


WHITE PAPER

A circular inset image showing a close-up of green leaves and small white flowers, likely from a plant like a willow or similar, set against a blurred green background.

How to measure greenhouse gas soil fluxes

> Know what's in the air.

Contents

Introduction to Greenhouse Gas Monitoring	2
How to measure GHG fluxes	3
A Practical approach: Chamber measurements	4
Typical soil flux setup and measurements:	6
Data Handling.....	6
How to calculate a soil flux	7
Step 1	7
Step 2.....	8
Calculation of flux from concentration data.....	10
Using FTIR technology in GHG measurements.....	11
How infrared FTIR works.....	12
Main benefits of FTIR for measuring GHG fluxes:.....	13
Gasmeter analyzers for flux measurements	14
FTIR-Based Soil Flux Analyzers – GT5000 Terra & DX4015.....	14
GT5000 Terra – Most Compact Ambient Air FTIR Analyzer in the World	15
DX4015 – Portable FTIR Analyzer for Humid Conditions	15
Calcmeter Software	16
Calcmeter Easy & Expert for GT5000 Terra	16
Technical Data for DX4015 & GT5000 Terra	17
Customer Testimonials.....	18





Introduction to Greenhouse Gas Monitoring

The natural emissions of Greenhouse Gases (GHGs), such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) can be disturbed by human activities and pose an enormous environmental threat. The measurement of GHG fluxes which exist between soil surfaces and the local atmosphere is critical to understanding the impact that human activity is having on the ecosystem as a whole and key to understanding what best practices can be used to mitigate subsequent human impact on the environment.

In this guide, a static chamber method is used to measure soil fluxes. In the static chamber method, a chamber is placed at the soil surface and the chamber accumulates the gases emitted from the surface of the soil. An analyzer, in this case an FTIR analyzer, is used to dynamically measure the soil fluxes accumulated within the chamber.

In this guide we will introduce you to how to measure GHG soil fluxes. The guide is aimed at all academics aiming to measure GHG fluxes at soil surfaces.





How to measure GHG fluxes

There have, over the years, been many experimental methodologies developed to measure the flow of gases (fluxes) from the soil into the surrounding localized atmosphere. Today, by far the most common method is the so-called chamber method in which an open chamber is placed on the soil surface of interest to allow the emitted fluxes to accumulate prior to analysis of the gases by a suitable analyzer.

The analysis of the accumulated gases typically falls into two broad practices:

1. Sampling the gases in the chamber using a syringe for subsequent off-line analysis in a laboratory
2. Dynamically measuring the gases in-situ, in real time, using a closed loop arrangement with an analyzer close coupled to the chamber

The popularity of the dynamic in-situ method, apart from the speed and accuracy at which the analysis can be conducted, relates to the ability to make numerous successive gaseous analyses over time allowing data to be easily averaged.

This is in contrast to syringe methods where the methodology is more time consuming and errors can accumulate through sampling anomalies and sample transportation. In addition, the syringe method is fundamentally intrusive to the measurement setup itself ultimately restricting the possibility of analyzing and averaging large simultaneous data sets.



There are numerous types of analytical analyzers on the market today which can be utilized for in-situ dynamic measurements. Available analysis techniques include cavity ring-down spectroscopy, non-dispersive infrared spectroscopy, gas chromatography and the like.

None of these analysis techniques however offer the versatility, practicality and analytical robustness that the technique of Fourier Transform Infrared (FTIR) Spectroscopy offers. Modern FTIR instrumentation offers the portability and robustness to enable an analyzer to be practically taken out into the field, it is not limited to measuring just a few pre-determined gases it can measure a large number of gases simultaneously, FTIR requires no calibration or reference gases, FTIR gives simple concentration results requiring no interpretation and FTIR is above all fast and stable.

This article is intended to give a practical approach to measuring Greenhouse Gas fluxes out in the research field, using the chamber method in conjunction with a modern Gasmeter FTIR gas analyzer. In general, with the correct setup, the correct analyzer and a rigorous systematic approach analyzing GHG fluxes can be a relatively straightforward procedure.

A Practical approach: Chamber measurements

There are many variations and possibilities for experimental chamber setups. The most common technique is to use a chamber with a circulating loop. In this setup, chamber gases are pulled (pumped) from the chamber, passed through the analyzer then returned back to the chamber in a closed loop. This gives a non-intrusive sampling method which is both simple and less prone to any systematic errors



Illustration 1. A chamber for GHG flux measurement placed on the soil surface with a Gaset FTIR in a closed loop configuration

Typically, each chamber consists of two parts:

- > A collar, which can be rectangular or circular in profile, which is sunk into the ground at the point of interest.
- > The chamber itself (rectangular or circular) which is placed over the collar and is sealed to the collar with a suitable seal arrangement.

Collars are important: They ensure that the whole system is consistently sealed to prevent leaks, they offer consistency either for automated arrangements or for arrangements where a single chamber is used in conjunction with numerous collars and they define the area of the surface of the soil to be measured. There are numerous schools of thought as to how deep the collars should be set into the ground, notwithstanding the science they do offer containment of the soil depth profile eliminating migration of any surrounding fluxes.

Chamber geometry appears to have little direct effect on flux estimates as long as adequate air mixing is achieved. Chambers can be made of various rigid materials that don't react with the target gas matrix (e.g. stainless steel, aluminum, acrylic plastic and polyvinyl chloride).

More than one chamber can be used in an experimental setup, allowing topological and geographical spatial data to be acquired. In such a setup one analyzer can be used in conjunction with multiple chambers using an automated multiplexed closed loop arrangement. However, in a simpler arrangement, the same data can be achieved by utilizing numerous spatially arranged collars and a single chamber and single closed loop analysis system. In this instance both chamber and analyzer can be moved from one collar to another.

Commercial, automated chambers and homemade chambers are both equally suitable for Gaset gas analyzers.



Typical soil flux setup and measurements:

1. Sink the collar into the ground to a chosen pre-determined depth. Ideally do this 24 hours prior to analysis. Collars are usually left in place for later use.
2. Consideration should be made of any 'headspace' between the soil surface and the seal of the chamber. Any headspace should be measured and included as part of the volume calculation below.
3. Connect the analyzer to the chamber forming the closed loop arrangement
4. Set the analyzer to measure the gases of interest. Common gases of interest are CO₂, N₂O, CH₄. In this experimental setup we are using an FTIR spectrometer which has the advantage that more gases can be added such as NH₃, NO, NO₂. Remember that with the FTIR technique samples can be retrospectively analyzed for more gases at a later date.
5. Place the chamber over the collar ensuring a firm fit and tight seal. Consideration should again be made to ensure that any 'headspace' is consistent with the seating of the chamber, i.e. ensure that the chamber is always seated the at the same depth over the collar.
6. Begin analyzing. The rate at which individual gas fluxes pass through the soil surface depends on a host of factors but it is common for enough data to be acquired within a 5-minute analysis window. Within this window, an analysis time of 20 seconds will give 15 datapoints for each gas of interest, enough for any statistical averaging.
7. At the end of the analysis, the FTIR computer will typically have 15 spectra (which can be used for subsequent analysis) and a file of 15 concentrations for each gas of interest.
8. Remove the chamber from the collar, stop the analyzer, and move on to the next site with another collar if necessary.

Data Handling

The Gasmeter FTIR analyzer is operated using Gasmeter's propriety 'Calcmeter' software. This software stores data in two distinct ways:



1. Individual **sample spectra** are recorded every 20 seconds (in this case). These spectra contain all analytical data of all measurable gases in the chamber at any time. These spectra can be re-analyzed for more gases at a later date if required thus broadening the scope of research without the complication of monitoring numerous gases from the onset.
2. A **data file** which contains a matrix of the concentrations of each chosen gas of interest against time (every 20 seconds). This data file is excel compatible and this is the data that we will use to calculate the fluxes of each individual GHG gas.

How to calculate a soil flux

Gas flux is the flow of a gas per unit of area across a soil/atmosphere interface. In our experiment we are using the FTIR spectrometer to measure the individual fluxes for individually speciated gases.

Step 1

To calculate the flux for each gas, consecutive measurements of the individual gas concentrations over time is required. The concentration of each gas component will change with time as long as the chamber is in place. In this instance the experiment lasts for 250 seconds with 13 readings of gas concentrations taken in total.

The CO₂ concentration can be seen to rise from a baseline of <400ppm when the chamber is put in place to a maximum of <600ppm when the chamber is removed after ca.5 minutes. This was repeated 3 times to both illustrate and ensure consistency of data.



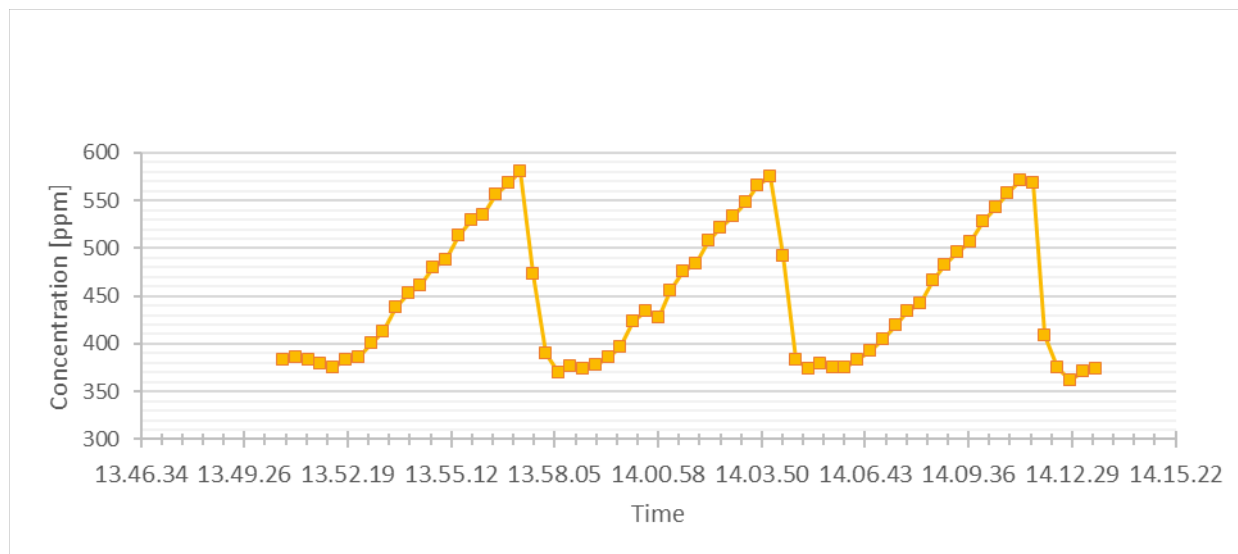


Figure 1. CO₂ soil flux data acquired using a closed loop chamber with FTIR analyzer

Step 2

Gas concentration is measured in ppm for each gas species in the chamber at that moment in time Figure 1. We need to convert each gas concentration into gas flux which has the units mol m⁻² s⁻¹

The following equation is used to calculate the flux (for CO₂ in this example)

$$\text{Soil CO}_2 \text{ flux} = \frac{\partial C}{\partial t} \cdot \frac{v \cdot 10^{-6}}{v_a \cdot \frac{T_2}{T_1}} \cdot \frac{1}{A} \quad (\text{mol m}^{-2} \text{s}^{-1})$$

where

- $\frac{\partial C}{\partial t}$ is the rate of change of concentration of CO₂ [ppm] with time
- v volume of the vessel including cell, sample lines and any headspace (m³)
- v_a molar volume for ideal gas at 273 K = 22.4 x 10⁻³ m³/mol
- T_1 air temperature (K)
- T_2 standard temperature (K)
- A Footprint area of the chamber (m²)

However, the data shows that the increase in CO₂ concentration with time approximates to a linear increase. So, we can apply a linear regression algorithm to the data.



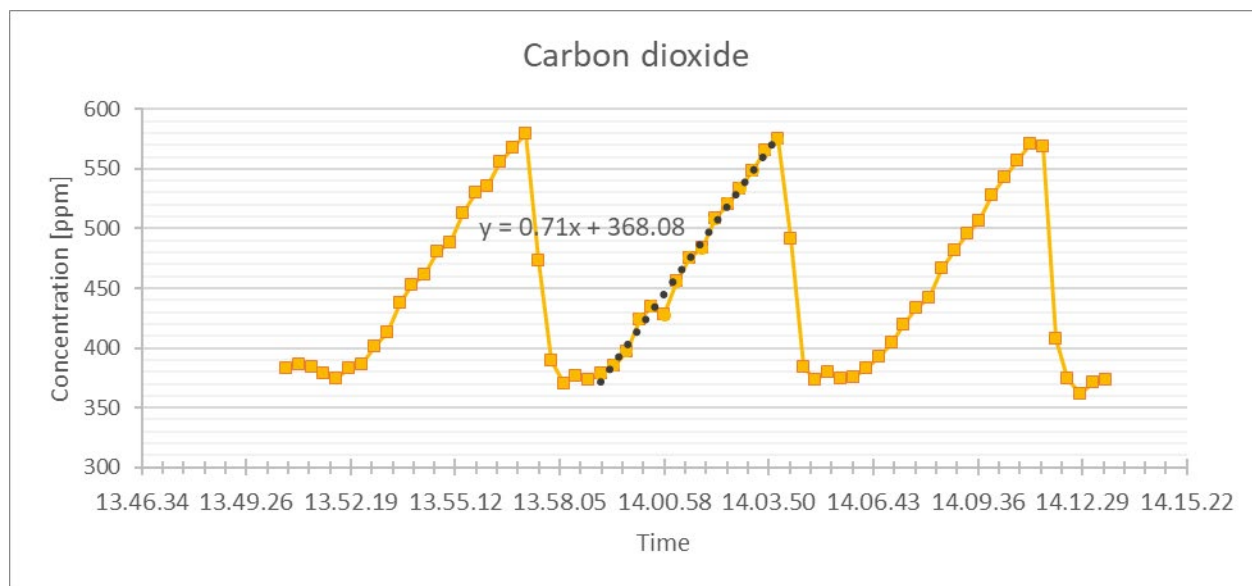


Figure 2. CO₂ soil flux data with a linear regression fitted to CO₂ concentration

Apply a linear regression algorithm to the data approximates the $\frac{\partial C}{\partial t}$ term to the slope of the line and we can rewrite the equation as

$$\text{oil CO}_2 \text{ flux} = \left\{ \frac{C2 - C1}{t2 - t1} \right\} \cdot \frac{v \cdot 10^{-6}}{v_a \cdot \frac{T_2}{T_1}} \cdot \frac{1}{A} \quad (\text{mol m}^{-2}\text{s}^{-1})$$

Convert the units from $\text{mol m}^{-2}\text{s}^{-1}$ to $\mu\text{mol m}^{-2}\text{s}^{-1}$ by multiplying by 10^6 in the equation giving

$$\text{Soil CO}_2 \text{ flux} = \left\{ \frac{C2 - C1}{t2 - t1} \right\} \cdot \frac{v}{v_a \cdot \frac{T_2}{T_1}} \cdot \frac{1}{A} \quad (\mu\text{mol m}^{-2}\text{s}^{-1})$$

where

- C1** is the starting concentration of CO₂ [ppm]
- C2** is the final concentration of CO₂ [ppm]
- t1** is the starting time of the analysis (s)
- t2** is the finishing time of the analysis (s)

Hence, $\left\{ \frac{C2 - C1}{t2 - t1} \right\}$ is the slope of the regression



v	volume of the vessel including cell, sample lines and any headspace (m^3)
v_a	molar volume for ideal gas at 273 K = $22.4 \times 10^{-3} m^3/mol$
T_1	air temperature (K)
T_2	standard temperature (K)
A	Footprint area of the chamber (m^2)

Calculation of flux from concentration data

As well as the analytical data from the FTIR analyzer, other parameters are required:

1. The volume of the entire closed loop must be calculated. The volume is the sum of the analyzer cell and pipework (0.4L), volume of the interconnecting pipework (0.6L), any headspace between the soil surface and the chamber (0.1), and the chamber volume itself (2.55L).

v - volume of the vessel including cell, sample lines and any headspace (m^3) = 3.65L

2. Air temperature. Temperature of the air in the actual chamber should be measured with a thermocouple and used to compensate for volume accordingly in the equation. Note it is also common to measure and record the surface temperature of the soil but this is not required for the calculation

T_1 - air temperature [K] = $273+16= 289K$

3. The footprint area of the chamber should be measured. Strictly speaking this should be the internal diameter of the collar

A - Footprint area of the chamber (m^2) = 0.0189 m^2

4. The slope of the regression shown in figure 2.

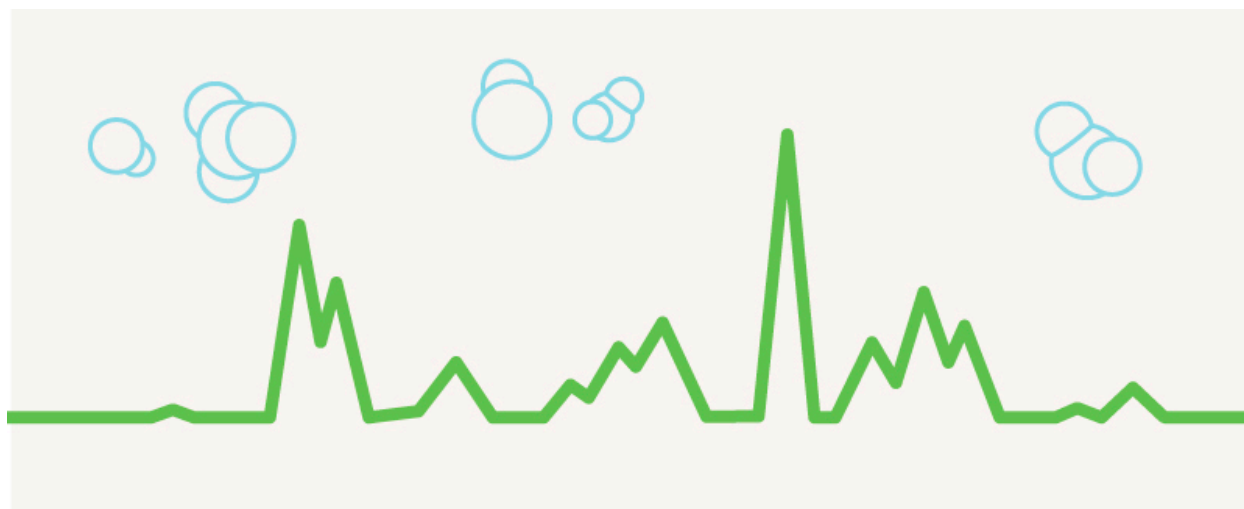
$\left\{ \frac{c_2 - c_1}{t_2 - t_1} \right\}$ the slope of the regression = 0.71 ppm/sec

Substituting into the equation we get

$$\text{Soil } CO_2 \text{ flux} = \{0.71\} \cdot \frac{3.65}{22.4 \times 10^{-3} \cdot \frac{273}{289}} \cdot \frac{1}{0.0189} \quad (\mu\text{mol } m^{-2} s^{-1})$$

$$\text{Soil } CO_2 \text{ flux} = 6.49 \mu\text{mol } m^{-2} s^{-1} .$$





Using FTIR technology in GHG measurements

One of the most reliable and effective technologies for greenhouse gas monitoring is Fourier-transform infrared spectroscopy (FTIR). It is the most powerful technology for simultaneous measurements of multiple gases. What is more, its flexibility and versatility make it a very cost-effective and multipurpose tool for measurements of all GHG compounds and much more. FTIR enables all key gas compounds to be measured simultaneously in just seconds.

The following GHGs are typically measured:

Compound	Formula	Unit
Water	H ₂ O	%
Carbon Dioxide	CO ₂	ppm
Methane	CH ₄	ppm
Nitrous Oxide	N ₂ O	ppm
Ammonia	NH ₃	ppm
Carbon Monoxide	CO	ppm

In addition to the gases listed in the table, FTIR technology allows you to measure VOCs, sulphur compounds or any other inorganic or organic compounds. Check Gasmeter



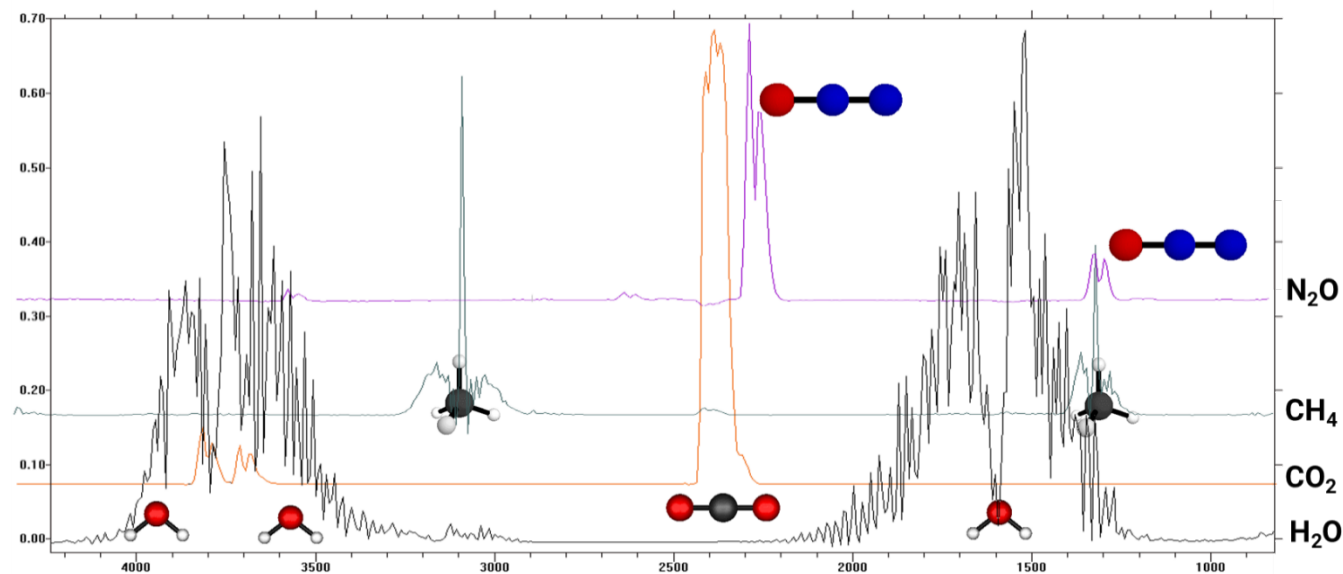
Spectrum Library tool on the website or download the Gasmeter FTIR spectrum library smartphone app (for iOS and Android), to see the list of gases that can be measured and analyzed by FTIR.

How infrared FTIR works

Nearly all molecules can be identified by their characteristic absorption spectrum as each molecule absorbs infrared radiation at their characteristic frequencies. Every molecule has a unique combination of atoms, which produces a unique infrared absorption spectrum. The exceptions are noble gases and diatomic molecules such as N_2 and O_2 , which do not absorb IR light, H_2S is also infrared inactive. IR absorption spectrum can be thought of as a fingerprint unique to each molecule.

The infrared spectrum is a plot of infrared absorption against wavenumber. According to Beer-Lambert law, the absorption (peak height) is directly proportional to concentration, and in this way the IR spectrum can be used to determine concentrations of gases in the sample.

Below is an illustration of typical greenhouse gases in an FTIR spectrum. Individual gases are identified by the shape and position of absorptions and quantified by the height of absorptions.



Main benefits of FTIR for measuring GHG fluxes:

- > **Multicomponent capability** – FTIR is the only technology that measures such a wide range of gases simultaneously. All key GHG compounds such as N₂O, CH₄, CO₂, H₂O, CO and NH₃ can be measured.
- > **High precision and fast acquisition times** – FTIR analyzers can accurately measure very low-level concentration changes in the chamber. This means that a workable dataset can be acquired in a very short timescale and hence any (time dependent) secondary effects that can affect the analysis are minimized: This is shown by the linearity of the data.
- > **Futureproofing your research** – FTIR is a very versatile technology. The number of measurable gases is unparalleled, and the system is easily configurable to measure new compounds without need for hardware changes. As all compounds are measured from the same spectral data, the spectral data can be re-analyzed at a later date for other gases expanding the scope of research.
- > **Proven technology** – large number of successful research projects all around the world, all the way from the Arctic and to the Amazon, by our customers worldwide.
- > **Reliability** – FTIR is extremely accurate and robust technology. It isn't sensitive to changes in surrounding conditions, such as changes in weather.





Gasmeter analyzers for flux measurements

The development of portable, robust, battery-powered soil flux analyzers by Gasmeter Technologies has enabled the reliable onsite analysis of GHGs. These analyzers can be used for different measurements in different ecosystems and soil types with varying GHG emissions:

- > Forest soils
- > Wetlands
- > Agricultural fields
- > Aquatic ecosystems
- > Hydropower reservoirs
- > Ruminants

FTIR-Based Soil Flux Analyzers – GT5000 Terra & DX4015

Gasmeter provides two field deployable non-destructive FTIR based soil flux analyzers for continuous multicomponent gas analyses: GT5000 Terra and DX4015. These robust gas analyzers enable the measurement up to 50 different gas compounds simultaneously. Both soil flux analyzers are ideal for field work and capable of taking samples from several chambers automatically.



GT5000 Terra – Most Compact Ambient Air FTIR Analyzer in the World

The key features of the [Gaset GT5000 Terra](#) include a high sensitivity sample cell for lowest possible detection limits, true multicomponent capability and a built-in-pump, which means that there is no need to use a separate sampling system. The portable gas analyzer is also lightweight (9.4 kg), splash proof (IP54 rated) and battery powered providing unparalleled portability for such a powerful analyzer.

The sample cell of the Gaset GT5000 Terra is at ambient temperature providing low energy consumption for maximum battery life while also minimizing warm-up time of the analyzer.

The analyzer can be operated with Calcmeter software on a Windows tablet or laptop. This software is designed to maximize the portability and ease of use, enabling one-click measurements and immediate results. You can control GT5000 Terra with Calcmeter software via built-in Wifi or Bluetooth and you can even operate it remotely through VPN. The software comes in two versions, Calcmeter Easy for accessible on-field work and Calcmeter Expert for further analysis with advanced tools.

Key advantages of GT5000 Terra

- > Portable and quick set-up
- > Battery operation
- > Wireless communication
- > Simultaneous measurement of all gases
- > Splash proof, IP54 rated

DX4015 – Portable FTIR Analyzer for Humid Conditions

[Gaset DX4015](#) is a portable FTIR gas analyzer for ambient air analysis. The DX4015 include a built-in-pump which means that there is no need to use a separate sampling system. The analyzer can be powered with 12 VDC from for example an external battery, so it can easily be used in field conditions where main power is not available.

The Gaset DX4015's sample cell is heated to 50 °C, which allows measurements to be done in conditions where high humidity is expected and provides temperature stability in changing conditions.

The Gaset DX4015 is operated with the Calcmeter software running on an external laptop computer. This provides a flexible and easy to use user interface for taking measurements and viewing on-line results.



Key advantages of DX4015

- > Portable
- > Quick and easy set-up
- > Built-in pump
- > Heated sample cell for humid air applications
- > Possibility to use external battery power
- > Simultaneous measurement of all gases

Calcmeter Software

All Gasmeter FTIR analyzers come with the Calcmeter software. The software collects, stores and visualizes the FTIR spectra of the sample gas and analyzes the concentrations of gas components.

The Calcmeter software analyzes the sample spectrum using a sophisticated algorithm. It can simultaneously detect, identify and quantify up to 50 different gas components from a single sample. Cross-interference effects are compensated for, and analysis accuracy is maintained even when analyzing complex gas mixtures where gases have overlapping absorption spectra.

Calcmeter software comes with a user interface allowing simultaneous viewing of concentration results, sample and reference spectra and time trends for the analyzed gases. Sample spectra can be easily re-analyzed, since the sample spectra are stored as separate files on an external computer or tablet.

Calcmeter Easy & Expert for GT5000 Terra

Calcmeter Easy is designed for accessible on-field work. With Easy, you get one-click measurements, instructions that guide the user, 5 different views, easy way of exporting the data, trend view and safety features for concentration alarms.

Calcmeter Expert for is for further analysis with advanced tools. On top of everything you get from Calcmeter Easy, Calcmeter Expert offers identification tool for identifying unknown compounds, fine tunable analysis settings, application development tools, simulation tool and customizable views. Both software versions are operated with a Windows 10 laptop or tablet.



Technical Data for DX4015 & GT5000 Terra

	DX4015	GT5000 Terra
Cell temperature	50 °C	Ambient (non-condensing)
Sample pump	1.5 l/min (ambient air)	2 l/min (ambient air)
Power	100-115 OR 230 V / 50 – 60 Hz 12 VDC	115/230 VAC or Rechargeable battery*
Power consumption	300 W (max)	150 W
Operating temperature	0 – 40 °C	-5 – 40 °C
Interface	PC with Windows 10	Tablet or PC with Windows 10
Water vapor (V/V%)	0 – 5 %	0 – 3 %
Sample cell volume	0.4 liters	0.5 liters
Measurement range	sub-ppm to % - levels	sub-ppm to % - levels
Weight	14.9 kg	9.4 kg
Typical analysis time	20 seconds	20 seconds
Measurable compounds	400+ gases including key greenhouse gases, VOCs, etc.	400+ gases including key greenhouse gases, VOCs, etc.
Identification of unknowns	Yes	Yes



Customer Testimonials

Professor Francesco Morari of the University of Padua and Dr. Gemini Delle Vedove of the University of Udine used the DX4015 with an automated multiplexed chamber system for their studies on GHG soil effluxes in croplands.

How was the DX4015 beneficial to your research project?

We used Gaset's DX4015 gas analyzer to monitor continuously GHG's emissions from the soil in shallow water table conditions. While many studies of GHG emissions in shallow water table conditions have been carried out in organic soils, there is not much, if any, previous research regarding shallow water table conditions in mineral soils.

What unique capability does the DX4015 provide your research?

Previously, a closed dynamic system with 12 automated chambers was used to monitor continuously soil respiration (CO₂ soil efflux) every 2h. N₂O soil effluxes were seldom monitored connecting the automated chamber system with an auto-sampler, to collect air samples in 20 ml vials that were then analyzed later in the lab using a gas chromatograph. This methodology is expensive and limits the accuracy and the precision of the measured effluxes. We substitute the auto sampler with DX4015 gas analyzer using the existing pneumatic circuit. The data of DX4015 were time matched with the operations made by the multiplexed chamber system. In such way we were able to measure continuously simultaneously and on-site the GHG soil effluxes and up to 50 other gases. Now we are able to save time and costs and, above all, to monitor from 12 sensors (chambers) sudden changing soil effluxes of trace gases like CO₂, N₂O, CH₄ and NH₃. To our knowledge such apparatus is unique at the moment and it allows a strong and cost-effective improvement in the research of GHG and other gases soil emissions.

How was the experience of working with Gaset?

Thanks to collaboration with Gaset and Ital Control Meters technicians we found an easy and efficient solution in matching the automated chamber system with the DX4015 analyzer. When we encountered set-back due to faulty laser, Gaset and the local retailer were all very collaborative. The spare part was changed quickly without any additional costs to us, and we were soon able to continue. We've been happy with the collaboration and we're in the process of buying another portable gas analyzer from Gaset.



Rajen Bajgain, a post-doc student from the University of Oklahoma, has been using the Gasmeter DX4015 for his studies.

How was the DX4015 beneficial to your research project?

The analyzer was used in understanding the contribution of nitrogen (N) addition to CO₂, N₂O, CH₄ emissions from grasslands. We observed temporal variation in CO₂, N₂O and CH₄ fluxes of key N sources: urine and chemical fertilizer in grazing pasture.

What unique capability does the DX4015 provide your research?

The DX4015 was very helpful to measure major green house gases from soil with one analyzer at one time. Most of the other commercially available analyzers are capable to measure either only CO₂ and CH₄ OR N₂O. With Gasmeter FTIR gas analyzer, the DX4015, we are able to measure all the key compounds, up to 50 gases simultaneously.

Why is it important to be able to measure multiple GHGs in your research?

Management practices and climate change are changing the soil environment which result in harboring different microbial community. It is important to measure all the gas compounds from the soil because varying soil conditions affects gas emissions. We must be able to measure all gases regardless of the soil conditions.

Jenny Bussell, a Soil Scientist at The Allerton Project, UK has been using the Gasmeter DX4040 for agricultural research.

How was the DX4040 (the predecessor of GT5000 Terra) beneficial to your research project?

We've been using the analyzer to understand how changing management strategies affect green house gas emissions from agricultural systems. We've been investigating if shifting to reduced cultivation systems is beneficial for reducing greenhouse gas emissions from soils, particularly CO₂ and N₂O.

What unique capability does the DX4040 provide your research?

The main benefit for us is the ability to simultaneously measure different green house gas emissions directly from the soil. This means we can measure how CO₂ and N₂O are affected by management, but also how changes in soil temperature and moisture affect



gas fluxes, because we can repeatedly measure the soil within our plots as the weather and seasons change.

Why is it important to be able to measure multiple GHGs in your research?

If we are going to change agricultural practices in order to reduce green house gas emissions, we need to fully understand how all the green house gasses respond. CO₂ production often reduces when cultivation is reduced, but with reduced cultivation there is a risk of increased compaction and anaerobic conditions, which favor N₂O production. In order to tackle climate change and reach targets of net zero emissions we need to fully understand how management affects all green house gas fluxes from the soils to find the best solution with the lowest environmental impact.



> Know what's in the air.



Gasmeter Technologies is a Finnish high technology company that develops, manufactures and markets FTIR gas analyzers and monitoring systems for a variety of industrial, environmental and safety applications. Our customers worldwide include, but are not limited to, power plants, waste incinerators, first responders and universities. Our mission is to provide solutions that help improve air quality, protect the environment, help in the fight against climate change, and save lives. Our vision is to live on a clean and green planet with less emissions.



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