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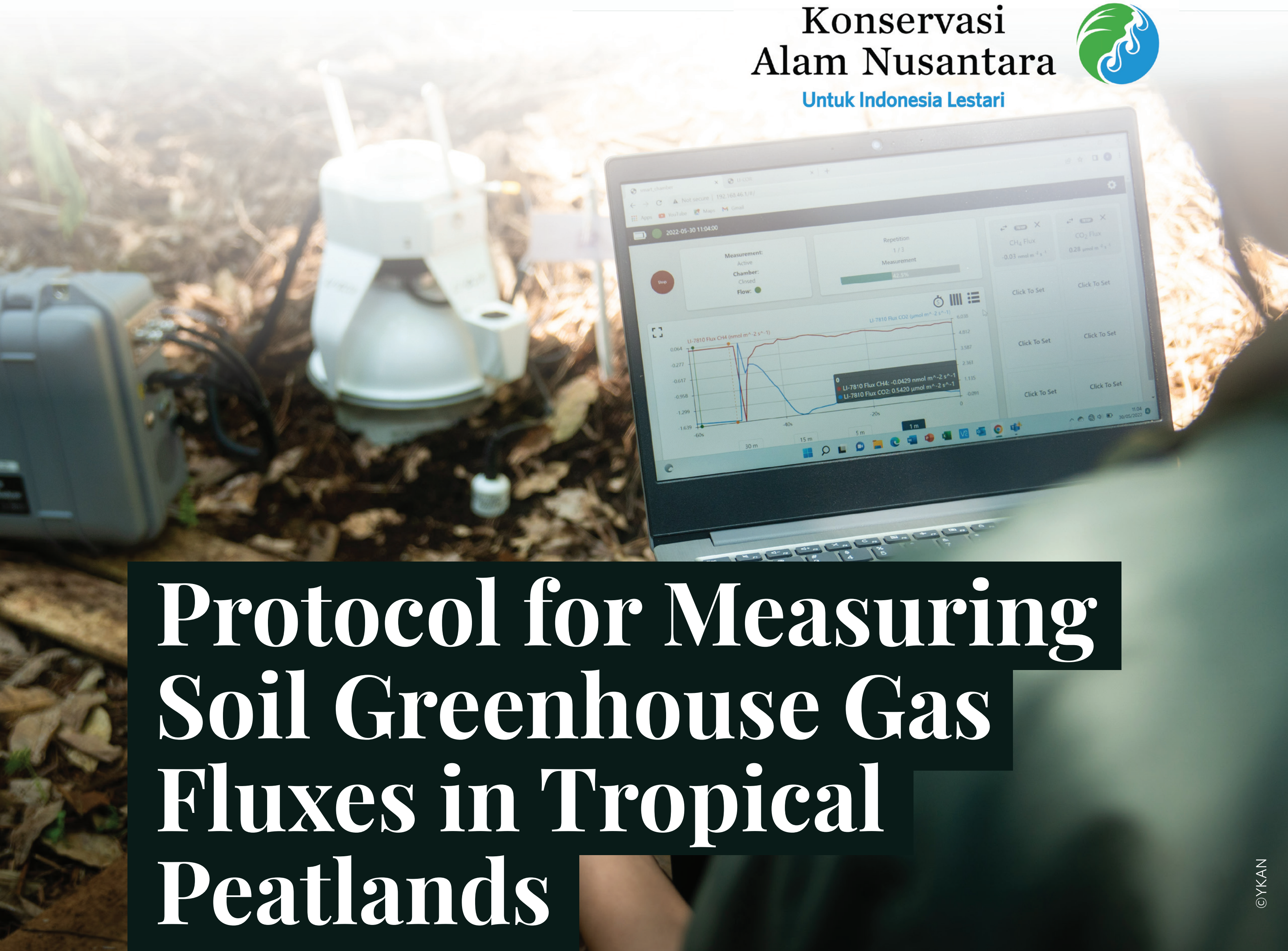

Protocol for Measuring Soil Greenhouse Gas Fluxes in Tropical Peatlands

Handbook

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Handbook | **Protocol for Measuring Soil Greenhouse Gas Fluxes in Tropical Peatlands**

Foreword

Peatlands — waterlogged ecosystems rich in soil organic matter — cover only three percent of the earth's surface yet store one-third of the world's soil carbon. They are some of the most underappreciated ecosystems on the planet and have been regulating climate, moderating water flow, and fostering biodiversity for millennia. Conversion and drainage from various development activities in the tropics put massive pressure on peatlands, potentially reversing their role from carbon sink to carbon source. For example, in South America, dam construction, infrastructure projects, oil and gas exploration, forest logging, and drainage for agriculture and pasture lands are some common threats. In Southeast Asia, particularly Indonesia and Malaysia, the development of smallholder and industrial plantations have been identified as the major source of peatland conversion. In Africa, peatlands are still relatively intact, yet that does not necessarily mean that they will be exempt from conversion, development, and other forms of disturbance in the future. Anthropogenic disturbances and the climate crisis threaten the function of peat and risk transforming them from carbon sinks to carbon sources.

This protocol is developed under the Natural Climate Solutions (NCS) – Peatland Playbook project, providing a step-by-step procedure to measure soil CO_2 and CH_4 fluxes from tropical peatlands. This manual serves to provide insight into how to conduct greenhouse gas (GHG) flux measurements across tropical peatlands using reliable approaches. In turn, it contributes to the growing body of work in tropical peatlands and provides the basis for generating comparable results, which will be valuable for decision-making processes. Methods proposed in this manual were developed from our on-the-ground experience using several portable GHG analyzers. We hope this manual will be helpful to a wide range of readers interested in conducting GHG flux measurements. This protocol was developed prioritizing clarity and detailed instructions so that an early researcher can follow it and measure soil fluxes with minimal supervision. Procedures were provided from the early stage of the research, starting from project planning and data collection in the field, up to data analysis.

We are grateful to the Bezos Earth Fund for providing financial support to develop this manual. We thank Tryan Budiarna and Eko Yuono for their invaluable comments on this manual.

Yayasan Konservasi Alam Nusantara

2023

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Glossary

Natural Climate Solution (NCS):
Conservation, improved land management, and restoration actions that increase carbon storage or avoid GHG emission in forests, wetlands, grasslands, and agricultural lands across the globe, while also supporting people and biodiversity.

Flux:
The transfer of GHGs between the atmosphere and natural systems, quantified as the amount of sequestration or reduced emissions per unit of extent applicable for an NCS pathway.

Global Warming Potential (GWP):
A measure of the total energy that a gas absorbs over a given period of time (usually 100 years) relative to the emissions of 1 metric ton of carbon dioxide.

Carbon (C):
One of the most abundant elements on earth and the foundation for all living things.

Carbon dioxide (CO_2):
A molecule consisting of one carbon and two oxygen atoms. CO2 from the air is absorbed by plants and stored via photosynthesis in the form of carbon. In the atmosphere it is an abundant and long-lived GHG, emitted primarily through burning fossil fuels, as well as by land sector activities resulting in burning or decomposition of organic matter.

CO_2e:
For ease of comparison, GHGs other than CO2 are translated to their carbon dioxide equivalents based on their varying global warming potential.

Methane (CH_4):
A potent GHG emitted from industrial activities, waste management, livestock, and natural systems such as wetlands.

Nitrous oxide (N_2O):
A potent GHG emitted primarily from industrial activities and agricultural practices such as fertilizer use.

1. Introduction

1.1 Background

Nature is the climate solution hiding in plain sight. At the global level, The Nature Conservancy (TNC) led the development of the pioneering science that has shown that Natural Climate Solutions (NCS) can provide one-third of the greenhouse gas (GHG) emissions reductions needed by 2030 to keep global average temperature rise below 2°C (Griscom et al., 2017). In Indonesia, Yayasan Konservasi Alam Nusantara (YKAN) led a study reporting that Indonesia offers dramatic opportunity to contribute to tackling climate change through the deployment of NCS with a maximum NCS mitigation potential of 1.3 ± 0.1 $GtCO_2e\ yr^{-1}$ by 2030 (Novita et al., 2022). Of the mitigation options, peatlands offer the most mitigation potential up to 960 ± 15.4 $MtCO_2e\ yr^{-1}$, equal to 74% of the total NCS potential in Indonesia.

While peatlands' contributions to climate change mitigation are under-appreciated, they are considered a powerful NCS due to the climate benefits they offer, such as climate regulation, moderating water flow, and fostering biodiversity (Page et al., 2011; Harrison et al., 2020). Peatland ecosystems are among the largest natural terrestrial carbon reservoir, storing an estimated ~644 Gt of carbon worldwide (~30% of total terrestrial stored carbon), and undisturbed peatlands sequester carbon at a rate of 0.37 $GtCO_2\ yr^{-1}$ (Dargie et al., 2017; Leifeld & Menichetti, 2018). Each year, drained peatlands emit around 2 $GtCO_2e$ globally, contributing to ~5% of global anthropogenic carbon dioxide (CO_2) emissions (Günther et al., 2020). This is remarkable, as drained peatlands occupy only 0.3% of the global land surface, thereby flipping peatlands from a globally significant carbon sink to a significant source of GHG emissions (Joosten et al., 2016).

Figure 1. Tropical peatland ecosystem, consisting of unique vegetation formations, black water, and rich organic soil (West Kalimantan)

Tropical peatlands are formed from the accumulation of organic materials due to frequently waterlogged conditions, resulting in a lower decomposition rate.

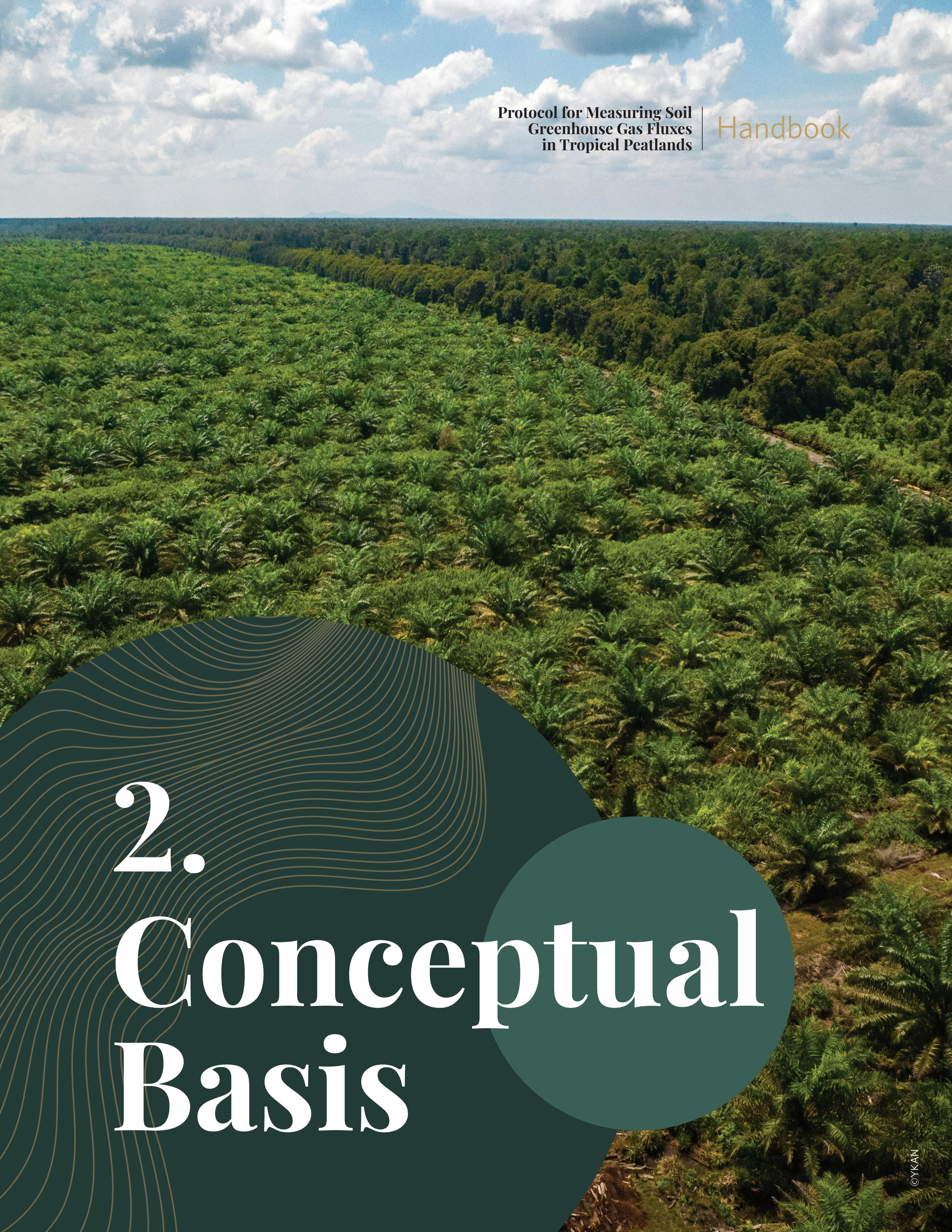
Current estimates of the total tropical peatland area are estimated from 56 Mha (Page et al., 2011) to 170 Mha (Gumbricht et al., 2017; Xu et al., 2018). Despite their relatively small area compared to other ecosystems, tropical peatlands play a substantial role in the global carbon cycle. Tropical peatlands cover around one-third of the global peatland area and are major land surface carbon reservoirs, storing around 152-288 GtC (Ribeiro et al., 2021). The most extensive and deepest tropical peatlands are found in Southeast Asia, mostly in Indonesia (Gumbricht et al., 2017). Unfortunately, in Southeast Asia, land use changes followed by fires and drainage due to peat swamp forest conversion will abruptly affect soil CO_2 and methane (CH_4) emissions to the atmosphere (Page & Hooijer, 2016). Thus, any disturbance in the system can significantly influence the global carbon budget.

Despite the importance of tropical peatlands for mitigating climate change, soil GHG emissions over different land use types in tropical peatlands are poorly studied compared to temperate and boreal peatlands, leaving significant gaps in knowledge. Recently, efforts have been underway to minimize uncertainty in GHG emissions of tropical peatlands through the establishment of intensive studies for GHG emissions monitoring.

1.2 Purpose and Scope

This protocol is developed under the Natural Climate Solutions (NCS) Peatland Playbook project, providing various approaches to accurately measure, monitor, and report soil CO_2 and CH_4 fluxes of tropical peatlands using various GHG analyzers. We outline the conceptual basis, brief description of instruments, field procedures, data analysis, and reporting for GHG emissions quantification in peatland ecosystems. While this protocol focuses on peatlands, the approach can be generally applied to other types of ecosystems such as dryland or mangrove ecosystems in the tropics. We address soil GHG emissions monitoring using only a closed chamber technique from three different GHG analyzers, weighing the pros and cons of each instrument based on our experience collecting field measurements. In the absence of an Eddy Covariance tower, chamber measurements play an important role in the improvement of emissions factors as most of the emission factors listed in the IPCC report are derived from chamber systems. Additionally, the closed chamber approach is one of the most common methods to employ for GHG soil flux monitoring, and it's relatively easy to operate while producing reliable flux measurements.

Improved knowledge for measuring comparable and reliable soil GHG emissions in tropical peatlands is crucial to understanding the impacts of land use and land cover change and to better quantify the global carbon budget. This protocol was developed based on our experience measuring soil GHG emissions from various land uses with different characteristics from peatland ecosystems located in West and East Kalimantan, Indonesia. We hope this manual will be helpful for a wide range of readers interested in conducting soil GHG flux measurements.



2. Conceptual Basis

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2.1 GHG Flux Measurement Method

In general, GHG flux measurement methods can be classified into two categories of techniques: (1) closed and (2) open. In a closed technique, the gas volume in which the flux is determined is constrained physically by an enclosure (i.e., a closed chamber), and thus the footprint area from which the flux is computed is well-defined (Batsviken et al., 2022). The flux is measured from the change of GHG concentrations over time within the enclosure. This technique is relatively easier to be deployed in the field without the need for expensive analytical instrumentations which could make GHG flux quantification affordable (Oertel et al., 2016). Two main limitations of a closed GHG flux measurement technique are that (1) the enclosure prevents the open exchange of gas with the surrounding environment, which may influence the GHG flux, and (2) the enclosures often have small footprints which yields uncertainty when extrapolating to larger areas (Oertel et al., 2016).

The open technique on the other hand is based on gas measurements taken directly from the open air (Batsviken et al., 2022). Some examples of this technique are Eddy Covariance, tracer studies, and the open mass balance approach. This technique enables flux measurements over a much larger footprint area (Zaman et al., 2021). Open methods require information about GHG concentrations, air movement, and sometimes other ancillary variables to estimate GHG flux and footprint location and size (Batsviken et al., 2022). Despite its advantages compared to the closed technique, open GHG flux measurement techniques do have some limitations, which include (1) higher demands on measurement accuracy and precision, and consequently, more expensive and power-demanding equipment, (2) the need for long-term commitment to secure research sites, and (3) greater overall complexity in maintaining the instrument and in evaluating the data (Batsviken et al., 2022).

These two GHG flux measurement techniques can contribute to GHG flux assessments in different ways. In a closed GHG flux measurement technique, measurements targeting specific sites in certain land cover types can be extrapolated and summed to generate bottom-up assessments at the landscape scale. On the other hand, measurements of GHG fluxes at the landscape scale using the open technique, combined with air transport models and estimates of atmospheric GHG residence times generate top-down assessments.

2.2 Measurements of GHG Fluxes using the Closed Chamber Technique

The dynamic closed chamber technique is a type of closed GHG flux measurement technique, which enables the circulation of open air into the chamber. Field measurements with chambers were first introduced by Lundegardh at the beginning of the 20th century (Lundegardh, 1927). In this technique, GHG fluxes are calculated using the changing rate of gas concentration within the chamber. This technique enables the estimation of GHG fluxes from a known area and time and is one of the most used GHG fluxes measurement approaches due to its practicality and cost-efficiency (Batsviken et al., 2022). However, it is important to consider some aspects of measurement using this technique. When the chamber is closed in order to accumulate the concentration of the measured GHG, it can alter the natural soil pressure and gradient, thereby influencing GHG flux movements from the soil to the atmosphere (Davidson et al., 2002). In addition, the mass flow of GHG fluxes from the soil to the chamber headspace can develop even from small differences in air pressure between the inside and outside of the chamber (Lund et al., 1999). In order to anticipate this undesirable occurrence, the measurement of GHG fluxes using this technique should be done over a short period of time.

There are two common ways to measure GHG concentrations within the chamber, namely (1) using a portable gas analyzer and (2) collecting gas samples in the field for further laboratory analysis.

1. *Using a portable gas analyzer*

   The dynamic closed chamber system is applied in this method by circulating air from the chamber into a portable gas analyzer and back into the chamber. This method is also known as a non-steady-state through-flow chamber (Livingston & Hutchinson, 1995).

2. *Collecting gas samples in the field for further laboratory analysis*

   In this case, a closed static chamber is applied by closing the chamber over a given period of time (typically 10 to 60 minutes) in order to accumulate gas inside the chamber. Gas samples are collected using a plastic syringe at specific time intervals. Gas samples should be kept in glass vials for further analysis in the laboratory using gas chromatography. This method is also known as a non-steady-state non-through-flow chamber (Livingston & Hutchinson, 1995).

In this protocol, we present only the methodology for measuring GHG fluxes using a portable gas analyzer. The use of a portable gas analyzer enables researchers to monitor gas concentration over time during the measurement period. Therefore, any leakage and false measurement can be observed and rectified directly in the field.

2.3 Major GHGs and Their Controlling Variables

In the context of climate change, the major GHGs that are commonly monitored include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These GHGs have both natural and anthropogenic sources. Naturally, CO_2 is simultaneously sequestered by the ecosystem through photosynthesis and emitted via respiration and decomposition processes. The agricultural activity could drive land cover change and drainage of peatlands, further exacerbating CO_2 emissions. CH_4 can be an important contributor to GHG fluxes in peatlands. This gas is both produced and consumed by the microorganisms present in peat. N_2O emissions are generally small but can be substantial for peatlands that are nitrogen-fertilized (Smith, 1997). The production and consumption of N_2O in peat are mainly the results of microbial nitrification and denitrification activity. Nitrification is the aerobic oxidation of ammonium (NH_4) to nitrate (NO_3) and denitrification is the anaerobic reduction of NO_3 to dinitrogen (N_2). N_2O is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere (Smith, 1997).

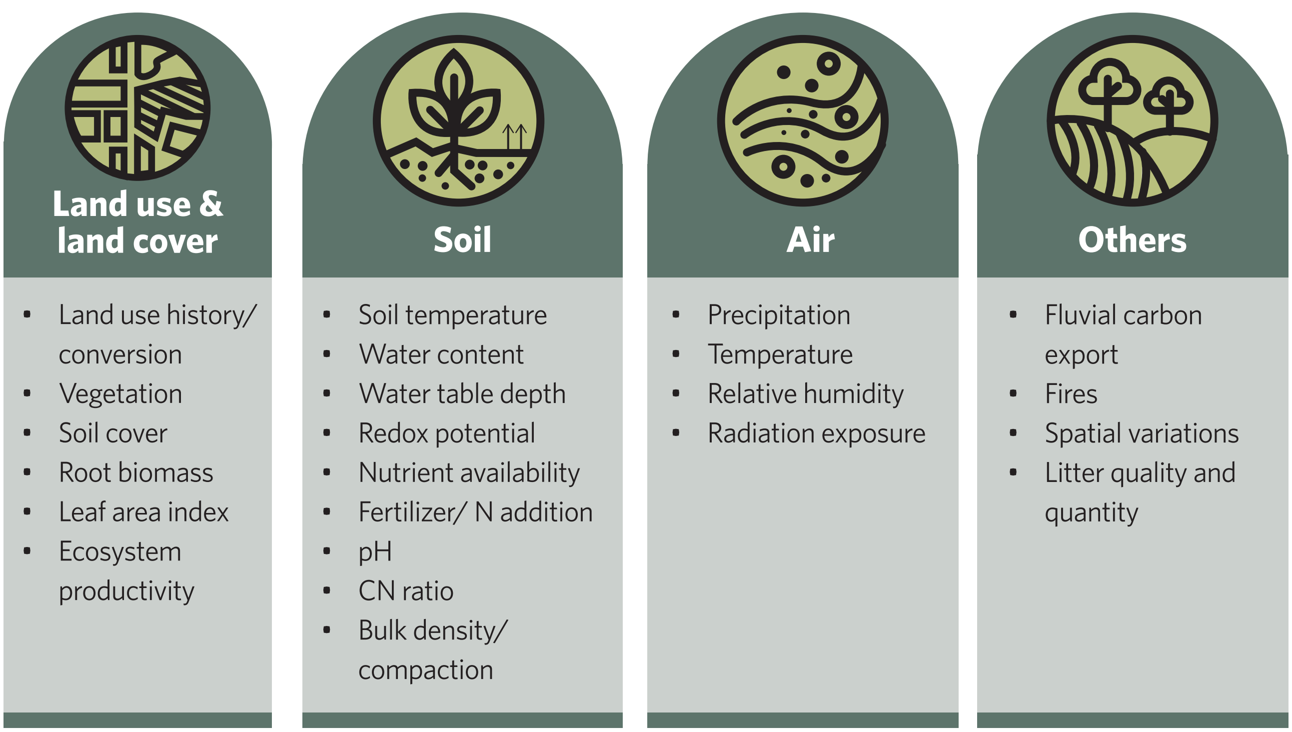

Figure 2. Controlling variables of GHG fluxes

The atmospheric heating capacity is different for each GHG. This capacity is called global warming potential (GWP), which is listed in **Table 1** below. CH_4 and N_2O are more potent than CO_2, and thereby have a greater impact on warming the atmosphere over short periods of time. However, CO_2 has a higher cumulative warming potential as the atmospheric residence time is much higher than CH_4 and N_2O, which have lifetimes of approximately 11.8 and 109 years, respectively (Table 1). Given the short atmospheric lifetime of CH_4, deep reductions in emissions can result in reduced peak global warming (IPCC, 2022).

Table 1. Greenhouse gas lifetime and global warming potential (GWP)

Major Greenhouse gas	Lifetime (years)	GWP 20-year	GWP 100-year	GWP 500-year
Carbon dioxide (CO_2)	-	1	1	1
Methane (CH_4)	11.8	79.7	27.0	72
Nitrous oxide (N_2O)	109	273	273	130

Source: IPCC, AR6 (2022)

GHG fluxes from peatlands are affected by several environmental variables. In particular, the significant effect of the water table on soil CO_2 flux has been observed in previous studies (Inubushi et al., 2003; Furukawa et al., 2005; Melling et al., 2005; Hirano et al., 2009; Couwenberg et al., 2010; Busman et al., 2022; Hoojier et al., 2012; IPCC, 2014). In addition, CO_2 flux is regulated by peat moisture and organic matter content. Meanwhile, CH_4 flux is mainly dependent on the water table, peat moisture, and peat temperature (Busman et at., 2022). The magnitude of peat CO_2 and CH_4 fluxes varies across climate regions and land cover types. A list of prior publications compiling studies on peat CO_2 and CH_4 flux measurements from Indonesian peatlands can be found in Novita et al., (2021).

3. Instruments

In this protocol, we will describe three GHG analyzers that are available on the market. Please note that this list of equipment is solely intended to inform the reader. The trade names must not be construed as endorsements or recommendations over other similar products.

3.1 LI-COR LI-7810 $CH_4/CO_2/H_2O$ Trace Gas Analyzer

Figure 3. LI-COR LI-7810 $CH_4/CO_2/H_2O$ Trace Gas Analyzer

The LI-COR LI-7810 $CH_4/CO_2/H_2O$ Trace Gas Analyzer utilizes Optical Feedback — Cavity-Enhanced Absorption Spectroscopy (OF-CEAS), a technique that produces high-precision and high-stability gas analysis. This tool is equipped with a smart chamber to measure GHG fluxes and record and store CO_2 and CH_4 flux data in its internal memory. Although it is designed for outdoor use, GHG flux measurements can only be conducted on land. Thus, a floating chamber system needs to be developed to measure GHG fluxes on water bodies (see Chapter 4). The complete operation manual, with setup, installation, and operation guidelines can be found here[1].

[1] https://tnc.box.com/s/cgdqt8ppvd3o7p9yvc5al03lzisnm3m8

3.2 LGR-ICOS™ GLA131 Series

The LGR-ICOS™ GLA131 Series is ABB's new micro-portable gas analyzer that can measure CO_2, CH_4, and H_2O simultaneously. The LGR-ICOS is equipped with Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS) technology as well as Microportable Greenhouse Gas Analyzers (M-GGA -918 and M-GPC-918) that start measuring the gas concentration quickly after powering on[2]. For the GHG flux measurements, it is required to develop a closed chamber system as shown in Figure 4. The complete operation manual, with setup, installation, and operation guidelines can be found here[3].

Figure 4. LGR-ICOS™ GLA131 Series with a developed close chamber system

[2] https://www.lgrinc.com/documents/DS_LGR-ICOS_MGGA_MGPC-EN%20RevD.pdf
[3] https://tnc.box.com/s/cgdqt8ppvd3o7p9yvc5al03lzisnm3m8

3.3 EGM-5 Portable CO_2 Gas Analyzer

The EGM-5 is a portable CO_2 analyzer, which functions by continuously measuring CO_2 concentration using an infrared gas analyzer (IRGA). In addition to CO_2, there are also optional O_2 and H_2O sensors which can be mounted on the device. The EGM-5 IRGAs are stable related to their construction, calibration, and thermal environment. For the GHG flux measurements, similar to the LGR-ICOSTM GLA131 Series, it is required to develop a closed chamber system. The complete operation manual, with setup, installation, and operation guidelines can be found here[4].

Figure 5. EGM-5 Portable CO_2 Gas Analyzer

[4] https://tnc.box.com/s/cgdqt8ppvd3o7p9yvc5al03lzisnm3m8

3.4 Pros and Cons for each GHG Analyzer

We do understand that each instrument is unique and has its own design to serve the purpose of GHG flux measurements. Here, we compiled information to describe each instrument's pros and cons based on each tool's specifications and our on-the-ground experience.

Table 2. Pros and cons of each GHG flux measurement instrument

Comparison	LI-COR LI-7810 CH_4/CO_2/H_2O Trace Gas Analyzer	LGR-ICOS™ GLA131 Series	EGM-5 Portable CO_2 Gas Analyzer
Pros	• Designed for indoor and outdoor use • Generates CO_2, CH_4, and H_2O fluxes data automatically • Comes with a backpack to assist with transporting the device	• Compact • Measures CO_2, CH_4, and H_2O at the same time, thus make it effective and efficient to use in the field • Easy to operate	• Lightweight, requiring less physical strength to carry the instrument • Designed to operate with minimal maintenance • Easy to operate • Most inexpensive instrument of the three
Cons	• Not water resistant, therefore not recommended to use in wet environments • Relatively heavy (around 10.5 kg), requiring more physical strength to carry the instrument • The most expensive instrument of the three	• Manual calculation using formula required to generate GHG flux data • Less resistant to extreme environmental conditions present in tropical ecosystems, causing technical problems such as battery error and corrosion	• Manual calculation using formula required to generate GHG flux data • Only measures by default CO_2, additional sensors must be purchased for O_2 and H_2O

4. Field Procedures

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4.1 Preparation

4.1.1 Collar Installation

Measurement using the dynamic closed chamber technique using any GHG analyzer instrument requires the placement of the collar (commonly made of perforated polyvinyl chloride-PVC pipe or galvalume) in the ground at about 5 cm depth to seal it and prevent leakage, thus creating a chamber headspace. To avoid possible bias flux from disturbance due to the installation process, the collars need to be installed a few days prior to the initial measurement and can stay in place permanently as long as their presence does disturb the environment. It should be noted that it is necessary to minimize cutting surface roots to avoid a trenching effect while inserting the collar into the soil. In this protocol, we do not define a standard chamber design because different ecosystems and measurement purposes require different designs, which should be assessed accordingly on a site and project basis.

Figure 6 Collar with chamber system used for LICOR and LGR

Once all collars have been installed as required, we recommend constructing a boardwalk around the collars. A boardwalk will minimize the disturbance to the collars when stepping on the soil to conduct the GHG flux measurements. Thus, we can avoid any disturbance that could potentially influence the flux measurements.

4.1.2 Equipment Preparation

Before conducting field measurements, research operators should have all equipment prepared. Despite its importance, equipment preparation might receive less attention than necessary, especially for operators who conduct measurements regularly. Thus, creating a checklist could be helpful to ensure that essential equipment is not missing and in working order. Some research projects are located in remote areas and are difficult to access. Failure to prepare the equipment could cause delays in data collection and add unnecessary costs to your project.

Here are some important lists to check out before heading to the field:

a. **Battery.** Ensure the batteries for all instruments are fully charged. Batteries should be charged the night before going to the field, at a minimum.

b. **Field data sheets.** Prepare a template for recording data to save time in the field and to ensure we get all the required data.

c. **Other auxiliary measurements**. Depending on the research needs, ensure that all the tools for auxiliary measurements are functioning properly. For example, in our case, we needed to ensure the proper functioning of our barometer. Regularly testing the equipment ensures the continued collection of high-quality field data.

d. **Outdoor essentials.** The portable gas analyzer tools are less resistant to extreme environmental conditions. Caution is needed to minimize exposure to direct heat and humidity from the elements. The use of umbrellas or other preventative measures is recommended in such conditions.

e. **Calibration.** If you are using the latest version of the portable gas analyzer, calibration should follow the company's recommendations. The latest model has been designed so that after an initial calibration consequent calibration can be done every six months or after one year based on the machine's condition. If an older model is being used, independent calibration can be conducted every couple of months using several known gas concentrations. The lowest concentration of the standard gas should be similar to the atmospheric concentration of 410 ppm for CO_2, 1866 ppb for CH_4, and 332 ppb for N_2O (IPCC, 2021). We suggest using three different concentrations: 400, 600, and 1000 ppm for CO_2, 1500, 1700, and 2000 ppb for CH_4, and 300, 450, and 600 ppb for N_2O.

4.2 GHG FLUX MEASUREMENT

We made a short video to show how we conducted GHG flux measurements using LI-COR and LGR[5]. In general, there are two important steps, namely gas analyzer setup and gas measurement.

4.2.1 LI-COR LI-7810 $CH_4/CO_2/H_2O$ Trace Gas Analyzer

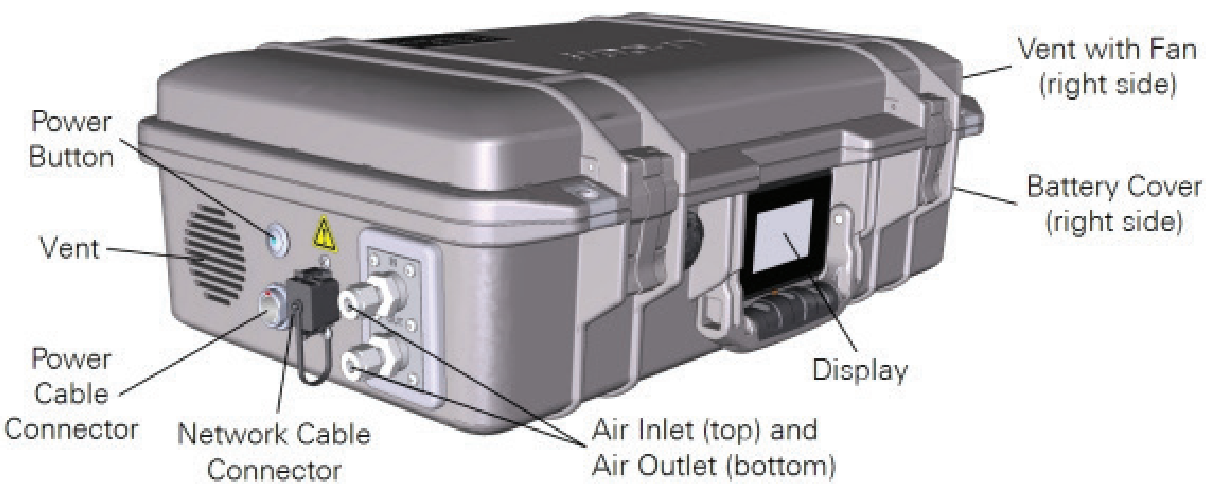


Figure 7 Layout of LI-COR LI-7810 $CH_4/CO_2/H_2O$ Trace Gas Analyzer (https://www.licor.com)

Turning on LI-COR trace gas analyzer

The first step is to set up the LI-COR trace gas analyzer. The complete manual can be found linked in Section 3.1, with a layout of the analyzer demonstrated in Figure 7. Briefly, here are some steps to get the LI-COR analyzer ready, as follows:

1. Insert the battery and push the power button. The pump will start running when the optical bench approaches 55°C. If the device is turned on at room temperature, it will take about 30 minutes before the

[5] https://www.youtube.com/watch?v=92kZXwAod84

instrument provides accurate measurements and is ready to use. This wait time may vary depending on the ambient air temperature of your site.

2. Connect the instrument to a smart phone or a computer via Wi-Fi. Windows, macOS, Linux, iOS, and Android OS are supported operating systems. Chrome, Firefox, and Safari are supported browsers that we have tested, but others may work as well.

3. When Wi-Fi is enabled, the LI-COR trace gas analyzer will create a local wireless network, indicated by the presence of a wireless network symbol on the display. Connect to the Wi-Fi with the network name tg10-nnnnn, where tg10-##### is the host name (and the serial number) of the instrument.

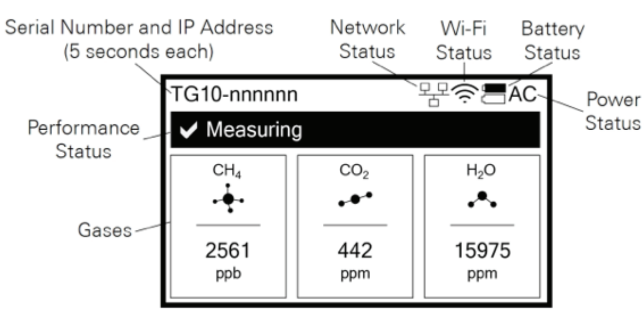


Figure 8 Layout display on LI-COR LI-7810 (https://www.licor.com)

4. Input http://192.168.10.1/ for the LI-COR analyzer and http://192.168.46.1/ for the smart chamber on your browser and check the status code on the software interface.

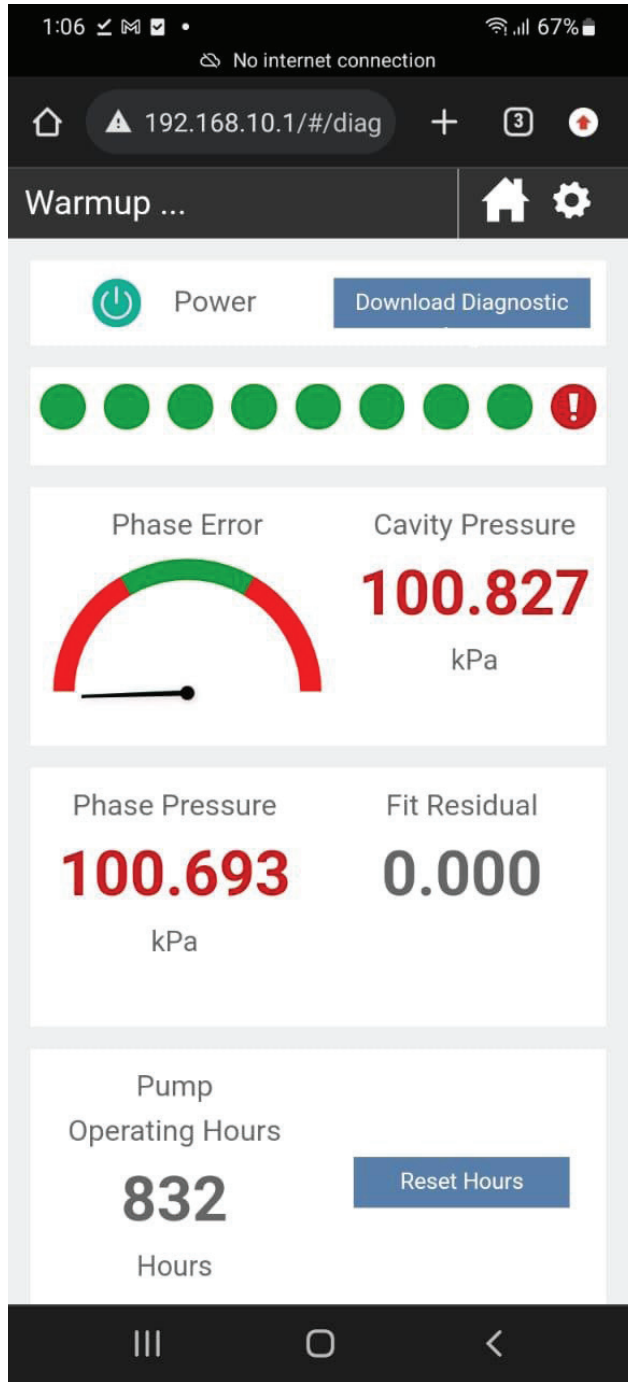


Figure 9 Software interface on android phone

5. The software indicators must turn green before the tool provides accurate measurements.

Table 2-2. Status codes provide information on the status of the instrument.

Display Indicator	Software Indicator	Status Code	Definition
✓	Green	0	Normal operation (measuring).
⚠	Yellow	1	Start frequency adjustment; Measurements may be noisy.
⚠	Yellow	2	Laser temperature adjustment; Measurements may be noisy.
⚠	Yellow	4	Incomplete scan resulted in missing cavity modes; Measurements may be noisy.
⚠	Yellow	8	Start-up mode finished; Measurements may be noisy.
⚠	Yellow	16	Start-up mode initializing; Measurements may be noisy.
⚠	Red	32	Spectral fit residual RMS too high; Measurements are invalid.
⚠	Red	64	Unregulated pressures or temperatures; Measurements are invalid.
⚠	Red	128	Inlet clogged. Triggered when the inlet is obstructed for 3 or more seconds. When triggered, the instrument turns off the pump and enters sleep mode. Clear the obstructions and restart the instrument.
⚠	Red	256	Instrument not ready; Measurements are invalid.
⚠	Red		SVC Required. This message may be issued during warmup. If not resolved after 60 to 90 minutes of operation, contact LI-COR or your sales representative.
⚠	Red		SD card error. This message may be issued briefly during warmup or during a firmware update. It should be dismissed quickly. If not, contact LI-COR or your sales representative.

Figure 10 Software interface on an android phone (https://www.licor.com)

6. Once all indicators turn green, measurements can be started.

Measuring GHG emissions

Once the LI-COR trace gas analyzer is ready, we can begin measurements based on the research design. Before using the trace gas analyzer, measure the height of the four collar sides and take the average value as the input for the application to calculate the GHG fluxes. In our case, here are the steps we took:

1. Measure the height of each side of the collar and calculate the average height.
2. Input the average height into the LI-COR smart chamber application.
3. Place the LI-COR smart chamber, which is already connected to the LI-COR trace gas analyzer, on top of the collar.
4. Start measuring CO2 and CH4 fluxes for two minutes, with three repetitions.
5. Monitor the GHG fluxes when running the gas analyzer.
6. Record the start and end time in a field data sheet to assist with data analysis later.
7. Measure and record other relevant environmental variables using available tools (please refer to section 4.3.2 for relevant supporting environmental variables).
8. Once finished, repeat the same steps for each of the other collars.

4.2.2 LGR-ICOS™ GLA131 Series

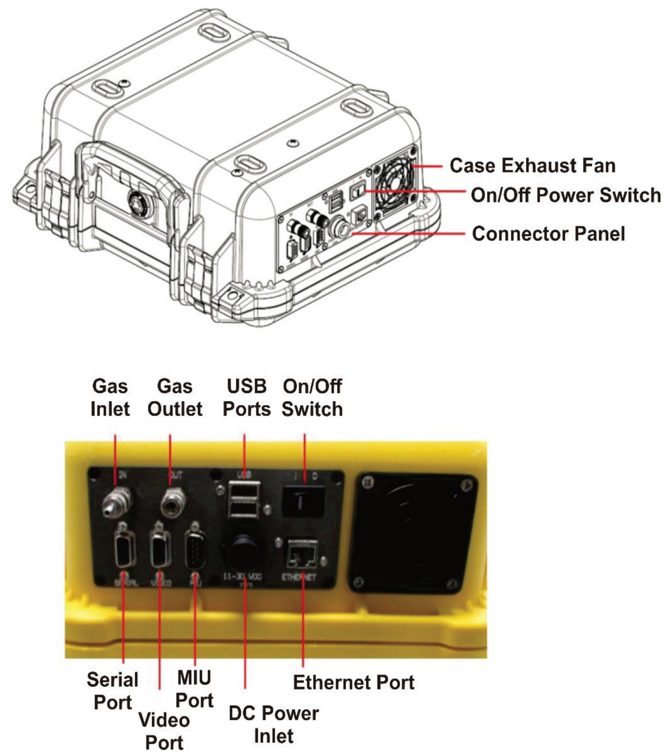


Figure 11 Layout of LGR-ICOSTM GLA131 Series (https://new.abb.com)

Turning on the LGR trace gas analyzer

Similar to the LI-COR trace gas analyzer, setting up the LGR trace gas analyzer is the first step that we have to take prior to taking measurements. The complete manual can be found in the link in Section 3.2, with a layout of the analyzer demonstrated in Figure 11. Briefly, the steps to prepare the LGR analyzer are as follows:

1. Once in the field, turn on and connect the Portable Gas Analyzer (PGA) to the chamber hood (lid) using a polytetrafluoroethylene (PTFE) tube.
2. Warm up the PGA for about 30 minutes prior to conducting measurements and ensure that the machine temperature has reached 50°C and that all indicators in the application have green checkmarks.
3. Ensure to step on the boardwalk installed near the permanent chamber when measuring GHG fluxes to avoid bias due to disturbance.

Measuring GHG emissions

After turning on the LGR trace gas analyzer, we follow similar steps as the LI-COR analyzer, as follows:

1. Measure the chamber height on all four sides and calculate the average height.
2. Take note of the average chamber height (it will be used for computing the GHG fluxes).
3. Close the chamber for 3-5 minutes depending on the chamber size. In general, shorter durations are appropriate for smaller chambers. In our case, we used 4-inch collars and closed the chamber for three minutes. You can adjust the time accordingly in function to the chamber size.
4. Record the start and end times of each chamber measurement.
5. Pay attention to the measurement data displayed on the computer or mobile phone to ensure that gas concentrations are increasing linearly over time (noisy data will be observed in the beginning of the measurement). Data will show a clear increasing trend around 10 seconds after closing the chamber.
6. Once finished, open the chamber hood (lid) and prepare to move on to the next chamber.
7. Record the start and end time in a field data sheet to assist data analysis later.
8. Measure and record other relevant environmental variables using available tools (please refer to section 4.3.2 for relevant supporting environmental variables).
9. Once finished, repeat the same steps for the other collars.
10. Upon completion of all collar measurements, download the data accordingly before leaving the research site.

4.2.3 EGM-5 Portable CO_2 Gas Analyzer

Turning on the EGM-5 analyzer

The complete manual can be found in the link in Section 3.3, with a layout of the analyzer demonstrated in Figure 12. Briefly, here are steps to prepare the EGM-5:

1. Connect the AC power cord to the main and the barrel connector into the EXT Power socket on the back of the EGM-5.
2. Press the ON/OFF switch to power up the instrument. The power switch should now have an illuminating blue ring indicating power is on.
3. Wait around 15 minutes for the instrument to warm up.

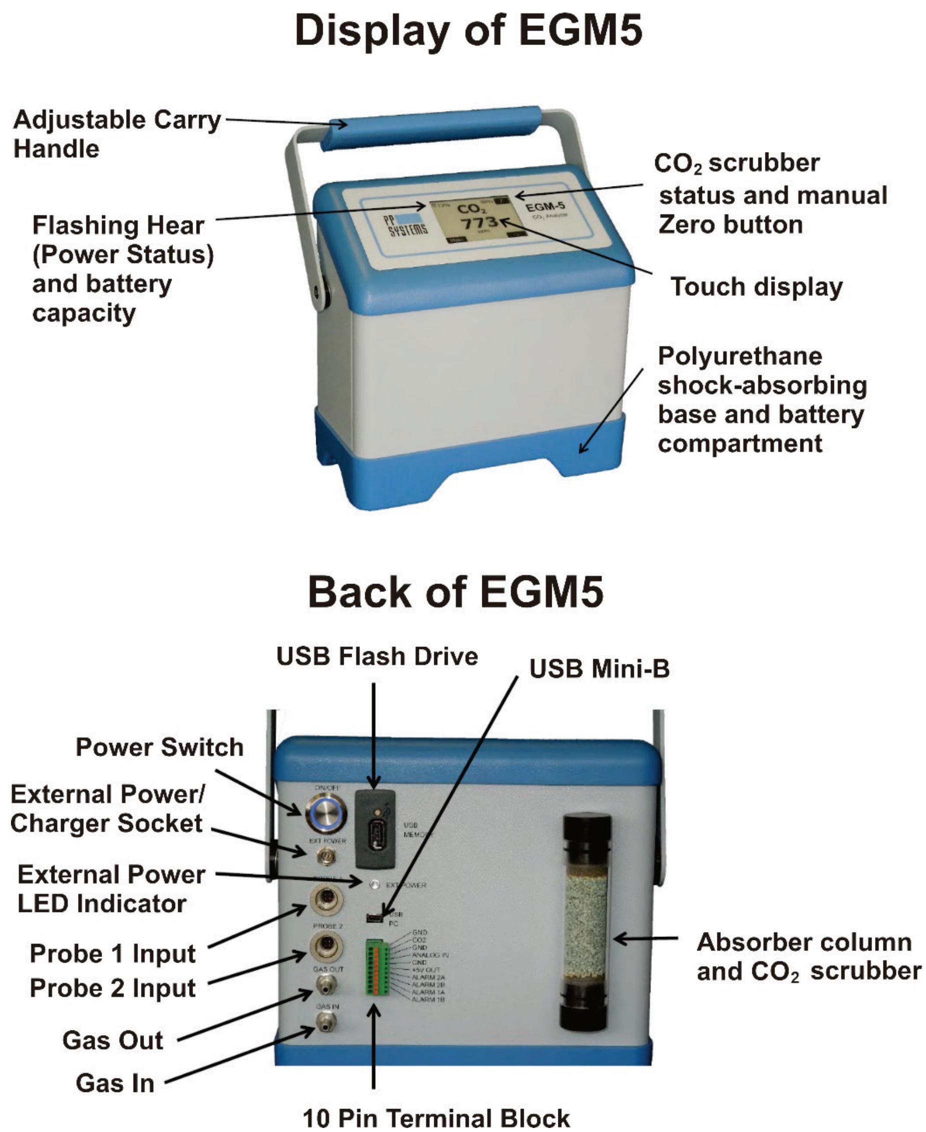


Figure 12 Layout of EGM-5 Portable CO_2 Gas Analyzer (https://ppsystems.com)

Measuring GHG emissions

Once the tool is on and ready, measurements may begin. Here are steps for measuring GHG emissions:

1. If using a chamber, measure the chamber height on all four sides and calculate the average height.
2. Record the start and end time in a field data sheet to assist data analysis later.
3. Monitor the tool during measurements to ensure that data is being collected properly.
4. After finishing one collar, repeat steps (1-3) for each consequent replicate measurement on the other collars in the site.

4.3 Auxiliary Measurements

4.3.1 Vegetation and soil data collection

Normally during plot installation, vegetation and soil surveys are necessary to understand the vegetation characteristics and soil properties in the research site. Some of the parameters which should be measured are given in the table below.

Table 3. Parameters to be measured periodically to supplement GHG fluxes measurement

Vegetation Characteristics	Soil Properties
• Land cover type • Dominant vegetation species • Vegetation density • Land management practices	• Soil type • Soil texture • Bulk density • Carbon content • Total Nitrogen • pH • Eh (redox potential) • Soil nitrate and ammonium*

**It is desirable that soil nitrate and ammonium be determined throughout the year at time intervals deemed appropriate by the individual investigator as dictated by resource availability and plot constraints*

4.3.2 Continuous Data Collection

Each GHG flux measurement should be instrumented with supporting environmental variables, such as:

- *Air temperature*

  Air temperature shows the microclimatic conditions surrounding the monitoring plot. In our research, we found that high air temperatures correlated strongly with high soil temperature, especially in the shrub sites, where there was no shade from tree canopy.

- *Relative humidity*

  Relative humidity refers to the moisture content of the atmosphere, expressed as a percentage of the amount of moisture that can be retained by the atmosphere at a given temperature and pressure without condensation. It can be measured using a portable sensor or weather station.

- *Precipitation*

  The precipitation rate can be monitored using an automatic weather station installed near the project area. In our case, we used ONSET HOBO Automatic Weather Station, shown in the figure below (Figure 13).

- *Soil temperature*

  Soil temperature is an important variable to explain variations in GHG soil emissions. In theory, an increase in soil temperature leads to higher CO_2 emissions as microbial metabolisms increase. The rate of change in the chemical and biological system, including GHG emissions with a temperature change of 10°C, is known as Q_{10} (Berglund et al., 2010). Soil temperature can be measured by inserting a probe into the soil adjacent to the sampling site at a depth of 10 cm.

- *Soil moisture*

  Soil moisture controls microbial activity and all related processes and is considered an important parameter for soil gas emissions. Soil moisture correlates positively with anaerobic conditions, resulting in CH_4 production. In contrast, CH_4 sinks require aerobic conditions. Soil water content is calculated from samples located close to the soil surface at around 5 or 10 cm.

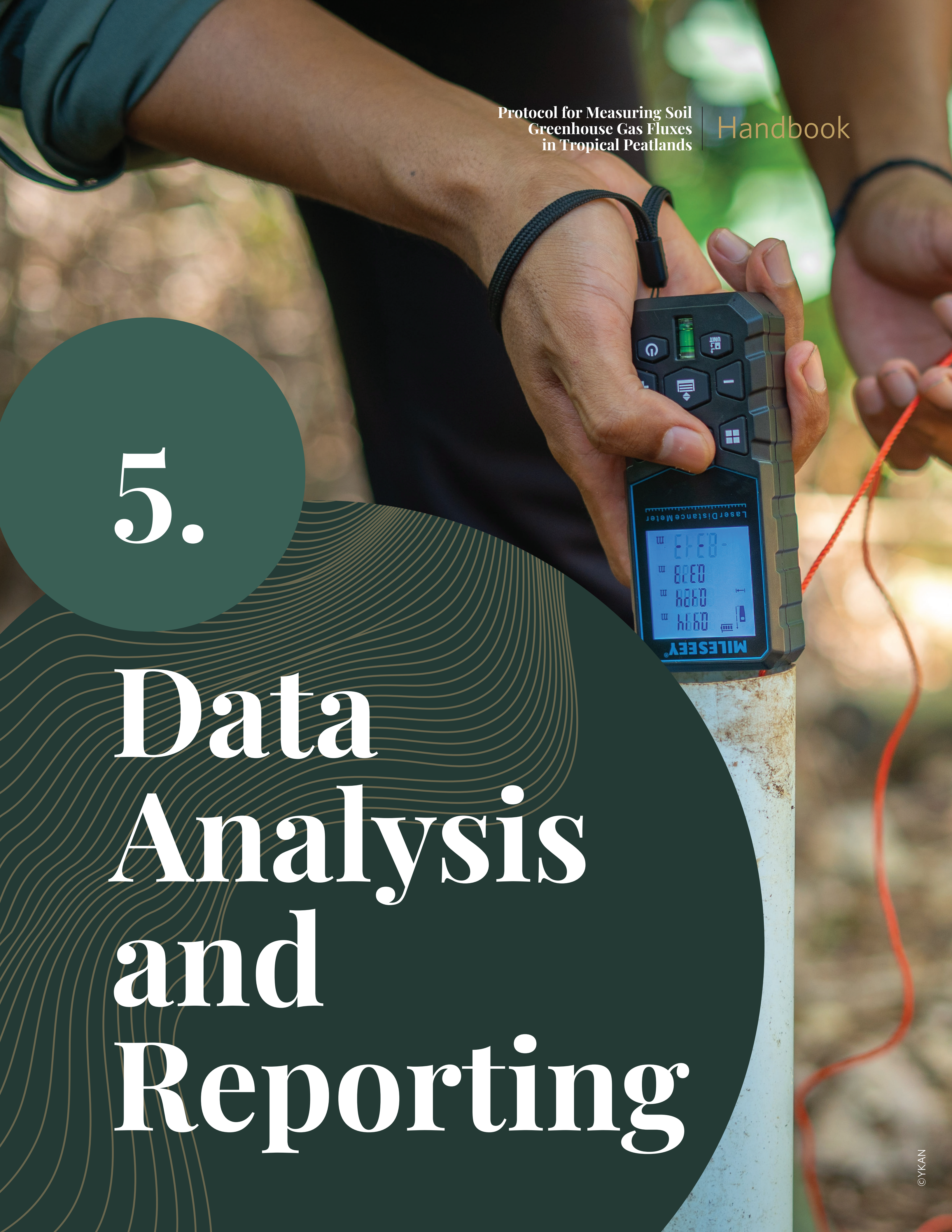
- *Groundwater level*

  The water table depth is measured as the vertical distance from the groundwater surface to the soil surface. Measurement frequency depends on the research needs. In our study, we measured the water table depth every other week for the whole year. We used PVC pipes inserted into the ground at a 2 m depth.

- *Collar height*

  As we used a closed chamber technique, we installed collars made from PVC with 4- and 8-inch diameters (10.16 and 20.32 cm) for the LGR and LI-COR analyzers, respectively. We customized 20 cm PVC heights for each collar and inserted it around 5 cm into the ground. When we began to operate the gas analyzer, we measured the height of the collars above ground on all four sides of the PVC pipe. It is important to input the height into the analyzer as it affects the functionality of the tool.

Figure 13 Weather station components to support GHG monitoring (East Kalimantan)



5. Data Analysis and Reporting

5.1 GHG Fluxes Calculation

GHG fluxes are calculated from the rate of changing gas concentrations over the time of measurement (slope) within the chamber headspace. This slope can be fit to linear and non-linear trends. Most published studies have reported linear trends in calculating GHG fluxes from peatland ecosystems (e.g., Comeau, 2016; Novita, 2016). Only a few studies have applied non-linear models to determine GHG fluxes (e.g., Dugas et al., 1997; Wagner et al., 1997). The selection of which trend to use will determine the slope for GHG flux calculations. Several considerations should be made when selecting linear trends for calculating the slope, including the chamber size and measurement period. Typically, shorter periods, i.e., 2-5 minutes, are suitable for linear trend modeling.

In this regard, we recommend performing statistical analyses on the gas concentration data to see if they follow a linear regression. This can be conducted by testing the goodness of fit to check if the regression residual variance of linear and non-linear regression is significantly different. Should the linear assumption be met, only the data with a regression coefficient above 0.85 can be included for further analysis (Comeau, 2016). Based on field experience, it takes several seconds after the start of the measurement (usually less than 10 seconds) before linearity can be observed from portable gas analyzers. This is due to the time needed for gas concentrations to increase inside the chamber headspace. This noisy data can be omitted to obtain proper and more representative samples.

Once the quality of the data has been assured, the slope of the gas concentration can be calculated using the following formula:

$$m = \frac{C_2 - C_1}{t_2 - t_1}$$ **... (Equation 1)**

In which,

- m = slope of the gas concentration over time (ppm s^{-1})
- C_1 = gas concentration at the start of the measurement (ppm)
- C_2 = gas concentration at the end of the measurement (ppm)
- t_1 = time at start of the measurement (s)
- t_2 = time at the end of the measurement (s)

This slope was then converted into gas flux using the equation based on the ideal gas law, as follows:

$$PV = nRT \quad \text{... (Equation 2)}$$

In which,
- P = air pressure (Pa)
- V = volume of chamber headspace (m^3)
- n = amount of substance (mol)
- R = gas constant (8.314 m^3 Pa K^{-1} mol^{-1})
- T = temperature (K)

To generate the flux for each corresponding gas per unit area (J), Equation 2 can be modified as follows:

$$J = m \frac{M_w P V}{A R T} \quad \text{... (Equation 3)}$$

In which,
- M_w = molecular weight for GHG (gr)
- A = chamber area (m^2)

(Please note the molecular weight of CO_2 is 44.01 gr and CH_4 is 16.02 gr, and P, V, R, and T are the same variables as described above in equations 1 and 2).

These calculations can be done using a spreadsheet, such as Microsoft Excel, or other similar software.

5.2 Database Management

5.2.1 Pre-measurement

To conduct a robust temporal monitoring analysis, the database must be clean and complete. It is important to have a data quality control system, where the research coordinator or project manager, together with the research assistant or operator, checks all field data sheets prior to leaving the field. This is to ensure that all necessary data has been collected properly and completely (please refer to Section 4.1: Preparation for a complete list of steps to follow to minimize error and ensure proper data collection). It is also important to consider carrying waterproof field notes assisted with a pencil (not easily faded by water) as a backup in case of a rain event to avoid losing the original data from the data sheets when conducting field monitoring. The original field data sheets should be kept for later use, should any clarifications need to be made, at least until the research or project report is published. The field data sheets from the first to the end of temporal monitoring should have a similar format.

Download the field data sheet here: Field data sheet_GHG Protocol

5.2.2 Post-measurement

Entering data into a computer spreadsheet immediately after fieldwork is encouraged to 1) avoid accumulation, 2) ensure that remarks on specific data are well recorded, and 3) create a backup of records, which minimizes the risk of losing or damaging information that is in the field sheets. The template should be designed based on how the data will be analyzed and summarized. Excel spreadsheets can be used to create the database template since it can store more than 1 million data rows. This is more than enough to keep all data in one format. In addition, databases in Excel format are also useful as they are compatible with most statistical software.

Since the monitoring activities include several types of measurements (e.g., chamber condition, GHG analysis, weather data, hydrology, and soil physical and chemical properties), the data that will be collected is can be quite large, and grouping the dataset will lighten the workload before moving on to the final calculations. Here, we suggest grouping the collected dataset by:

1. **General information**
   a. Date and time of data collection
2. **Plot or study area**
   a. Plot Code
   b. Land use
   c. Category (e.g.: rewetted or drained, forest or oil palm)
   d. Remark (e.g.: trenched and non-trenched)
3. **Hydrology parameters**
   a. Water table (from logger and manual measurement)

4. Weather parameters

a. Air pressure
b. Air temperature
c. Air Humidity

5. Soil conditions

a. Groundwater table depth
b. Soil temperature
c. Soil water content
d. Soil electrical conductivity

6. Collar and chamber conditions

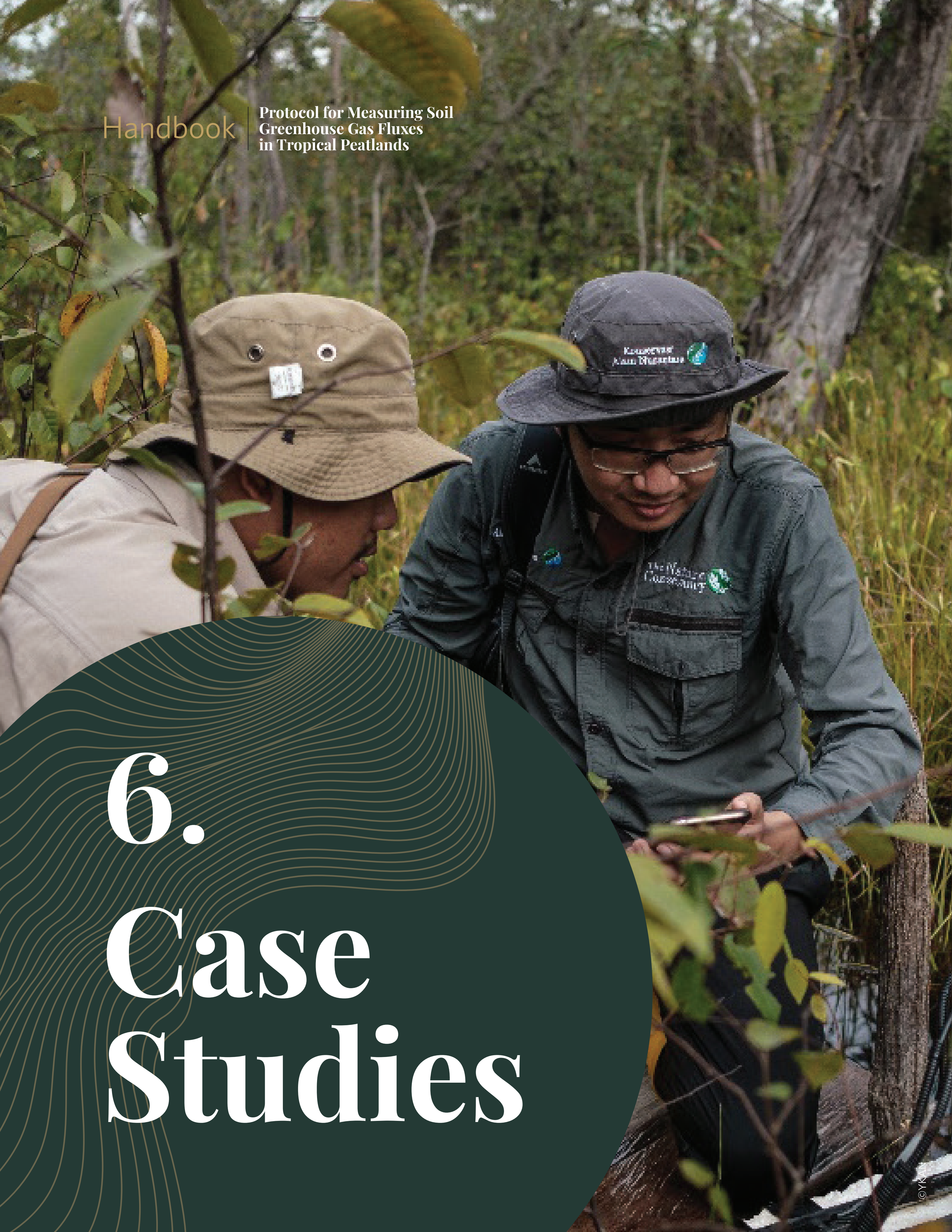
a. Soil collar height
b. Soil collar area
c. Chamber observation lengths
d. Chamber pressure
e. Altitude
f. Elapsed chamber measurement time
g. Chamber temperature

7. Soil gas measurement

a. CO_2 fluxes
b. CH_4 fluxes

Lastly, there will be two kinds of data sources that will be uploaded into the main database in Excel format: (1) the field data sheet, and (2) the compiled database covering all parameters from the gas analyzer. When the data is uploaded to the Excel database, it is necessary to give the appropriate parameter codes, units, and descriptions in an understandable manner. Despite format names from the Smart Chamber and Trace Gas Analyzer having technical codes such as "ETIME mean", we recommend using the original parameter names from the machine defaults for common understanding once the data is shared with colleagues.

Download the database format here: Database_GHG Protocol



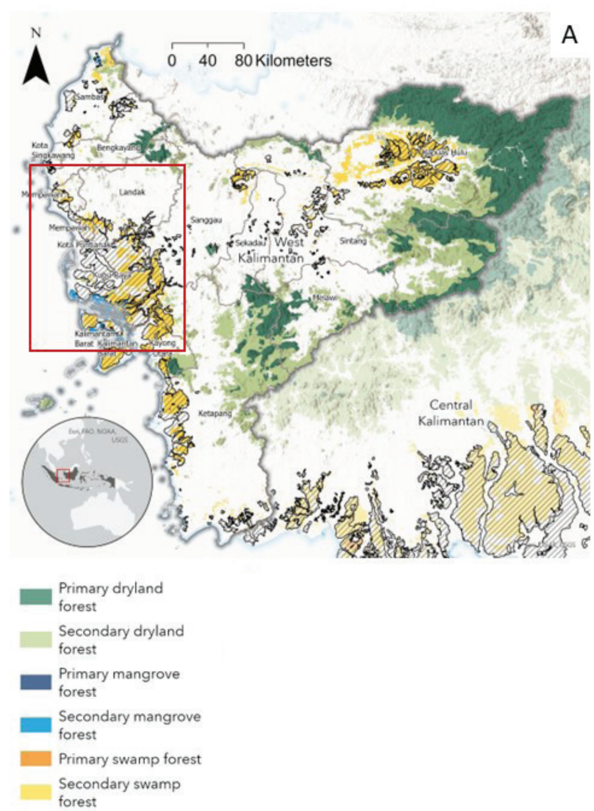
6. Case Studies

In this protocol, we will describe several case studies of GHG fluxes measurements from tropical peatland ecosystems. Please note that this list of case studies and approaches we are using is solely intended to inform the reader. The approaches and equipment to be used for GHG fluxes measurements for different sites may be adjusted based on research objectives and environmental conditions.

6.1 Measurement of GHG Fluxes from Peat Rewetting in Oil Palm Plantation in West Kalimantan

6.1.1 Overview of the study site

We conducted measurements at two sites in oil palm plantations within two regencies in West Kalimantan, Indonesia, namely Mempawah and Kubu Raya (**Figure 14**). The oil palm plantation site in Mempawah Regency is located in Anjungan District, where we installed monitoring plots in 10-year smallholder oil palm plantations. The peat depth in this site is measured to be about 200 cm. Here, peatland rewetting measures have been conducted by *Badan Restorasi Gambut dan Mangrove*-BRGM (Indonesia Peat and Mangrove Restoration Agency) by installing concrete canal blocking in 2018. The oil palm plantation site in Kubu Raya Regency is in Rasau Jaya District. Here, we established our monitoring plot in the oil palm concession, where the age of the plantation is about three years. The peat depth in this site is about 300 cm.



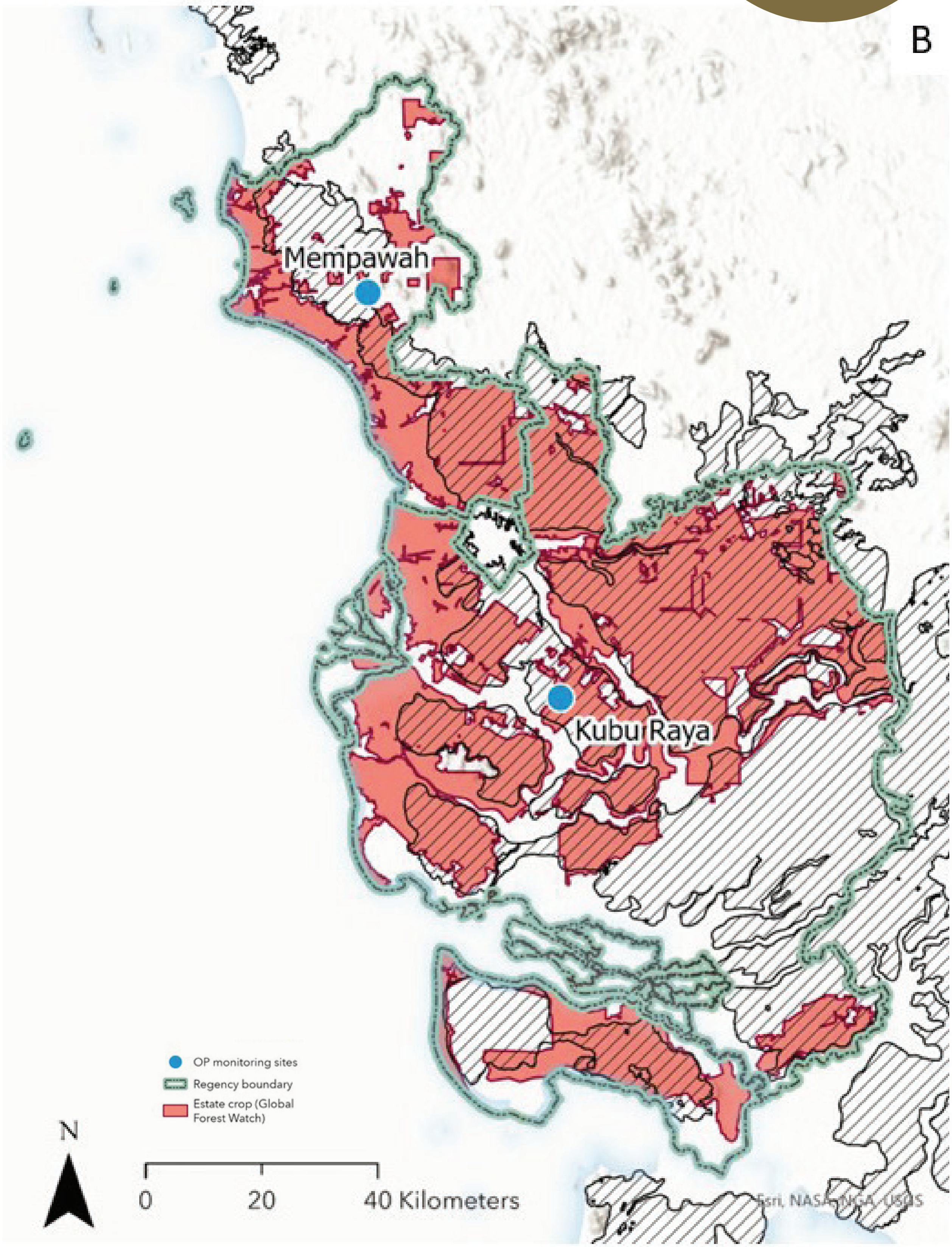


Figure 14. The location of the study area within oil palm plantations (OP) in Mempawah and Kubu Raya Regencies

6.1.2 Measurement design

GHG flux measurements were carried out on a bi-weekly basis starting from January 2022. For each site, the measurements were taken from five pairs of trenched and non-trenched plots for each transect (**Figure 15**), namely drained oil palm plantations and rewetted oil palm plantations. The trenching method was used to separate autotrophic and heterotrophic CO_2 fluxes, in which a trench of 1x1 m^2 in size and up to 1 m in depth was constructed out of a fibre plastic sheet for each plot. The CO_2 and CH_4 fluxes from the peat surface were measured using a LI-COR LI-7810 portable GHG analyzer. The measurements were conducted following a closed chamber technique using a LI-COR 8200-01S smart chamber equipped with a Stevens HydraProbe consisting of soil moisture, temperature, and electrical conductivity probes. During each measurement, about 5 cm of the collar was inserted into the ground until it was sealed to the ground surface. The gas measurements were taken for 2 minutes with 3 replicates (6 minutes in total). Upon data collection from the field, SoilFluxPro software was used to derive GHG fluxes. Photographic documentation from the field campaign is provided in Figure 16.

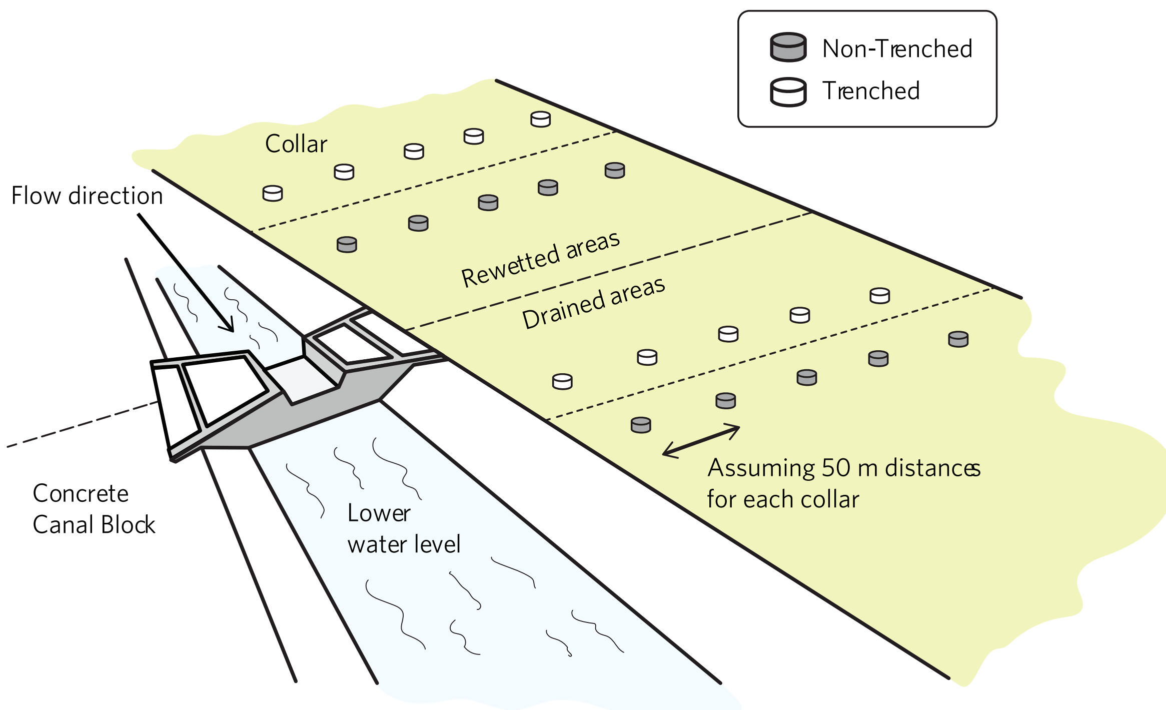


Figure 15. The measurement design for GHG flux measurements within drained and rewetted oil palm plantations

Figure 16. Documentation design for GHG flux measurements within drained and rewetted oil palm plantations

6.1.3 Preliminary results

Our results indicate that peat rewetting through the construction of canal blockings in oil palm plantation reduces both heterotrophic and total respirations with no impacts on CH_4 emissions (**Table 4**). The one-year data set indicates that reduction of heterotrophic respiration is larger than total respiration, indicating that rewetting drained peatland inhibits peat decomposition.

Table 4. The preliminary results of GHG fluxes from drained and rewetted oil palm plantations

No	Site	n	Total Peat Respiration ($Mg\ CO_2\ ha^{-1}\ yr^{-1}$)	Heterotrophic Respiration ($Mg\ CO_2\ ha^{-1}\ yr^{-1}$)	Methane Flux ($kg\ CO_2e\ ha^{-1}\ yr^{-1}$)
1	Drained Oil Palm	10	39.1 ± 3.1	32.9 ± 3.0	-10.5 ± 7.2
2	Rewetted Oil Palm	10	33.0 ± 2.3	22.6 ± 1.5	-7.7 ± 8.1

6.2 Measurement of GHG Fluxes from Secondary Forest in West Kalimantan

6.2.1 Overview of the study site

Similar with oil palm plantations, we monitor long term GHG fluxes in two regencies in West Kalimantan, namely Mempawah and Kubu Raya (**Figure 17**). The secondary forest site in Mempawah Regency is in Anjungan District, where we installed monitoring plots in community-owned secondary forest. The peat depth in this site is measured to be about 400 cm. The secondary forest site in Kubu Raya Regency is in Terentang District. Here, we established monitoring plots in the secondary forest managed under the social forestry scheme. The peat depth in this site is about 700 cm.

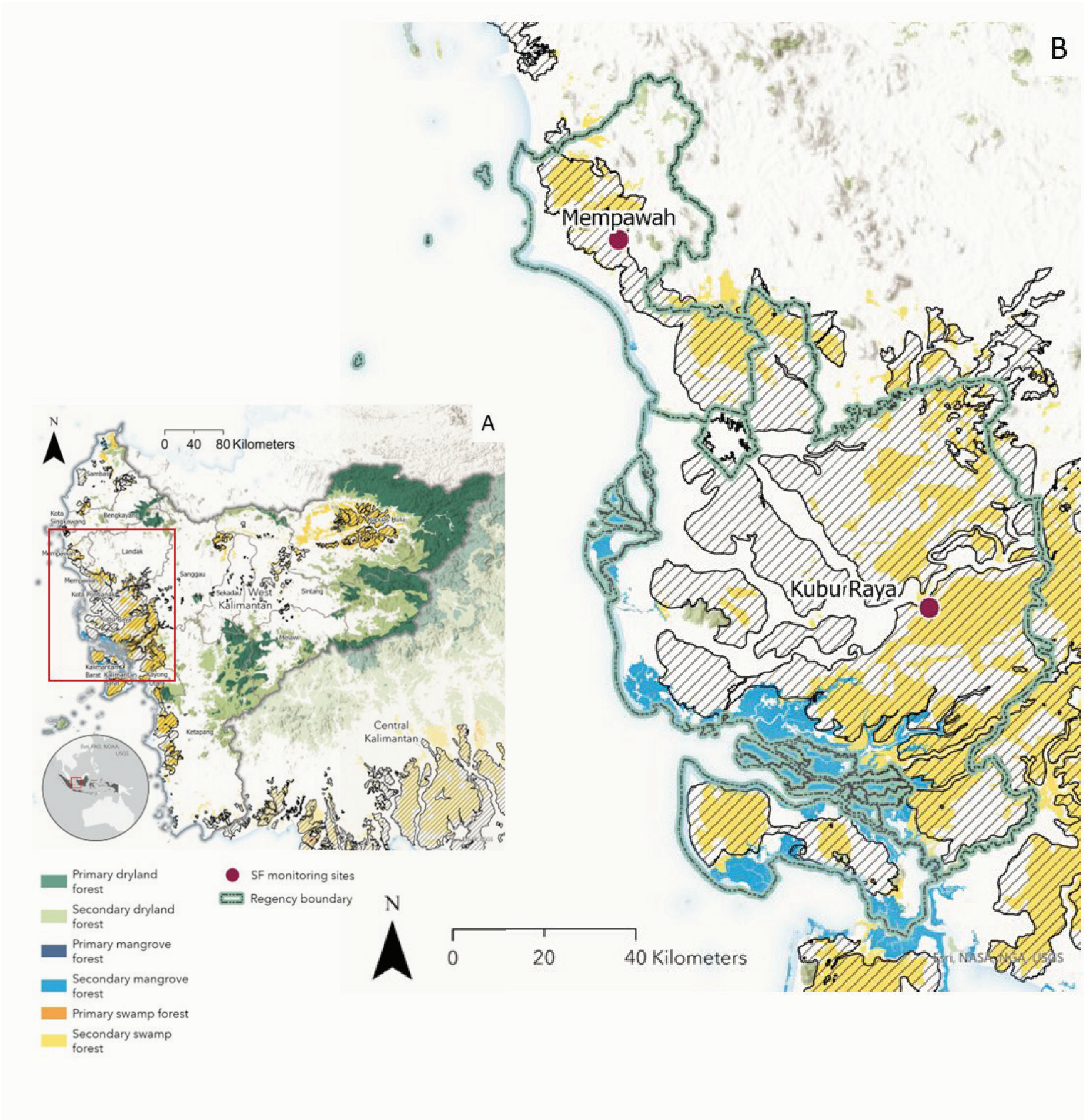


Figure 17. The location of the study area within secondary forest (SF) in Mempawah and Kubu Raya Regencies

6.2.2 Measurement design

Similar to oil palm plantations, GHG flux measurements were carried out on a bi-weekly basis for a period of one year from January 2023. Each site's measurements were taken from five pairs of trenched and non-trenched plots for each transect (**Figure 18**). Here, the trenching method was applied in an equivalent manner to those in the oil palm plantations. Nevertheless, due to the presence of woody debris and coarse roots within the peat, such a trench is more difficult to construct. The CO_2 and CH_4 fluxes from the peat surface were measured using a LI-COR LI-7810 portable GHG analyzer. The measurements were conducted following a closed chamber technique using a LI-COR 8200-01S smart chamber equipped with a Stevens HydraProbe consisting of soil moisture, temperature, and electrical conductivity probes. During each measurement, about 5 cm of the collar was inserted into the ground until it was sealed to the ground surface. The gas measurements were taken for 2 minutes with 3 replicates (6 minutes in total). Upon data collection from the field, SoilFluxPro software was used to derive GHG fluxes. Photographic documentation from the field campaign is provided in **Figure 19**.

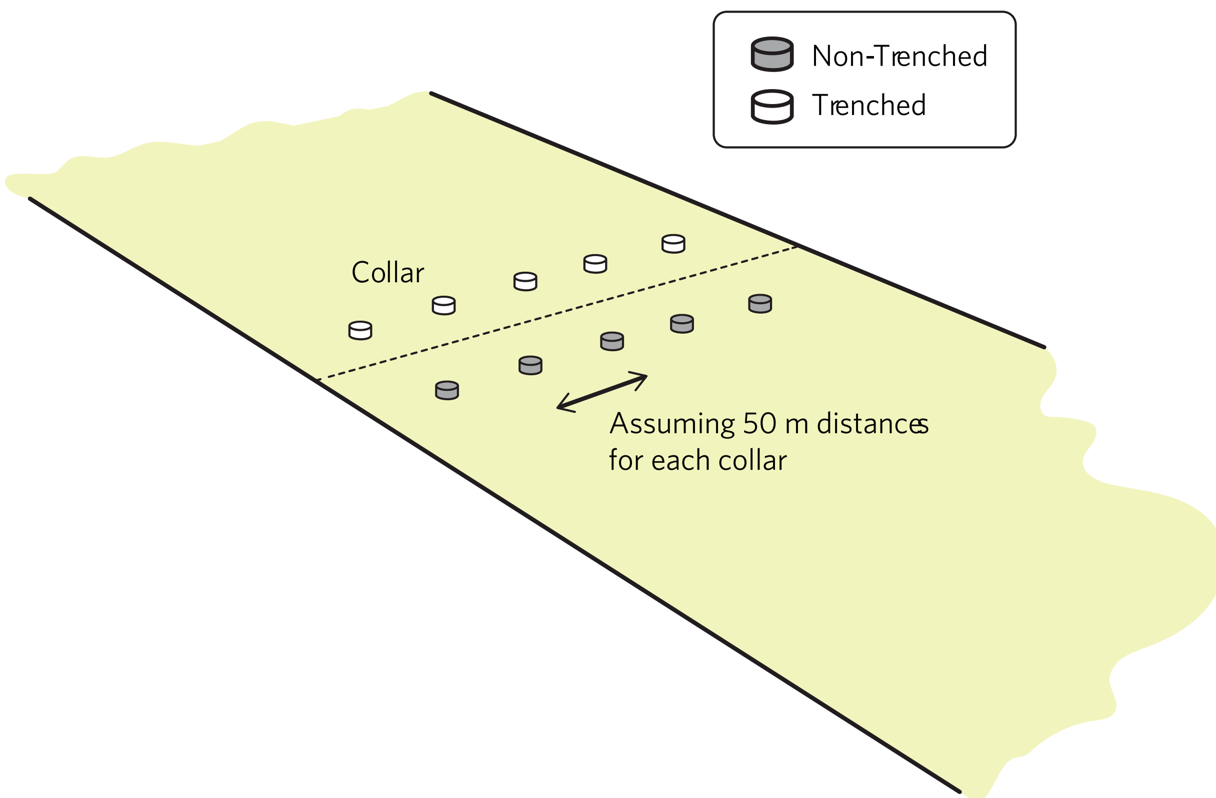


Figure 18. The measurement design for GHG flux measurements within secondary forest


LI-COR
LI-COR
31

6

Figure 19. Documentation design for GHG flux measurements within secondary forest

6.2.3 Preliminary results

Our results indicate that the secondary forest sites emit CO_2 and sequesters CH_4 (**Table 5**). The CO_2 emissions from the secondary forest are smaller than those from oil palm plantations.

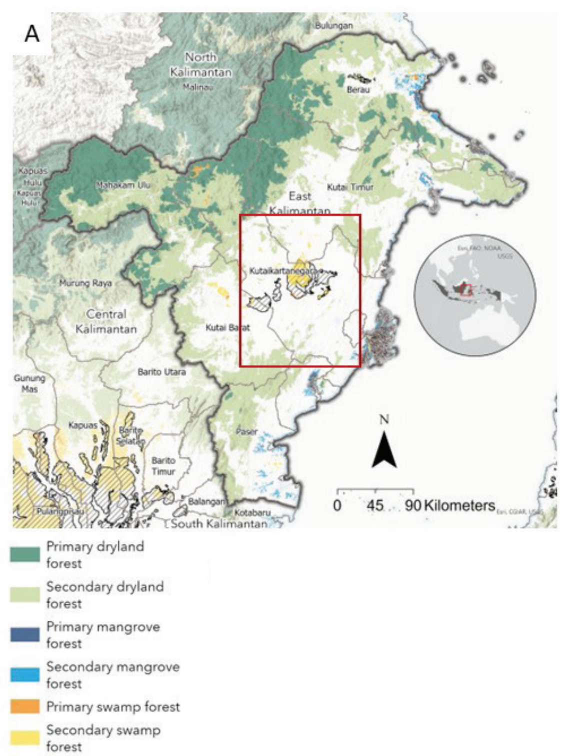
Table 5. The preliminary results of GHG fluxes from secondary forest

No	Site	n	Total Peat Respiration ($Mg\ CO_2\ ha^{-1}\ yr^{-1}$)	Heterotrophic Respiration ($Mg\ CO_2\ ha^{-1}\ yr^{-1}$)	Methane Flux ($kg\ CO_2e\ ha^{-1}\ yr^{-1}$)
1	Secondary Forest	10	23.1 ± 1.7	20.3 ± 1.8	-12.8 ± 5.9

6.3 Measurement of GHG Fluxes from Peat Swamp Forest in East Kalimantan

6.3.1 Overview of the study site

East Kalimantan has 183,050 ha of peatland, of which 42,200 ha can be found in the Muara Siran Village. Within the past decade (2009-2019), 7% of peat swamp forest in East Kalimantan has been converted to other uses. In 2019, based on satellite imagery analysis, 34% (61,407 ha peat swamp forest of a total 183,050 ha peatland area in 2019) of the peatland area in East Kalimantan remains covered by forest, while the rest of the area has been converted into largely oil palm plantations. The Muara Siran peatland is crucial for the livelihoods of surrounding communities and provides a habitat for many endemic species. Despite its positive environmental benefits, Muara Siran peatlands have experienced massive threats due to land use conversion, logging, and slash-and-burn practices. The economy in the area is centered around agriculture and fisheries, and slash-and-burn practices are a common way to open new land during the dry period, resulting in peat fires, which permanently destroy the peat and accelerate carbon dioxide emissions, reversing the natural role of tropical peatland ecosystems from carbon sink to carbon source.



Muara Siran Village is situated on the bank of Mahakam River, in the East Kalimantan province of Indonesia (**Figure 20**). The area can be considered a unique peat swamp landscape, typical to those from the Middle Mahakam region. The area's land cover is dominated by secondary peat swamp forest and wet shrubs, with a notable presence of Siran Lake in the middle of the area. The Siran River flows south of the lake to join Kedang Kepala River downstream of the village and functions as an outlet for the upper catchments. Hydrology plays an important part in the ecosystem functions of the landscape, with frequent flood episodes throughout the year.

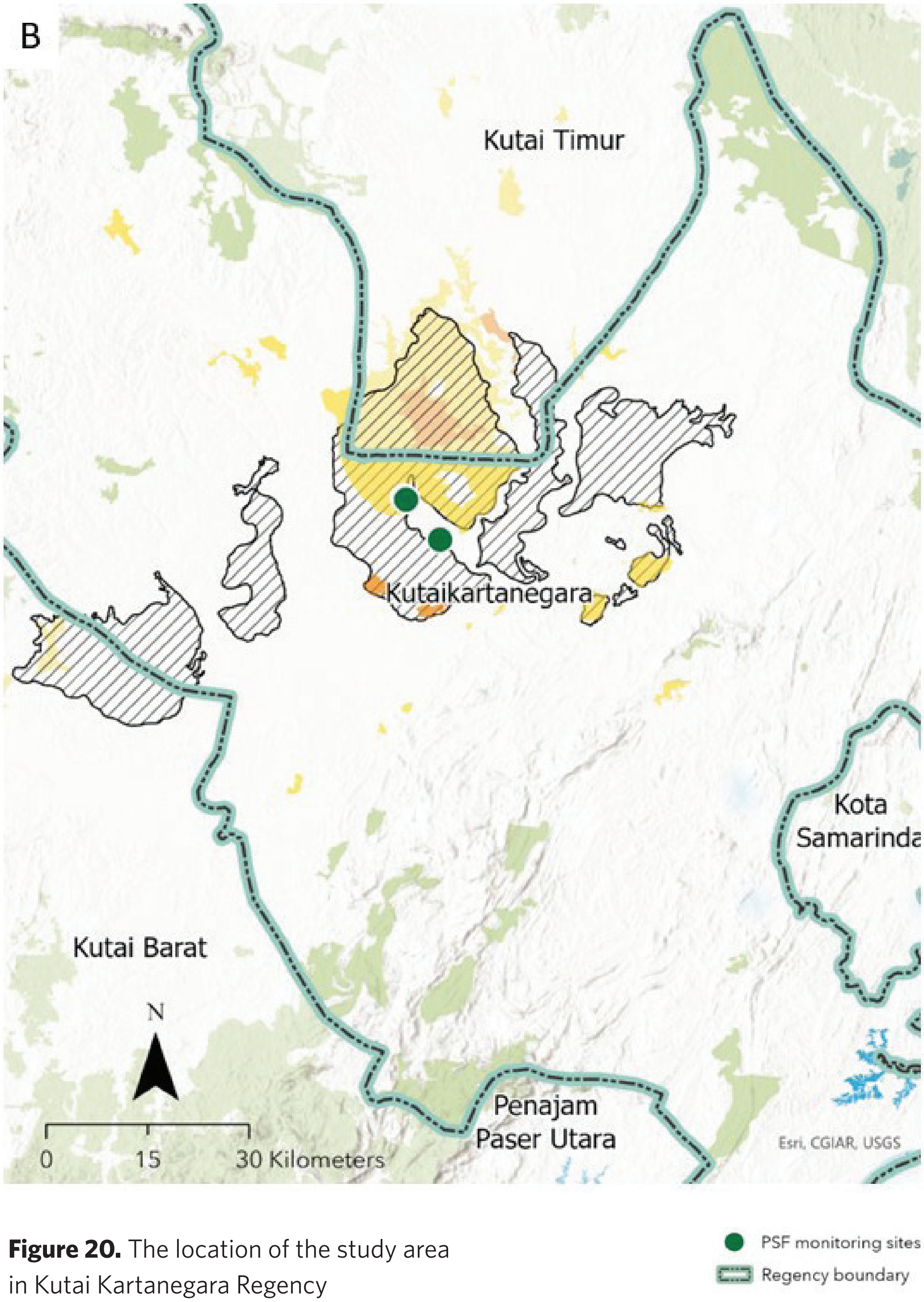


Figure 20. The location of the study area in Kutai Kartanegara Regency

6.3.2 Measurement design

In the peat swamp forest, GHG flux measurements were conducted in two transects with five soil chambers for each transect (**Figure 21**). Our sampling approach was designed to capture spatial heterogeneity in peat respiration and environmental conditions. As the study area is seasonally flooded, we utilized different chamber types to measure peat GHG fluxes in flooded conditions. For the measurements during the non-flooded period, we used 8-inch PVC collars inserted 5 cm into the peat, whereas, for the measurements during the flooded period, we used a floating chamber equipped with the same diameter as PVC. The peat GHG fluxes were measured using a LI-COR portable Trace Gas Analyzer (LI-COR, USA). We measured peat GHG fluxes and environmental parameters monthly from October 2022. For each monthly measurement, the plots were sampled on three consecutive days between the hours of 0800 and 1200. Photographic documentation from the field campaign is provided in **Figure 22.**

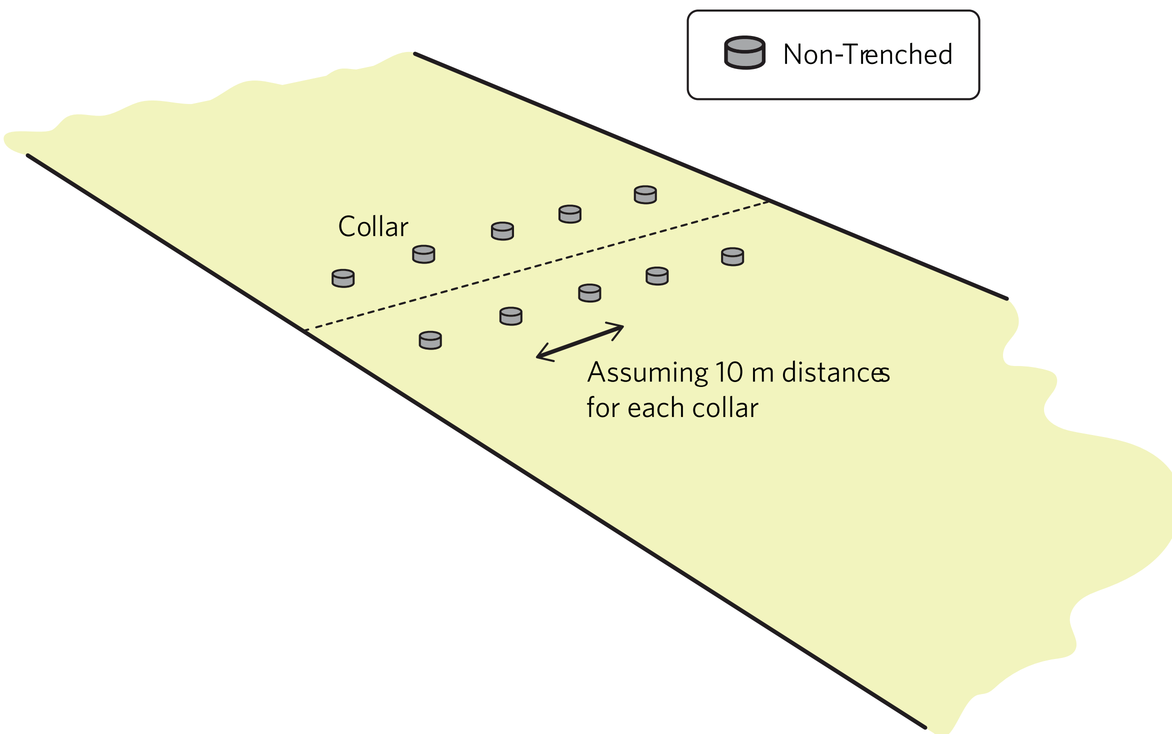


Figure 21. The measurement design for GHG flux measurements in peat swamp forest

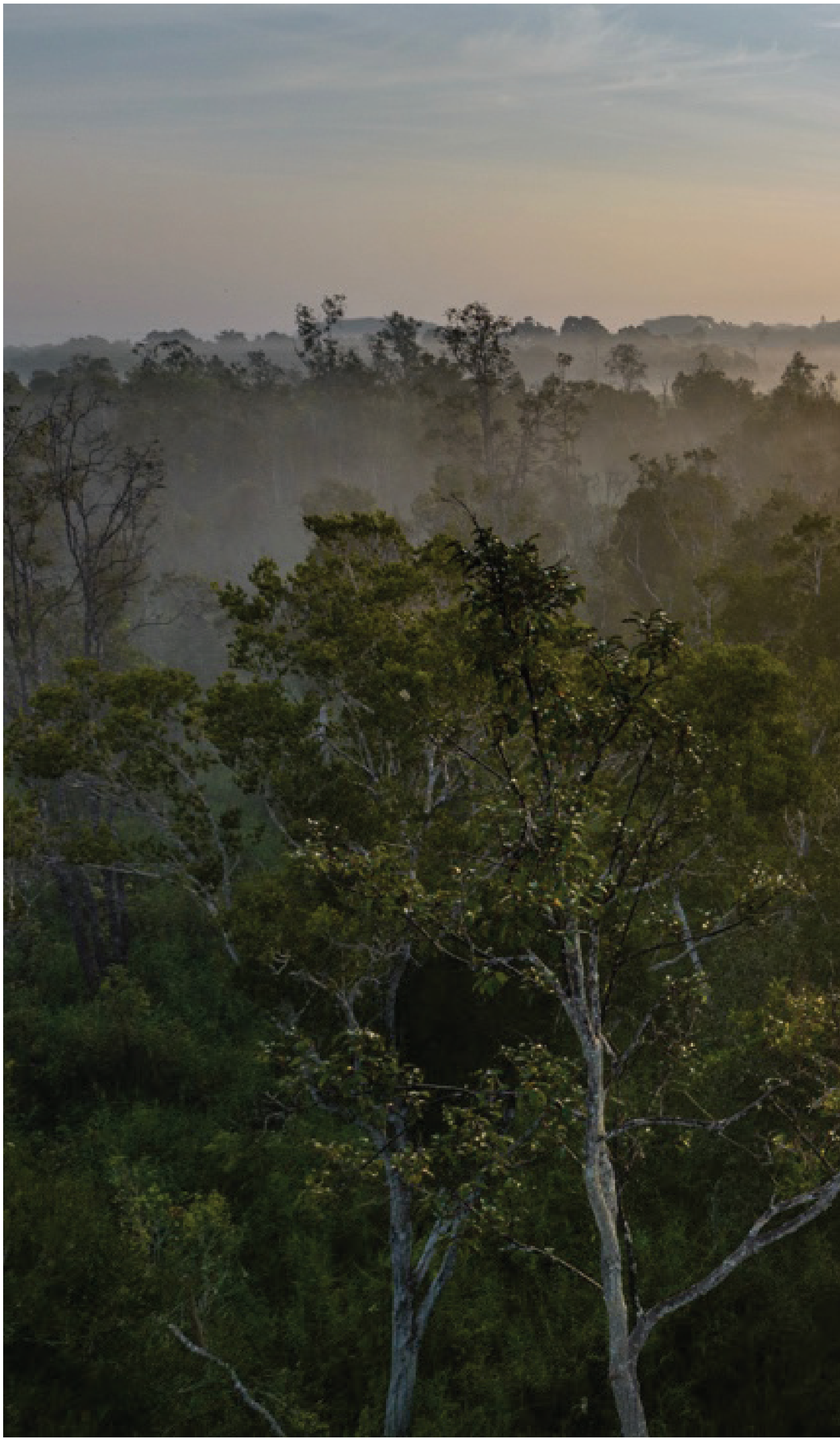


Figure 22. Documentation design for GHG flux measurements within peat swamp forest

6.3.3 Preliminary results

Our results indicate that the peat swamp forest in Muara Siran still emits CO_2, even though we cannot differentiate between the heterotrophic from total peat respiration (**Table 6**). Moreover, the peat swamp forest also emits quite substantial amounts of CH_4 compared to the secondary forest sites.

Table 6. The preliminary results of GHG fluxes from peat swamp forest

No	Site	n	Total Peat Respiration ($Mg\ CO_2\ ha^{-1}\ yr^{-1}$)	Methane Flux ($Mg\ CO_2e\ ha^{-1}\ yr^{-1}$)
1	Peat Swamp Forest	10	13.2 ± 0.7	1.3 ± 0.2

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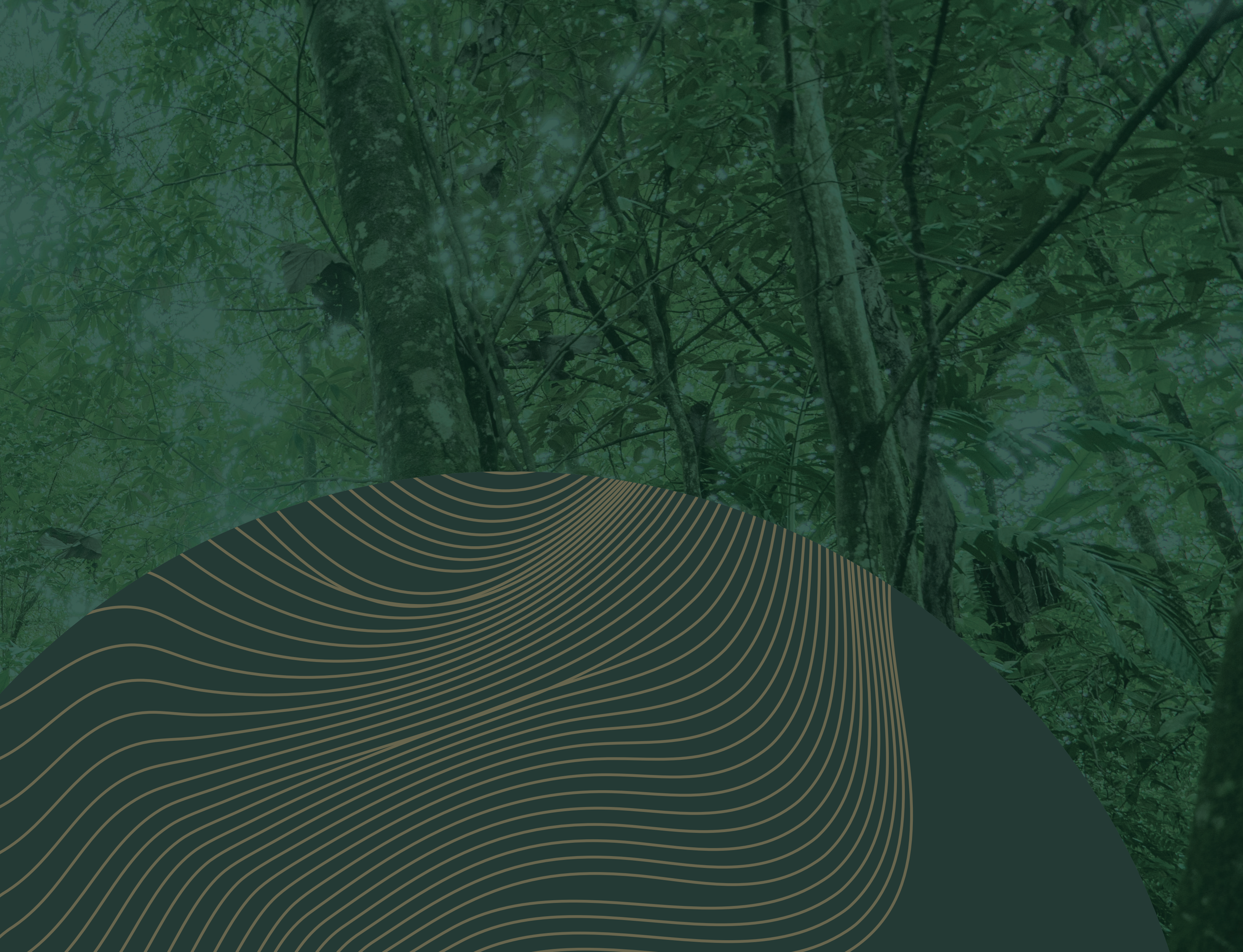

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