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Methods for Understanding GHG Flux from Floodplain Wetlands in Dry Landscapes

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Abstract

Despite the significant developments in methodological approaches to greenhouse gas (GHG) flux measurements, the selection of best method for GHG flux research remain very difficult owing to the fact that nearly all the approved methodologies have some observed limitations that affect the accuracy of flux measurements. In this short review, a comparison of field advantages and disadvantages of chamber-based and microtechnological approaches to GHG flux measurements was attempted. The strengths and weaknesses of flow-through and closed chambers were identified. Similarly, the microtechnological approaches; Eddy covariance technique, Eddy accumulation technique and Eddy relaxed accumulation technique were compared. Even though, these multiple approaches have some advantages over one another, the selection of best method, is to some extents reliant on the research objectives being addressed, resources available, landscape type, time and the skills of the investigator.

Keywords: Flow-through chambers; Closed chambers; Eddy covariance; Eddy accumulation; and Eddy relaxed accumulation

Background

Considerable research on global greenhouse gas (GHG) emissions between landscapes and the atmosphere has focused on measuring emissions of CH_4, CO_2 and N_2O from anthropogenic sources [1]. Recent studies on GHG flux are beginning to acknowledge the contributions of natural ecosystems such as wetlands to atmospheric GHG concentrations [2]. Wetlands including bogs, fens, swamps, marshes, floodplains and shallow lakes and groundwater table occur all over the world, and a global estimate of the extent of natural wetlands is about 5.7 x 10^6 km^2 [3]. These wetlands emit between 40 – 160 Teragram (Tg) of CH_4 per year [4]. While CH_4 fluxes are highly variable in time and space, current estimates of annual global CH_4 flux ranges from 40 – 50 Tg yr^{-1}, of which over 38 Tg yr^{-1} is added into atmosphere mainly from tropical wetlands [5]. Despite the observed fluctuations in atmospheric CH_4 concentrations, there are still large unexplained influences on the global CH_4 cycle, which include emissions from wetlands [6].

Programs designed for wetland restoration and conservation by governments across the world tend to address physical and biological factors, but despite these efforts it is important to note that the global atmospheric concentration of CH_4 is increasing at 40 – 50 Tg annually [7] and many of these emissions come from wetlands [8]. Increased CH_4 concentration in the atmosphere may lead to climate change through radiative forcing and impacts on atmospheric chemistry, consumption of hydroxyl, tropospheric ozone generation and formation of water vapour in stratosphere [1]. Understanding the GHG flux from wetlands helps to inform how they may contribute to global GHG flux in the future due to land use changes, population growth and global environmental change. Effective conservation and management of wetlands particularly in arid and semiarid landscapes (drylands) relies heavily on a thorough understanding of their biophysical and geochemical structure and functions, which operate to control GHG flux.

Wetlands in Dry Landscapes

Wetlands in drylands (WIDS) can be permanent, seasonal or ephemeral. Despite their location in drylands, they are able to support large, deep as well as shallow water bodies, and often are connected to sub-surface flows [9]. Methane emission estimates from wetlands range from 92 to 232 Tg CH4 y^{-1} based on several modelling studies over the last decades [10]. Similarly, GHG (particularly CO_2) emission from dry water courses can be significant, equivalent to that from rivers, permanently inundated wetland ponds and vegetation surfaces [11]. While frequently inundated

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wetlands produce large CH_4 emissions, CO_2 emissions increases with removal of soil moisture [8]. Although dry floodplains and wetlands may have low soil moisture and shallow moisture profiles, their annual CO_2 emission (202 – 326 mg m^{-2} h^{-1}) is nearly double that of the deep groundwater table [12]. In contrast, CH_4 emissions from wetlands (70 – 1437 µg $m^{-1}h^{-1}$) is about ten times greater than from deep groundwater [13].

However, WIDS have discrete and exceptional characteristics that are a function of the climatic variability of drylands and complex biophysical and geochemical processes that act jointly to control GHG flux [14]. The variability in biophysical and geochemical processes in WIDS make these environments disproportionate emitters of GHGs because oxidation on the floodplain causes soil carbon to decomposes more rapidly, thereby producing more CO_2 effluxes [15]. In the same vein, frequently inundated WIDS can be substantial CO_2 sinks [16]. WIDS can also be sources and sinks of CH_4 but the reasons why some wetlands emit more CH_4 than others are yet to be fully explained [17]. As a result, more knowledge of the global sources and sinks of GHGs, and particularly CH_4 in wetlands in dry landscapes, are essential to understand the underlying reasons for this variability in GHG effluxes between landscapes and atmosphere [6].

Methods of GHG Flux Assessment in Wetlands

Greenhouse flux research into wetlands is primarily field-based; relying on scientifically approved methodologies and robust field sampling strategies, standard laboratory procedures and advanced desktop techniques. The key GHG flux research on wetlands has focused on their seasonal variability in GHG fluxes e.g. [14,18]. Greenhouse gas flux during and after flood events [19], vegetation types [20] and diurnal and annual pattern of GHG fluxes [8] as well the prevailing environmental conditions under which these processes are operating [21]. This mini review addresses the most important research methods regarding the GHG flux of wetlands (particularly in drylands) in terms of various methodologies employed to measuring GHG flux between landscapes and atmosphere and the key developments in the field.

Wetlands can emit GHGs in response to a wide range of environmental controls (Table 1). As a result, there is a wide range of field and laboratory techniques which are used to determine the factors that control GHG fluxes.

The key techniques employed by Gatland et al. [19] to identify the impacts of flood on carbon loss and GHG fluxes from coastal wetlands in north-eastern NSW, Australia, were micrometeorological approaches in conjunction with time series sampling. Their study focused on quantifying GHG fluxes during inundation periods. Results of their investigation shows that over 90% of GHG fluxes from coastal wetland system occurred during a single event of a period of flooding. In the same vein, the flooded swamp accounted for ~95% of CO_2-equivalent fluxes. Akumu et al.'s [22] modelling of CH_4 flux from wetlands in north-eastern NSW used a process-based model and chambers in conjunction with a Geographic Information System to identify that CH_4 flux is controlled by wetland vegetation. Denmead et al. [23] used micrometeorological and chamber techniques which enable them to quantify CH_4 and N_2O fluxes from Australian sugarcane soils. They focused on frequent wetting and soil porosity and soil carbon content. The revealed that high carbon content of the soil and pore space are the major controls of CH_4 and N_2O fluxes in sugarcane fields in Australia.

In semi-arid regions characterized by low annual rainfall and high evaporation rates (e.g. Macquarie Marshes), the application of micrometeorological and chamber-based techniques in GHG flux measurements is necessary [24]. This allows for quantification of GHG fluxes and interpretation of flux characteristics using ancillary environmental factors. Therefore, research addressing the controls of soil carbon and GHG flux in wetlands is likely to focus on the influences of soil moisture, temperature, soil organic matter content, aboveground biomass and microbial activities. However, GHG flux from wetlands may vary because of internal threshold responses of GHGs to inundation frequency [21], which calls for a wide range of techniques to identify the controls and drivers of soil carbon and GHG flux in wetlands [25]. This calls for a multi-method-based approach to GHG flux measurement.

Chamber-based approaches to GHG flux measurement

One of the major and frequently used approach when measuring GHG flux between landscapes and atmosphere (including wetlands in drylands) are chambers, even though they represent the smallest scale of measurement, ~1m^2 [23,26-30]. The reasons for their wider application lies primarily in their low cost and maintenance, flexibility and portability [23,28]. Chambers are easy to operate with low field requirements and this makes chamber-based techniques comparatively inexpensive and adaptable to a wide range of environmental conditions [30]. Since meteorological techniques are very expensive with high field requirements, they are mainly used in specific locations with the required meteorological capability [28]. Chamber-based flux measurements have advantage of amplifying the concentration signal with a low instrumental precision due to the fact that the sensors used in for gas flux measurements do not require fast response sensors [27]. The guiding principle of chamber-based technique is to confine the volume of air with which gas exchange occurs to amplify variations in concentration of gas in the head space [23].

Karen and Harriss attempted a review characterising global CH_4 flux from wetlands, their synthesis indicates great variabilities in CH_4 flux between Tropical wetlands, Temperate and Sub-tropical wetlands, and Northern wetlands. Similar variabilities do exist within each climatic region and within wetland zones themselves. These disparities are hardly unconnected to internal environmental controls of GHG fluxes. Therefore, a multi-point sampling across wetlands is unequivocally necessary, and this justifies chamber-based techniques in terrestrial GHG flux investigations. Chambers can be classified in two types: closed and flow-through chambers.

Closed chambers

For more than two decades, there is an increase in scientific inputs on GHG fluxes from landscapes. Between 2010 to 2011, about 365 papers on GHG fluxes were published [31]. Closed chambers are more frequently used in terrestrial gas flux measurements due to their relatively simple design and the ease with which changes in gas concentration can be detected [23]. Closed chambers can be stationary or dynamic. In the former, no air circulates between the chamber and sensor, as a result power is not required. Similarly, replacement of air in the headspace is very negligible which leads to increasing gas concentration [23]. The fundamental principle involved in measuring trace gas concentration after chamber deployment is that gas samples are drawn from the chamber over the order of one hour [30]. Simple

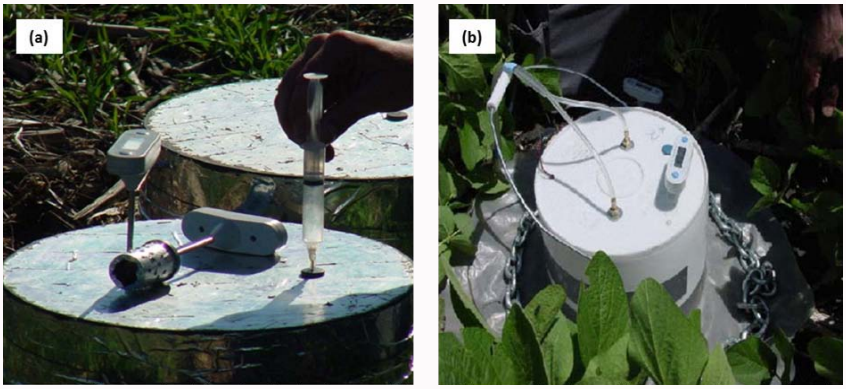

Figure 1: (a) Example of closed-static chambers used in GHG flux sampling from soil. Gas samples are collected using a syringe at a regular interval to facilitate gas flux calculation. (b) Example of flow-through chamber. The chamber has a connections chain of Polyethylene (plastic) skirt placed on soil surface. The chamber is monitoring GHG flux via an infrared analyser. Separate gas samples can be taken using a syringe as in (a) through a membrane for GHG analyses.
Photo: Adopted from [28].

design of a closed chamber is exemplified in Figure 1.

Gas sampling is usually perform at regular time intervals, for example 0, 10, 20, 30, 40, 50 and 60 minutes [28]. Regular timing is important since trace gas fluxes show high temporal variability. Although, time is not the only factor affecting rates of gas concentrations in a closed-static system, many studies support the assertion that significant GHG concentrations occur in chamber after 30 minutes [32], therefore using more than three points sampling will reduce the uncertainty in flux calculations [28]. It is generally accepted that in a closed-static system trace gas concentration occur between 30 and 60 minutes. Therefore, chambers are deployed for a short-time period because prolonged deployment may cause changes in relative humidity, which may cause gas solubility effects [28].

Flow-Through chambers

While closed chambers are widely recommended owing to their low field requirements, using flow-through chambers require some level of expertise, as they are more sophisticated and expensive to assemble and move with compared to closed static system. Chambers are generally flexible and allow for multi-point sampling. The flexibility and theoretical advantages they have over micrometeorological techniques led to wider application of chambers in GHG flux research. Denmead [23] outlined many advantages of using both closed and flow-through chambers; His review cited no example of a study that employed this technique, representing a major gab in His review. In flow-through chambers, the headspace air is changed at a high rate and gas concentrations are calculated from the difference in gas flux at the inlet and outlet of the chambers [33]. The volume of gas concentration in the chamber is then multiplied by the gas flux. The major problem associated with using this approach in measuring GHG flux from soil is that related to pressure gradient that may be caused by the air flow through the chamber [34]. To avoid the pressure irregularities, Norman et al. [32] recommended using chambers with a large inlet (340mm^2) and an air seal so that pressure incongruities are less than 0.004 Pa for a flow rate of 1 L/min. Redding [34] identified that even small gradients <4 Pa can result to multiple increase in gas flux. Despite these shortcomings, associated with flow-through chambers, it is important to understand that this technique has some theoretical advantages over non flow-through system. Redding [34] identified three advantages of using flow-through chambers including: (1) the ability to maintain gas species before chamber deployment; (2) temperature control and (3) humidity control.

However, it will be wrong to draw conclusions on the accuracy of flow-through chambers based on theoretical advantages identified by Redding [34] as well as the operational advantages explained by Denmead, [23] because it is difficult to maintain uniform environmental conditions at all the times within wetlands zones. In addition, if fluxes are very large relative to background atmospheric concentrations, it will be very difficult to maintain even the headspace gas concentrations at the initial time at pre-deployment concentrations [34]. Apart from these limitations outlined above, flow-through chambers are increasingly being used because of their adaptability to long-term continuous monitoring of gas fluxes from small areas compared to non-flow-through chambers [34]. Rochette and Eriksen-Hamel [29] compiled data from a set of 356 closed chamber-based studies and evaluated the quality of these studies based on some standard factors and characteristics to determine the confidence level in the reported N_2O flux. They identified that poor methodologies and incomplete reporting accounted for 60% of the reported errors in absolute values of N_2O flux measurements. However, they acknowledged the improvements in GHG flux measurement methodologies in recent times. Despite the recorded developments in the methodological approaches, about 50% of studies published from 2005 – 2007 have low to very low confidence levels, and studies with high confidence level constitutes <10 % [29].

Freijer and Bouten [26] in their analysis of methods for measuring CO_2 fluxes from soil identified that all GHG flux measurements methods impose a new artificial boundary condition upon the original situation. In closed-chambers, GHG emissions start decreasing within a short period after chamber deployment. They further argued that the correction methods of Hutchinson and Mosier do not account for increasing gas concentrations in the soil profile. However, in flow-through system (Figure 1b), gas concentration gradient stabilizes, and emissions differ very slightly from the original situation. In addition, laboratory analysis indicates that a closed-static absorption method is not capable of absorbing all the effluxes between sampled gases and caustic solution [35]. In flow-through system, which uses a circulation, driving air through the caustic solution, efflux results tend to be more accurate. Notwithstanding these limitations, chamber-based method is inarguably gaining more and more acceptance because they are very cheap, flexible, and adaptable to wide range of environmental conditions.

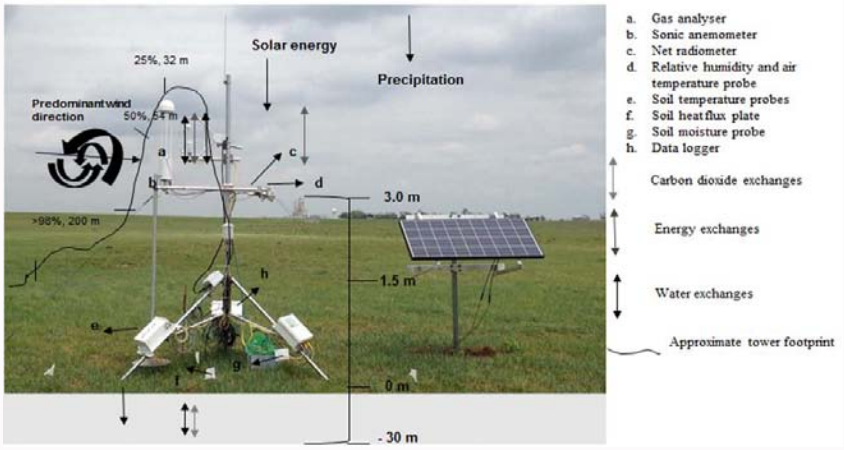

Figure 2: The eddy covariance system measures the exchange of carbon dioxide, water vapour, methane and various other gases between the earth's surface and the atmosphere in different ecosystems.
Modified from (Earth Observation and Modelling – University of Oklahoma 2017).

Micrometeorological approaches to GHG flux measurements

The application of micrometeorological techniques to GHG flux measurements have more field demands compared to chamber-based techniques. The first requirement is to have a relatively homogenous fields with little or no influences from trees, buildings, roads and highlands [29]. Micrometeorological approaches assume that GHG fluxes are approximately constant with height and that concentrations change vertically rather than horizontally [23]. These approaches are therefore very difficult to apply over different environments particularly in grazed fields [29]. Theoretically, a neutral condition of 85 % of flux measurements is required at height *z* originating from the 100 *z* upwind with highest contributions 10 *z* and in practice the fetch to height ratio to be used should be 100:1 [34]. In a highly variable and unstable environments the foot print (source contributing to measured fluxes) is relatively small therefore in practice, expanded fetch to height ratio of 200 – 350: is required for accurate flux measurements [34]. Most of micrometeorological techniques are associated with many problems, which include high instrumentation requirements, incapable of measuring meteorological variables at very high frequencies with multiple heights and the footprint must be smaller than the surrounding source area. In addition, they are very expensive. This means that an accurate flux measurement using micrometeorological techniques over heterogeneous landscapes with high variably of meteorological variables is very difficult. Many types of micrometeorological approaches to GHG flux measurements are well documented in literature. These include eddy covariance, eddy accumulation and relaxed eddy accumulation.

Eddy covariance technique

Eddy covariance technique is widely used in GHG flux measurements. This method enables direct determination of vertical transport of total gas fluxes [23]. It is however, unaffected by stability requirements and its requires no simplifying assumption [34]. The emission/deposition flux *(Fc)* of gas is defined as the covariance between the vertical wind speeds *(w)* and the gas concentration *(C)* measured at point, thus; $Fc = w^{\prime} C^{\prime}$ [27]. Wang, et al. [14] have measured CH_4 fluxes using eddy covariance technique in a temperate forest in Central Ontario, Canada. They identified that CH_4 fluxes correlate strongly with seasonal changes with mean emissions increasing from June to October. However, they established a network of soil static chambers at the tower site and the measured chamber fluxes showed a lot of agreement with the seasonal trend and the overall magnitude of effluxes measured by eddy covariance. Figure 2 illustrates eddy covariance tower installed in grassland environment. Gas fluxes are automatically recorded by gas sensors and stored in data logger.

However, Janne et al. [36] reported similar seasonal correlations of CH_4 fluxes using eddy covariance technique (Figure 2) in a Boreal fen, Finland. In contrast, Hensen, et al. [27] observed that micrometeorological techniques are more reliable than chamber-based methodologies in measuring N_2O flux, because of their ability to measure fluxes over wider range of spatial and temporal scales. At the same time, they failed to acknowledge the fact that this technique do not allow for multi-point flux measurements. In addition, the environmental conditions of the tower station may differ significantly from the surrounding environment which the tower represents. While Denmead, [23] has provided detailed explanations on flux calculations from effluxes measured by eddy covariance technique, he cited no study that compared this method with chamber-based techniques even though recent studies have shown consistencies between the two methodologies.

Eddy accumulation technique

Desjardins et al. was the first to use this procedure. It have a comparative advantage over eddy covariance because it requires no fast response gas analyser [23]. In this technique, gas samples are usually collected using devices that collect discrete updraft and downdraft gas samples, relative to the magnitude of their perpendicular speeds. Gas samples requires no instantaneous field analysis [34]. This make it cheaper compared to eddy covariance technique, even though it uses similar sonic anemometer to measure the perpendicular wind speed. Like eddy covariance technique, in eddy accumulation precise measurements of vertical wind speed is needed and errors between sampling time and wind speed measurements cannot be eliminated [34]. Hicks and Millen test the sensitivity of eddy accumulation technique to errors, using artificial pollutant concentrations signals. They observed that most of the errors and difficulties in using this method are closely related to corresponding deposition velocity. Graus et al. have used eddy accumulation technique to measure isoprenoid canopy-fluxes with an online gas chromatographic analysis and PTR-MS. Turbulent fluxes of isoprenoids showed strong correlations

Table 1: Different controls and drivers of GHG flux from wetlands and the key techniques employed by researchers.

GHG flux	*Controls and drivers*	*Methods used*	*Examples/citation*
High CH_4 flux from forested wetlands compared to open wetlands	Productivity factor, wetland area, methane flux precipitation ratio	A process-based model (Landsat ETM+) + chambers	North-eastern NSW, Australia [22]
CO_2 evasion contributed to wetland C loss, CH_4 evasion contributed to CO_2 emissions	Deoxygenation and acidification in waters	Micrometeorological techniques	Richmond River Catchment, Australia [19]
Seasonal CH_4 flux correlate strongly with soil temperature and organic acid concentrations	Temperature and microbial substrate availability	Static chambers (squared, 10 – 3- litres)	North-western Eurasian and Greenlandic North, Greenland [21]
High correlation between moisture content and reduction of CH_4 uptake rate.	Soil moisture content and temperature	Diffusion chambers (*H* = 600mm, *D* = 150mm)	Landfill, Schoten-Antwerp, Belgium [40]
Variability in GHG flux attributable to contrasting dry matter liability and soil physical properties	Soil water depth and soil properties	Drilling-based technique (Lysimetre)	Orke and Majne-gaden, Sweden [41]
Variation of CH_4 flux correlate to seasonal variation of temperature and precipitation.	Temperature and precipitation	Open-ended static chambers	Sanjian Mire, Sanjiang Plain, Hongyuan county, China [42]
CH_4 fluxes are 30 times higher from ponds compared to adjacent vegetated area.	Underlying peat and activities of N_2 fixing cyanobacteria	Micrometeorological techniques	Boreal and Sub-arctic, USA [43]
CH_4 flux rates varies with planting date, straw addition. Diel variation of CH_4 flux correlates strongly with temperature.	Solar radiation, temperature and straw incorporation	Static chamber technique	Rice fields, Texas, USA [44]
Large hourly variation in CH_4 fluxes, no systematic diurnal variation in CH_4 fluxes.CH_4 flux was exponential to peat and temperature	Peat depth and annual temperature	Eddy covariance technique	Boreal fen, Finland [36]

with primary flux data obtained from enclosure measurements and modelling results determined by a canopy-chemistry emission model (CACHE). Andreas et al.'s analysis of stability dependence of Eddy accumulation coefficient for momentum and scalars indicates that eddy coefficient for momentum depends heavily on surface layer stability. For accurate measurements of GHG fluxes using eddy accumulation technique, high quality plumbing and flow control are recommended [34]. While this method is particularly appropriate for trace gas measurements [23], and provides solution to high frequency sample analysis required in eddy covariance [34], there is a practical severities in maintaining smoothly accurate sampling throughout the range of vertical wind speed fluctuations that occur in the field [34]. This practical problem, led to the replacement of eddy accumulation technique with eddy relaxed accumulation technique.

Eddy relaxed accumulation technique

The fundamental principle of this technique is nearly the same with eddy accumulation. This technique, varies with eddy accumulation in the sense that, collection of gas samples proportional to vertical wind speed is not required [34]. A part from differences in gas sampling procedure, the fast response gas sensor used in Eddy accumulation is replaced with a fast solenoid valve [23]. Verification of GHG emission using relaxed eddy accumulation and eddy accumulation techniques by Horst et al. [37], demonstrates that the former provided more reasonable flux measurements and this pose doubt about the quality of eddy accumulation method. In addition, Ruppert et al.'s [38] scalar similarity for relaxed eddy accumulation techniques have identified different diurnal trend between CO_2 flux, sonic temperature and water vapour using scalar correlation coefficients and spectral analysis. However, poor scalar similarity was found to be related to variabilities in energy content of the low frequency of a section of the turbulent spectra - <0.01Hz [38]. While the strengths and weaknesses of these three techniques are well documented in the cited studies, none of these studies measured GHG fluxes in comparison with chamber-based methodologies [39].

Conclusion

While significant developments in GHG flux measurement methodologies, which led to increased GHG researches across the world, more investigations are needed in order to further advance frontiers of knowledge regarding the GHG flux measurements approaches from landscapes, particularly from wetlands, owing to the fact those wetlands are the major sources of global atmospheric CH_4. Although, there is general agreement among scientists regarding the role of wetlands in global CH_4 budget, there are still many unexplained questions relating to why some wetlands emit more CH_4 compared to other wetlands around the world and this is yet to be fully understood using the current methods of GHG flux measurements. These may hardly be unconnected to both biogeochemical and physical processes that operate to transform GHGs, leading to different emissions of GHG species from wetlands. In order to address these biogeochemical and physical complexities led to development of multiple methods and techniques for GHG flux measurements integrating both processes that act jointly together and influence GHG flux behaviour from landscape surfaces.

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