly—in negative numbers (indicating removals/sequestration) or positive numbers (indicating emissions).

- **Carbon stock:** The mass of carbon stored at a given time in a carbon pool (including aboveground biomass, belowground biomass, dead wood, litter, and soil organic and mineral carbon pools).

2.1.3 Activity and Ancillary Data

All of this report's technical chapters describe the activity data needed to estimate GHG emissions or carbon removals. Activity data include data on the magnitude of a human activity resulting in emissions or removals taking place during a given period (IPCC, 2019). Some available methodologies or approaches to collect activity data are presented in appendix 2-A.

Ancillary data are additional data needed to support the selection of activity data and emission factors. Examples of ancillary data include temperature, precipitation, elevation, and soil nutrient levels from references.

2.1.4 Emission and Removal Factors

An emission or removal factor is a coefficient that provides quantitative estimates of emissions or removals of a gas per unit. Emission and removal factors reflect the net flux of GHGs associated with a land-use transition or management activity. For example, for forest clearing, the emission factor is the summation of the carbon emitted from all included carbon pools for the type of forest cleared. An emission factor describes emissions (i.e., total carbon emitted during a deforestation event), whereas a removal factor describes removals/sequestration (i.e., carbon accumulated through a forest management activity).

Emission or removal factors may be derived from existing sources, such as published literature and emission factor databases (e.g., the Intergovernmental Panel on Climate Change [IPCC] Emission Factor Database[1]), or developed from inventories. The latter approach calls for comprehensive, regular field sampling using locally calibrated models, which can be a large commitment of resources and time. When choosing emission or removal factors, an entity should balance needs for precision, accuracy, and lower uncertainty (see section 2.1.5) with costs and long-term goals for GHG accounting. In most cases, emission and removal factors are used in more simplified estimation methodologies (such as IPCC Tier 1 or Tier 2), not more advanced (IPCC Tier 3) ones.

2.1.5 Uncertainty, Accuracy, and Precision

IPCC (2019) provides the following definitions:

- **Uncertainty:** Lack of knowledge of the true value of a variable that can be described as a probability density function characterizing the range and likelihood of possible values. Uncertainty depends on the analyst's state of knowledge, which in turn depends on the quality and quantity of applicable data as well as knowledge of underlying processes and inference methods.
- **Accuracy:** A relative measure of the exactness of an emission or removal estimate. Estimates should be accurate in the sense that they are systematically neither over nor under true emissions or removals, so far as can be judged.
- **Precision:** Closeness of agreement between independent results of measurements obtained under stipulated conditions. Better precision means less random error.

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[1] https://www.ipcc-nggip.iges.or.jp/EFDB/main.php

2.2 System Boundaries

System boundaries define the scope of GHG estimation. The boundaries are critical to the interpretation of results and define important aspects of the analysis (e.g., number of management practices, number of GHGs, timeframe, geography). Entities should consider four types of system boundaries, which are discussed in the following sections.

System boundaries should include the GHG emissions and carbon sequestration occurring (or established) onsite for the source category and management practice in question. For example, this report does not address indirect offsite land-use changes or biogenic GHG flux related to subsequent use of agricultural or forestry outputs (e.g., food processing, pulp and paper manufacture, biomass combustion). However, it does address certain offsite carbon storage considerations (e.g., flow of harvested wood into harvested wood products, or HWPs) to maintain consistency with national inventory efforts.

2.2.1 Physical Boundaries

The physical boundary is the geographic area in which project activities take place. Physical boundaries address the area and the management practices to consider in estimations. Because there can be a number of scenarios for setting boundaries for emissions and sequestration estimation, clarity, and consistency are important. For example, consider answers to the following questions when defining physical boundaries:

- What constitutes an entity or a farm/ranch/forest operation?
- What activities are associated with that entity? For example, does fertilizer use on a farm include manufacturing processes and fertilizer delivery?
- How should a larger entity with multiple land uses (such as grazing land and cropland) within its boundaries be subdivided?
- How should management practices be associated with the most relevant methods (including any guidance on size limits, what constitutes management, and how to address changing land uses)?

Within the boundaries of an entity, there may be areas of cropland, grazing land, animal production, forestland, wetlands, settlements, and/or other land. The physical boundaries of each of these emission sectors must be identified.

2.2.1.1 Cropland Physical Boundaries

Croplands are areas used for producing adapted crops for harvest, including:

- Cultivated and noncultivated land
- Agroforestry area (e.g., alley cropping, windbreaks) where the primary activity is crop production
- Land that is fallow or set aside, such as lands in a conservation reserve program
- Areas of hay and pasture that are managed in a rotation with other crops
- Wetlands (including drained wetlands and hydric soils) where the primary activity is crop production

General guidance for delineating cropland physical boundaries:

- Delineate areas of cropland, roads, and railroads.
    - Evaluate areas of cropland as fields or groups of fields for which the basic rotations and management practices are similar. Use the methods in chapter 3.
    - Consider roads and railroads through the cropland as settlements and exclude them from the cropland area.

2.2.1.2 Grazing Land Physical Boundaries

Grazing lands are areas primarily used for grazing animals (not as part of a rotation with other crops). The plant cover is composed principally of grasses, grass-like plants, forbs, or shrubs suitable for grazing and browsing. Grazing lands may include:

- Pastures or native rangelands
- Savannas, tundra, or deserts
- Woody plant communities of low forbs and shrubs that do not meet the criteria for forestland
- Land managed with agroforestry practices (e.g., silvopasture) where the stand or woodlot does not meet the criteria for forestland and where the primary tract of land is used for grazing livestock
- Some wetlands (including drained wetlands and hydric soils) where the primary tract of land is used for grazing livestock

General guidance for delineating grazing land physical boundaries:

- Delineate areas of grazing land, roads, and railroads.
    - Delineate grazing lands with similar stocking rates and management practices as contiguous areas. Use the methods in chapter 3.
    - Consider roads and railroads through the grazing land as settlements and exclude them from the grazing land area.
- For grazing animals, follow the relevant methods in chapter 4.
- Integrate methods where lands match the definition for both grazing land and forestland. For example, if any active management is focused on enhancing tree growth and timber production, identify these areas as forestland and integrate the methods to account for the impact of grazing management on the forestland.

2.2.1.3 Animal Production Physical Boundaries

Animal production systems raise animals to produce commodities for human consumption (e.g., meat, milk, eggs, wool). Although animal production is not necessarily a spatially defined activity, it must be considered as part of the physical boundary of the operation. Areas to consider are:

- Emissions from the animals themselves through enteric fermentation
- Emissions from housing
- Emissions from the management of manure

Be aware that GHG emissions from animal production vary greatly depending on species, growth stage, diet, and manure storage and management. Timing is also a challenge because emissions per animal change dramatically as a young animal grows and matures, as feedlot cattle are finished, or as dairy cows cycle between gestating and lactating.

General guidance for delineating animal production physical boundaries:

- Use the methods for animal production in chapter 4.
- In most cases, it may be necessary to estimate emissions for a herd using average weight, average age, and other representative characteristics.
- In other cases, it will be necessary to generalize by seasons. For example, manure management can be different in winter than summer.
- Apply assumptions consistently across the herds and timeframes.
- In some cases, such as for manure applied to cropland under the ownership and or management control of the entity, chapter 3 methods will also be relevant.

2.2.1.4 Forestland Physical Boundaries

Forestlands are lands that are at least 120 feet (36.6 meters) wide and 1 acre (0.4 hectare) in size with at least 10 percent tree crown cover (or equivalent stocking level) and trees able to reach at least 6.6–16.4 feet (2–5 meters) at maturity in situ, including land that formerly had such tree cover and that will be naturally or artificially regenerated.

Forestland can include:

- Closed (trees of various stories and undergrowth covering much of the ground) or open (continuous vegetation cover in which tree crown cover exceeds 10 percent) forest formations
- Land primarily used for woody biomass production or that is tree-covered and managed for recreational or conservation purposes
- Agroforestry and silvopasture areas where the primary management objective is forest-related production
- Wooded or forested wetlands managed primarily as forests and woodlands
- Managed systems, such as woodlots and plantations

General guidance for delineating forestland physical boundaries:

- Follow the forestland methods in chapter 5.
- Delineate areas of forestland, unimproved roads and trails, streams, and clearings in forest areas.
  - Evaluate areas of unimproved roads and trails, streams, and clearings in forest areas wider than 120 feet (36.6 meters) or larger than 1 acre (0.4 hectares) as settlements and exclude them from the forestland area.
  - If areas of forestland are in an urban setting, evaluate them as settlements.
- Delineate forest tracts so that each one includes trees of a similar stand age and species mix and the entire entity is under one uniform set of management practices.
- If an entity includes trees outside clearly defined forests (such as orchards, vineyards, farmstead shelterbelts, and field windbreaks), it may be useful to blend methods (for

example, cropland methods from chapter 3 and forest methods from chapter 5) or evaluate individual trees or small stands of trees using chapter 5 methods.

- Account for emissions from HWPs, even though they may be moved outside the operation boundary, since harvested wood moves through several long-term carbon pools at differing rates of decay.

2.2.1.5 Wetland Physical Boundaries

Wetlands are areas with hydric soils, native or adapted hydrophytic vegetation, or a hydrologic regime where the soil is saturated during the growing season in most years. They can include:

- Swamps, marshes, bogs
- Undrained forested wetlands, grazed woodlands and grasslands, impoundments managed for wildlife, and lands being restored to a wetland after conversion to a nonwetland condition
- Engineered wetlands (e.g., stormwater detention ponds, constructed wetlands for water treatment, farm ponds, or reservoirs)
- Riparian areas of natural lakes and streams

General guidance for delineating wetland physical boundaries:

- If a wetland area has been included in one of the other categories, its management will be captured in the estimation for that category. If not, identify the area as either a managed wetland or a natural, unmanaged wetland and use chapter 6 methods.
- Do not include natural, unmanaged wetlands—that is, naturally occurring wetlands that are not being actively managed to increase productivity or provide other environmental services. Categorize these wetlands as “other lands” as defined below.
- Use the chapter 6 estimation methods for emissions from palustrine wetlands influenced by management options such as water table management, timber or other plant biomass harvest, and management with fertilizer applications.

2.2.1.6 Settlements Physical Boundaries

Settlements are areas of developed land consisting of units of 0.25 acres (0.1 hectares) or more, including two broad categories:

- Land where the entity manager imposes management decisions (e.g., livestock feed yards, dairy barns, poultry houses, manure piles)
- Land where the manager does not regularly impose management decisions that affect carbon balances (i.e., homes, yards, driveways, workshops, roads, railroads, and parking areas).

Guidance for delineating settlements physical boundaries:

- Include only the areas with GHG flux implications.
    - Use the livestock and manure management methods presented in chapter 4 for animal production areas.
- Do not include areas without GHG flux implications, such as homes, yards, driveways, workshops, roads, railroads, and parking areas.

2.2.1.7 Other Land Physical Boundaries

Any land that is actively managed in a way that affects biomass growth or otherwise affects production-related GHG emissions should have been captured within the boundaries defined for the land-use categories listed above. Categorize any remaining land as “other lands” or “unmanaged land,” and do not consider them in the estimation. Other lands can include:

- Wetland and developed areas without active management (e.g., unmanaged wetlands and unmanaged settlements)
- Other areas within the entity boundary that represent barren, mined, abandoned, or otherwise unmanaged land (e.g., bare soil, rock, ice)

Land cover change is a variation from year to year in what is growing on a parcel of land, such as rotating corn and soybean crops, and is not considered land-use change. Do not consider land cover changes in the GHG estimation.

In contrast, land-use change is a fundamental shift in purpose or production of a parcel. Land-use change should be accounted for in the GHG flux estimate. Land-use change can include the following events:

- Part of a cropland field is converted to an animal feedlot.
- Shelterbelt or riparian trees are planted onto former cropland.
- Abandoned land reverts to grazing land or forestland cropping.
- Cropland reverts to forest production or vice versa.

Guidance for delineating land use physical boundaries:

- Use the methods in chapter 7 to account for land-use change in the annual GHG flux as the impact (either positive or negative) on biomass and soil carbon.
- Identify parcels where the land use has changed. This may require delineating new parcel boundaries or dissecting one parcel into several parcels with more than one management strategy.

2.2.2 Temporal Boundaries

The temporal boundary is the timeline in which the activity is taking place. It is important to account for short- and long-term management decisions that have implications for carbon balances and address the movement of spatial boundaries over time and with land-use changes. The methods in this report provide a means of annual accounting and reporting of GHG fluxes. Annual changes are easy to quantify for some emissions, but more difficult for others. For example, it may be necessary to estimate carbon stored in trees over a longer period and then convert the change to an annualized estimate.

Box 2-1. Temporal Scale

The report methodologies assume an accounting period of 1 calendar year (i.e., 365 days) when estimating annualized emissions in a particular sector or source category.

Management decisions also affect the accounting time horizon. For example, a forest management plan might call for timber harvest. In the harvest year, the annual accounting will reflect a loss of standing live and/or standing dead carbon stocks, yet the longer-term management strategy could cause a net increase in total carbon stocks.

A manager might also take corrective action or temporarily deviate from a long-term management plan. For example, a cropland manager might have adopted a no-till management strategy, but after several years need to use tillage for 1 year because of weather, pests, or other extenuating circumstances. In this case, the methods used should be sensitive enough to capture the GHG impact of the management plan deviation.

2.2.3 Activity Boundaries

Activity boundaries distinguish which activities within an entity are subject to GHG accounting. The accounting in this report focuses on land-based activities such as tillage and harvesting, not on GHG emissions related to fossil fuel use. Thus, emissions from tractor fuel or fuel used in crop drying are not counted, nor are the energy inputs required to manufacture fertilizer or farm tools or to heat farm buildings. The activity boundaries do not include emissions from fossil fuel use.

Methods in this report do not constitute a life cycle assessment. The exception is the chapter 5 HWP method, which includes stages of HWPs from forest harvesting to product manufacturing.

2.2.4 Material Boundaries

Material boundaries define which materials—for this report, which GHGs—are considered in the estimate. It is important to determine initially which gases are included and which are not. It is also important to determine how much freedom the user has in where these boundaries lie to ensure that a management change that reduces emissions in one sector does not inadvertently cause emissions to increase outside the reported boundaries.

2.2.4.1 Global Warming Potentials

Global warming potentials (GWPs) are important when considering GHGs. Warming potential correlates to how much heat the molecules absorb in the atmosphere, which drives climate change. A GWP is a ratio: the radiative forcing (or heating effect) that would result from the emission of 1 ton of a gas, over a defined period, versus the forcing from the emission of 1 ton of CO_2 over the same period. In this report, the defined period is 100 years and the GWP is the energy 1 ton of a gas will absorb over 100 years, relative to 1 ton of CO_2.

Multiplying the mass of a GHG by its GWP produces results in units of CO_2-eq. While CO_2 has a GWP of 1, methane (CH_4) is more potent and nitrous oxide (N_2O) is significantly more potent; see table 2-1 for GWP values applied in this report. These GWPs are from the IPCC Fifth Assessment Report (IPCC, 2013). Note that policies, registries, or markets may use other GWPs.

Table 2-1: Global Warming Potentials Used in the Report

GHG	Chemical Formula	Lifetime (Years)	GWP[a]
Carbon dioxide	CO_2	Variable	1
Methane	CH_4	12.4	28
Nitrous oxide	N_2O	121	265

[a] Source: IPCC (2013). GWPs used have a 100-year time horizon, in accordance with the IPCC Fifth Assessment Report (IPCC, 2013).

Emissions and removals of the main GHGs—CO_2, CH_4, and N_2O—are accounted for in the estimation methodologies for the croplands, grazing lands, wetlands, animal production, forestry, and land-use change sectors. This report presents emissions and sequestration values in terms of the mass (not volume) of each gas, using metric units (e.g., metric tons of CH_4).

2.2.4.2 Direct and Indirect Emissions

The methods in this report focus on the direct emissions resulting from management decisions made within the entity boundaries. Indirect emissions related to inputs into the entity are excluded from this report, since the manufacturer producing the inputs would account for them. There are notable exceptions involving cases when management decisions for an operation have a specific influence on emissions leaving the entity's boundary. For example, this report includes:

- Indirect nitrogen emissions within the operation that are carried offsite via volatilization, erosion, or leaching and contribute to N_2O emissions offsite.
- An assumption that grains or other agricultural commodities are consumed relatively quickly, resulting in no net gain or loss for GHG accounting. (HWPs are somewhat different: much of that harvest will end up in long-term carbon pools as structures, furniture, or other wood products or in landfills.)

2.3 Estimation Process Overview

2.3.1 Estimation Scenarios

Some entities may wish to develop basic estimates of the current management practices. For example, an entity might develop an entity-level GHG inventory. This estimate would represent the baseline or "business as usual" estimate. This scenario would have a set timeframe with current business practices defined and included.

Other entities may wish to use these methods to estimate emissions or GHG removals from practices that will be maintained over a period of time or from altering management practices.

2.3.1.1 "Basic" Estimate

This option serves the entity seeking to estimate the GHG flux from maintaining a current management practice. Maintenance is very broadly defined and can include no active management. This estimate would be the baseline scenario or status quo for a given entity. For example, a livestock producer would include the number of animals currently housed, the current diet and feed situation, as well as the current housing and manure management practices.

For a forest (see chapter 5), a basic estimate could describe a forest parcel maintained as a forest or even a planned harvest and subsequent changes or stored carbon over time. Typically, the baseline is the current carbon stock or the carbon stock at a specified prior year. However, in situations where the carbon stocks are changing, the baseline is computed over time as the forward-looking carbon stocks that would occur in the absence of the project or intervention.

2.3.1.2 Estimated Impact of a Management Change

To estimate the impact of a change in management practice, the entity manager needs to produce estimates for both the baseline scenario (see section 2.3.1.1 above) and the management scenario. The same method should be used for both estimates, recognizing there will be assumptions about the future for the management scenario. In the case of forests, assumptions on forest growth might be needed; these could be based on basic biological principles and historical monitoring of forest dynamics.

The difference between the two scenarios represents the net benefit from switching management practices.

2.3.2 Basic Steps for Estimation

Chapter 1 describes the general principles of GHG inventories and carbon accounting, but practically speaking there are four basic steps to estimating GHG fluxes using the methods in this report. These steps are described below.

2.3.2.1 Define the Project

The first step involves establishing which activities will be accounted for in the estimation, defining the boundaries in which these activities take place, and defining a baseline scenario that articulates what would most plausibly have happened in the absence of a planned activity or project intervention.

- **Identify activities.** One project may feature a range of activities, and it is important to clearly delineate them to set up separate accounting frameworks and consider interactions and potential for double-counting. The combined impact of these activities would be needed to estimate the net GHG flux. Examples:
    - An entity managing forested land that includes both new replanted area and the existing forest might consider methodologies for two “activities”: reforestation and extended rotation.
    - An entity implementing no-till may need to increase fertilizer use. Both activities need to be considered.
- **Define boundaries.** There are several types of boundaries to consider, as described in section 2.2.
- **Describe the baseline scenario.** The baseline represents the total GHG or carbon emissions or removals anticipated in the absence of the planned activity or project. The baseline should reflect the most plausible scenario for the absence of the planned project intervention. It is best practice to fully document the baseline scenario, articulating management practices and general conditions in the absence of the project intervention. See section 2.3.1 for details on estimation scenarios.

2.3.2.2 Decide on the Level of Accuracy and Precision, Assess Data Availability, and Identify Calculation Approach

The methods in this report accommodate a range of user needs, data availability, and GHG accounting experience. As such, the guidance allows for different desired levels of accuracy, precision, and accessibility while ensuring accounting consistency. However, consistency should not come at the expense of enhanced precision or methodological integrity. Improvements in accounting methods and data can be anticipated over time. Therefore, it is important to document assumptions made and data used so that estimates can be updated if new methods or data become available.

2.3.2.3 Collect/Assemble Data

Based on the chosen approach, collect or assemble data and quantify results. More detail can lead to more precise GHG estimates, but even broad generalizations can result in a GHG estimate. The objective is to obtain accurate, consistent estimates over time at a reasonable level of effort and cost. Depending on the method chosen, this could simply involve assembling basic information on the nature and area of planned activity—or it could require establishing a network of sample plots and collecting inventory data on key variables over time.

2.3.2.4 Produce Estimates

Using the appropriate method and required data, calculate the GHG flux estimate. Document the data, assumptions, methods, and boundaries used to develop the estimates to help ensure useful and credible results.

2.4 Chapter 2 References

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Appendix 2-A: Background Information on Field-Scale Carbon and GHG Detection Technologies

This appendix summarizes currently available and in-development field-scale carbon and GHG detection technologies. It puts these in three categories:

- Remote sensing techniques are primarily used to gather activity data used in emissions estimates but may also directly measure emissions using measurement techniques.
- Measurement techniques are used to directly measure emissions.
- Micrometeorological methods use environmental parameters and ultimately require mathematical equations to estimate emissions.

Note that this appendix is not intended to serve as a complete compendium of all technologies or techniques. It also does not compare the discussed technologies; these comparisons are available in other literature (e.g., U.S. EPA, 2018).

2-A.1 Remote Sensing

Remote sensing techniques use sensors at a distance (typically aboard satellites or aircraft) to acquire information. These techniques can be used to collect satellite images and aerial photographs that can provide information such as the presence and location of specific crops. In addition, they can be used to measure distances and temperatures. They can also directly detect and record atmospheric concentrations of GHGs.

Unmanned aerial systems (UAS) and small UAS (sUAS) are aircraft that are flown either remotely or autonomously. The use of UAS and sUAS for remote sensing allows for more precise data collection on a smaller scale. However, unlike satellites, UAS are limited by local air traffic restrictions (Shaw et al., 2021). UAS and sUAS can both use light detection and ranging (LiDAR) or aerial imagery technology (see sections 2-A.1.1 and 2-A.1.2).

The following subsections describe currently available and in development field-scale remote sensing techniques.

2-A.1.1 LiDAR

LiDAR uses a pulsed laser to measure distances to Earth (NOAA, 2021). A laser source emits light pulses, which reflect off objects of interest before returning to the system's sensor. LiDAR sensors can be mounted on satellites or aircraft (including UAS) or used in terrestrial applications.

LiDAR can be used to gather structural characteristics and data for agricultural and forestry applications (Lister et al., 2020). For example, it can be used for field mapping, monitoring forest canopy changes, determining soil types, and identifying grazing land. Airborne LiDAR has been used to map forested riparian buffers and quantify vegetation height, canopy cover, and corridor width to understand the impact of adjacent land use types (Wasser et al., 2014). LiDAR is used along with other data sources, such as Forest Inventory and Analysis (FIA) data. Together, LiDAR and FIA data can better estimate canopy cover, estimate tree heights, and inform models of forest volume or biomass and land cover class (Lister et al., 2020).

Static terrestrial laser scanning (STLS) can measure an entire environment from a fixed point using LiDAR. This method can be useful in forestry contexts to measure wood volume, tree height or diameter, and structural characteristics below the canopy, and to estimate biomass. Handheld mobile terrestrial laser scanning (HMTLS), developed for rough terrains, is an effective alternative to the time-consuming and costly STLS method. HMTLS has been demonstrated to be a precise, effective method for calculating tree diameter (Stal et al., 2021). A handheld LiDAR system has been used to measure grass heights, an indicator of growth conditions (Obanawa et al., 2020).

LiDAR can also be used to directly measure GHG emissions through integrated path differential absorption, which uses scattered laser signals from an aircraft or satellite to measure weighted vertical column concentrations of GHGs; these can then be converted into the emission rate (Kiemle et al., 2017).

As LiDAR develops further, it can improve data collection efforts and eliminate the need for certain manual measurements.

2-A.1.2 Digital 3D Aerial Imagery

Structure from motion (SfM) is a process for estimating a 3D image based on overlapping 2D images (Gatziolis et al., 2015; NOAA, n.d.). SfM is based on a type of algorithm—scale invariant feature transform—that automatically matches an object or land marker within photographs, even if the photographs vary in scale or angle, which is key to the overlapping that creates the 3D image (Gatziolis et al., 2015; Nissen et al., n.d.; Iglhaut et al., 2019). Because they provide higher temporal and spatial resolution than satellites, UAS can be used to derive 3D models of vegetation height and topography using SfM (Sankey et al., 2019). A UAS with a relatively basic camera can use SfM to provide an affordable alternative to terrestrial LiDAR (Gatziolis et al., 2015).

The National Agriculture Imagery Program (NAIP) aims to update the aerial imagery acquired during the U.S. growing seasons, produced about every 3 years (USDA, n.d.). Lister et al. (2020) describe how NAIP imagery is used in the Image-based Change Estimation project, which offers updates on land cover changes faster than during the FIA cycle (5 to 10 years).

2-A.1.3 Satellite Instrumentation

The Cross-track Infrared Sounder (CrIS) is a type of Fourier transform spectrometer designed to provide a vertical profile of Earth's atmospheric temperature and water vapor; it is currently onboard the Suomi National Polar-orbiting Partnership satellite (Bloom, 2001; O'Carroll and Leslie, 2012). CrIS also measures atmospheric gas concentrations: these gases absorb infrared light, which CrIS's sensor detects and translates to a concentration along the vertical path (Keesey, 2016). The sensor's data records are available for download (NOAA, 2018). Researchers have used CrIS data to verify modeled emissions estimates (Whaley et al., 2018).

The Phased Array type L-band Synthetic Aperture Radar (PALSAR) is one of three major remote sensing instruments on the Advanced Landing Observation Satellite (JAXA, 2008). It uses the L-band frequency (the microwave range) for day and night land observation (ASF, 2022; JAXA, 2008). NASA and the Indian Space Research Organization also have a synthetic aperture radar (called the NASA-ISRO SAR, or NISAR), with a 3-year mission, that operates in both L-band and S-band frequency and offers resolution of 3 to 10 meters (NASA, n.d.). Both of these instruments provide satellite imagery that can be used to identify forest cover and ultimately to estimate emissions. For example, Hamdan et al. (2016) described using PALSAR imagery to estimate the rate of deforestation and subsequent CO_2 emissions.

2-A.2 Measurement Technologies

Measurement technologies are chosen depending on the goals of the quantification as well as known underlying conditions and available resources.

2-A.2.1 Chamber Systems

The following sections describe enclosure-type measuring techniques in which the area or animal to be monitored is kept in an enclosure to allow for emissions measurements without influence of outside air. These systems can be disruptive to the environment, either to the animal or the normal state of the landscape where the measurements are taken.

Flux Chambers

Flux chambers are used to isolate emitting surfaces such as fields or pen surfaces to measure for gases such as CO_2, CH_4, N_2O, and nitric oxide (NO) (Oertel et al., 2016; Cole et al., 2018). Gas sensors such as gas chromatography or infrared spectrometry can be used with this method to analyze the samples (Oertel et al., 2016).

As described by Oertel et al. (2016), flux chambers can be nonflow or flow chambers:

- Nonflow, or closed, chambers can be either static or dynamic. In a static closed chamber, samples are taken from accumulated air in the chamber. In a dynamic closed chamber, samples are either analyzed externally before being pumped back into the system or analyzed inside the chamber continuously.
- In flow, or open, dynamic chambers, gas concentration is analyzed at the air inlet and outlet to calculate gas fluxes. Flow chambers are more expensive than nonflow chambers but are better in dry and hot conditions due to temperature and pressure gradients.

Wind Tunnels

Wind tunnels have been used to measure emissions from pens and retention ponds. The area to be monitored is partially enclosed, with the ends of the enclosure opened to allow for forced or natural air movement. The concentration of gases and the air flow rate are measured at both ends of the wind tunnel to calculate the flux rate. Typically, this practice is more suitable for comparing treatments or assessing relative emission rates than quantifying GHGs (Cole et al., 2018).

Respiration Chambers

Respiration chambers are used in measurements of enteric CH_4 from cattle, specifically to measure energy metabolism and gas production. Modern modifications to respiration chambers also allow the measurement of manure emissions (Chiavegato et al., 2015; Stackhouse-Lawson et al., 2013). In respiration chambers, a chamber houses the animal, the ducting and flow system, and the gas analyzer instruments (Arceo-Castillo et al., 2021). Open circuit, indirect systems are most common and involve the measurement of incoming and outgoing gas concentrations as negative pressure pulls air out of the chamber (Cole et al., 2018).

While this method allows for the accurate measurement of enteric emissions from individual animals, it limits the animal's activity and can only be used for short periods. Animals also need training and may have a smaller dry matter intake than in normal situations (Cole et al., 2018).

A less expensive option for respiration chambers is the head-box system. A system used by Ortega et al. (2020) includes a pen for the animal that allows for feeding, air circulation, manure collection, and gas collection. GreenFeed, a brand of head-box systems, has a chamber that takes gas measurements when the animal places its head inside to eat (C-Lock, 2022). Typically, the feed is provided in small quantities to encourage animals to provide multiple measurements each day (Hristov et al., 2015). The system provides a summarized report for calculated CH_4 and CO_2 fluxes (C-Lock, 2022).

2-A.2.2 Open-Path Analyzers

Open-path analyzers, such as infrared spectrometers, have been used in agricultural contexts. These analyzers use light beams to measure gas concentrations as an average over the path of the light (Cole et al., 2018). With this method, continuous, real-time measurements are possible in the field because the instruments are portable. However, these instruments often need careful maintenance and calibration (Cole et al., 2018).

Infrared absorption spectroscopy requires instrumentation to cause molecules to vibrate (radiation source), ultimately absorb light, and transform and process that signal (detector and processer) (Chair and Secretary, 2017). Common instruments that use infrared spectroscopy are:

- A Fourier transform infrared (FTIR) spectrometer provides real-time measurements of gaseous compounds using an infrared beam emitted from a mounted instrument (U.S. EPA, 2018). One benefit of FTIR spectroscopy is that multiple gaseous compounds can be monitored at the same time (U.S. EPA, 2018).
- A tunable-diode laser (TDL) absorption spectroscopy instrument relies on diode lasers for the light source and can be used in meteorological methods to estimate concentrations of gaseous species (Pattey et al., 2004; Edwards et al., 2003). TDL is highly sensitive, provides a fast sampling rate, and has been used to analyze for N_2O and CH_4 over agricultural fields (Pattey et al., 2004). TDL is generally used when only one or two compounds are targeted and is limited to a relatively small list of compounds that can be measured (U.S. EPA, 2018).

2-A.2.3 Sulfur Hexafluoride (SF_6) Method

The SF_6 method can be used to measure enteric CH_4 emissions from individual cattle. A cylindrical tube with permeable walls releases SF_6 at a predetermined rate into an animal's rumen, and the gases released from the animal's nostrils are collected via tubing attached to mounted canisters. When the canisters are full, they are removed and analyzed for CH_4, CO_2, and SF_6 using gas chromatography and electron capture and flame ionization detectors (Grainger et al., 2007). With the SF_6 method, animals have a near-normal environment. However, background gas concentrations in barns can affect the results (Cole et al., 2018). One study recommended using the SF_6 method for grazing cattle (McGinn et al., 2006).

2-A.3 Micrometeorological Methods

Micrometeorological methods use climate parameters—temperature, wind speed and direction, net radiation—and mathematical equations to quantify emissions (Cole et al., 2018; Hicks and Baldocchi, 2020). These methods rely on the basic concept of atmospheric gas molecules' eddying motion behavior (Hicks and Baldocchi, 2020; Zaman et al., 2021). Implementing these methods requires measurements of the applicable climatic parameters, including atmospheric gas concentration (Cole et al., 2018). Therefore, these methods often need equipment such as the following (Hicks and Baldocchi, 2020; McGinn et al., 2006; Nelson et al., 2017):

- Open-path analyzers (see section 2-A.2.2) or another way to measure gaseous concentration or estimate fluxes
- Retroreflector to terminate the laser path and return the light to a receiver (U.S. EPA, 2018), if needed (depends on the instrument configuration)
- Climate parameter sensors, which must typically take measurements at the same spatial and temporal plane:
    - Anemometers to measure the speed and direction of the wind
    - Temperature sensor/gauge
    - Net radiometer to measure net radiation
    - Hygrometer to measure humidity
- Canister or tube for gas storage
- Computer and software to collate sensor data
- Power source(s) to power all equipment

The physical setup for the method depends on the theory of the method, equipment needed, and chosen location. Some methods need measurements at two different heights if they depend on the vertical changes within an air column (Nelson et al., 2017; Zaman et al., 2021). Direct micrometeorological techniques do not disturb vegetation or soil or animal habits, unlike other methods (e.g., respiration chambers); however, they can be expensive and more difficult to replicate given the relatively large land area they need (Cole et al., 2018).

Note that the following sections do not include the whole range of micrometeorological methods. Several other methods may be more appropriate for studies or projects, given the goals and limitations or project setup.

2-A.3.1 Modified Bowen Ratio

The modified Bowen ratio, or Bowen-ratio energy balance, is a commonly used flux gradient micrometeorological method with a relatively simple theoretical basis and less complex equipment (Wolf et al., 2008; Meyers and Baldocchi, 2005). The measurement of vertical differences is used to determine air-surface exchange rates and fluxes. This method has been used to measure CO_2 fluxes for till and no-till crop management systems (O’Dell et al., 2014). Air intake boxes at two different heights recorded temperature, humidity, and CO_2, measured with a nondispersive infrared gas analyzer (O’Dell et al., 2014).

2-A.3.2 Eddy Covariance (Flux Tower)

Eddy covariance is a direct micrometeorological method that requires measurements of wind speed, wind direction, and gas concentrations to ultimately determine average flux density (Baldocchi, 2014; Kumar et al., 2017). Parameters include (Meyers and Baldocchi, 2005):

- Vertical velocity
- Molar density
- Time
- Eddy flux measurement height
- Vertical distance
- Molar mixing ratio (of the gas) relative to dry air

Practical application for quantifying emissions typically uses a tower, or a pair of towers. The technique requires rapid measurements, so fast sensors are critical (Harper et al., 2011). Measurements are most accurate in a steady atmosphere, with homogeneous underlying vegetation and flat terrain. This is conducive to determine the flux over a large agricultural area. Typically, sensors in eddy covariance systems analyze for CO_2, CH_4, and N_2O gases (Kumar et al., 2017).

Several hundred flux measurement sites globally, including FLUXNET,[2] provide widespread data (Baldocchi, 2014).

2-A.3.3 Integrated Horizontal Mass Flux

Integrated horizontal flux is a mass balance method that can be used to estimate the rate of gas transfer from the ground to the atmosphere. However, it is a limited technique that does not take into account turbulent flux, like eddy covariance. Parameters include (Harper et al., 2011):

- Wind speed and direction
- Gas concentration
- Height (from the ground to the top of the gas plume)

The method is generally limited to smaller plots and also assumes emissions from the source are uniform (Harper et al., 2011; Todd et al., 2006). Todd et al. (2006) used integrated horizontal mass flux to estimate NH_3 flux from a simulated feed yard situation, focusing on small 10-meter-wide circular plots.

2-A.3.4 (Relaxed) Eddy Accumulation

The eddy accumulation method estimates the vertical flux of gas using two canisters for up- and downdrafts. The relaxed eddy accumulation method builds on this, but the sample is collected at a constant volume rate rather than with proportional sampling. This method does not need fast-response sensors for either rate, unlike eddy covariance (AMS, 2012; Hicks and Baldocchi, 2020). On the other hand, it is more labor-intensive than methods like eddy covariance (Nelson et al., 2017). It has been used to measure NH_3 fluxes (due to fertilizer application) over a corn canopy (Nelson et al., 2017). Parameters include (Harper et al., 2011; Nelson et al., 2017):

- Wind speed and direction
- Temperature sensor
- Gas concentration of both updrafts and downdrafts (two canisters)

2-A.4 Data Sources and Tools

Below are brief descriptions of known data sources and tools (hybrid methods), which may be used in conjunction with the methods described above.

2-A.4.1 Operation Tillage Information System (OpTIS)

OpTIS uses satellite-based remote sensing data to monitor conservation practices using maps of tillage, residue cover, winter cover, and soil health practices (CTIC, 2022). The system uses farm-field-scale data to perform calculations. OpTIS data are available for 2005 through 2019 for the U.S. Corn Belt, an area that—as of December 2021—includes Illinois, Indiana, and Iowa, as well as parts

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[2] FLUXNET is a network of regional eddy covariance measurements to aid data exchange (U.S. DOE, 2021).

of Kansas, Kentucky, Michigan, Minnesota, Montana, Nebraska, Ohio, Oklahoma, South Dakota, Tennessee, and Wisconsin.

2-A.4.2 Landsat

Landsat is a series of U.S. satellites that collect Earth observations, which can be used to detect and measure land cover/land-use change, evaluate the health of ecosystems, and determine water availability (NASA, 2022). The most recent Landsat was equipped with sensors in the visible, near-infrared, short wave, and thermal infrared to collect moderate-resolution measurements of Earth (Roy et al., 2014; NASA, 2022).

The remote sensing data collected from Landsat can be used in agriculture and forestry applications. Landsat data were used to compare high-resolution maps of forest cover from 2000 to 2012 to understand how forests have changed on a global scale, allowing the study to be spatially explicit and determine annual trends in gross forest losses and gains (Hansen et al., 2013). Imagery from Landsat has been used since 1972 to monitor croplands. Field conditions can be identified using zone-mapping to aid in field-level management and increase crop yields (Leslie et al., 2017).

2-A.4.3 Sentinel Data

The European Space Agency’s Earth observation program, Copernicus, has a series of satellite missions called Sentinels for land, ocean, and atmospheric monitoring. The TROPOspheric Monitoring Instrument (TROPOMI) is an imaging spectrometer that monitors greenhouse gases aboard the Sentinel-5P (ESA, 2022a). Sentinel-1 can classify forest types, map forest fire scars, and estimate biomass for forest applications, as well as monitor croplands, crop conditions, and soil degradation for agricultural applications (ESA, 2022b).

2-A.4.4 Planet Data

Planet is a privately owned company that provides daily satellite RGB (red-green-blue) composite images and near infrared images to customers for applications in defense, agriculture, and forestry. Planet has deployed a series of nanosatellites called constellations to allow for expansive coverage of Earth for daily image delivery (Planet Labs, 2022). Planet images combined with airborne LiDAR measurements have been used to develop a map of the aboveground tropical forest carbon stocks and emissions of Peru (Csillik et al., 2019).