60. Soil Chamber Measurements

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Chamber measurements form a fundamental approach in quantifying the exchange of trace gases between soils and the atmosphere. A range of chamber approaches has been used, reflecting the progress in our understanding of soil gas flux dynamics and technical capabilities. Minimizing measuring artefacts that are associated with soil chamber measurements have mainly driven these advances, along with a need to obtain soil flux data of appropriate spatial replication and temporal resolution. We here present an overview of the main *classic* CO_2 flux chamber approaches, noting that general principles apply also to chamber measurements of other trace gases. The chapter introduces measuring principles, data evaluation, and key parameters, and covers recent advances in autonomous measurements in the field. We explicitly address the respective strengths and weaknesses of some automated measuring approaches, as these are likely to be critical for long-term assessments of gas flux across many biomes and linked to other atmospheric gas exchange approaches.

Soil CO_2 efflux constitutes the most significant route for carbon assimilated by an ecosystem back into the atmosphere. It integrates a range of different sources of CO_2, such as heterotrophic decomposition of organic matter, metabolic processes by roots and associated mycorrhizas, respiration by soil-dwelling animals, and mineral CO_2 sources [60.1, 2]. Accurate measurement of this flux is fundamental for establishing C exchange dynamics within ecosystems, and chamber methods are the most commonly employed methodology to do so. Knowledge of soil CO_2 efflux dynamics over diurnal, synoptic, seasonal, or annual scales provides important insights into the processes underlying it and allows a more detailed analysis of ecosystem-scale fluxes (such as total ecosystem CO_2 exchange) into aboveground and belowground fluxes. As well as

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providing direct estimates of soil metabolic activity and its biotic and abiotic drivers, flux measurements are often coupled with experimental manipulations or complementary measurements that enable a more detailed investigation of flux sources (e.g., autotrophic versus heterotrophic C sources) and biological interactions (e.g., root and mycorrhizal dynamics, or soil faunal and plant phenological dynamics).

The exchange of other trace gases between soil and atmosphere is no less important and has similarly received considerable attention in the scientific literature. For example, the emission of methane (CH_4) in wetlands is an important component of the greenhouse-gas balance of these systems [60.3]. Uptake of methane through microbial oxidation in upland soils, on the other hand, also affects regional budgets, whilst emissions of nitrous oxide (N_2O) is of relevance in agricultural studies, particularly under high fertilizer use [60.4, 5].

The aim of this chapter is to give an updated appraisal of the main chamber designs in the scientific literature and to highlight current systems and recent advances. A number of overviews of chamber methods for soil trace gas exchange exist, and we acknowledge the range of information provided in these [60.6, 7]. We summarize information also given in earlier reviews, with our own critical appraisal of designs and data processing, and include recent approaches and instrumentation to measure soil–atmosphere gas exchange using chambers. Much of the overview focuses on soil CO_2 flux chambers, as the majority of published methods and applications are on CO_2 exchanges, but general principles apply to the measurement of other trace gas exchanges between soil and atmosphere, and we include some details on recent instrumentation and considerations for applications of chambers.

60.1 Measurement Approaches, Principles, and Parameters

The purpose of any chamber is to create an enclosed air volume in which changes in concentration of gases exchanged between soil and atmosphere can be monitored. As such, the placement of a chamber on the soil surface causes an alteration of the natural conditions in terms of abiotic parameters (e.g., temperature and humidity), as well as gas concentrations and exchange processes due to alterations of diffusive and turbulent transport across boundary layers [60.8, 9] or variations in static pressure [60.10–12]. The degree to which any artefacts resulting from chamber placement affect flux estimates depends on the type of chamber and measuring principle involved.

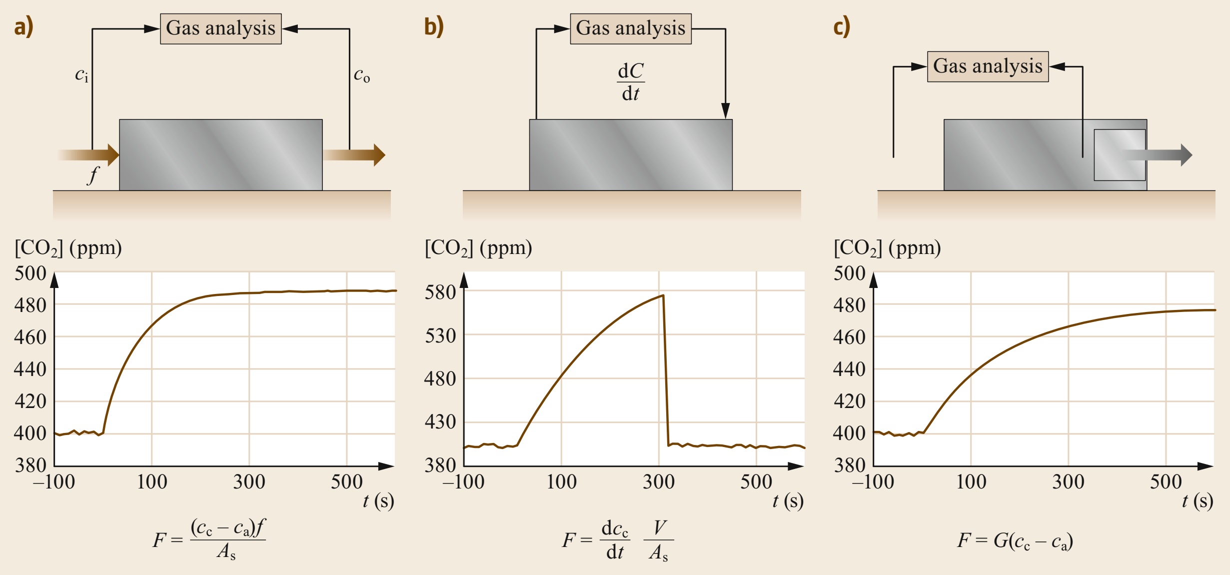

Fig. 60.1a–c Overview (principle, internal CO_2 concentration, flux calculation) of main chamber designs used to measure trace gas exchange between soil and atmosphere: **(a)** steady-state chamber, **(b)** non-steady-state chamber, and **(c)** forced diffusion chamber. See Table 60.1 for the meaning of measurement parameters of flux calculations

Soil chambers have been used to measure CO_2 flux for the past 100 years [60.13, 14], and different shapes, designs, and principles have evolved throughout this period. Chamber types have been categorized into *closed/open*, *dynamic/static*, *flowthrough/non-flowthrough*, or *steady-state/non-steady-state* designs [60.15]. Many of these descriptors are, in fact, synonymous, e.g., an *open* chamber is also necessarily *flowthrough* and *steady state*, and a *closed* chamber can be *flowthrough* or *non-flowthrough*, and measurements are derived from *non-steady-state* conditions. For simplicity, we here adhere to the classification of chambers based on whether fluxes are measured at *steady state* or *non-steady state* [60.16], but note the potentially confusing use of other categorizations used in the literature.

Non-steady-state chambers work on the principle that chambers are closed for a specific length of time, and fluxes are calculated from changes in chamber concentration during this period. *Steady-state* chambers monitor gas exchange based on the concentration differential between ambient air and chamber headspace volumes. The steady-state conditions are created by continuous exchange of CO_2 with the ambient atmosphere. *Open* chambers have a continuous flow of air through the headspace, maintaining a connection to the ambient atmosphere. Flux calculations are based on the concentration differential between air entering and leaving the chamber. A novel *steady-state* approach measures the rate of CO_2 diffusion across a permeable membrane to establish soil CO_2 efflux based on the CO_2 concentration within an otherwise closed chamber headspace (*forced diffusion*). Figure 60.1 gives an overview of the key features of these broad chamber categories, whilst a detailed description of theory of operation and implications for specific measurement tasks are given in Sect. 60.3.

Table 60.1 Measured parameters of soil chamber measurements

Parameter	Description	Unit	Symbol
All chamber approaches			
Gas concentration in chamber	Amount (mass) of gas species in chamber headspace	$kg\,m^{-3}$	c_c
Ambient gas concentration	Amount (mass) of gas species in ambient air	$kg\,m^{-3}$	c_a
Molar fraction	Fraction of a gas species in air	$mol\,mol^{-1}$ or ppmv	χ
Pressure	Air pressure in chamber headspace	Pa	p
Temperature	Air temperature in chamber headspace	K	T
Water vapor concentration	Fraction of water vapor in air	$mol\,mol^{-1}$ or ppmv	χ_{H_2O}
Chamber area	Area of soil covered by chamber	m^2	A_s
Chamber volume	Total volume of chamber (including external volume of tubing, analysis cell and pump)	m^3	V
Steady-state chamber			
Air flow rate	Volume flow of external air passing through chamber headspace	$m^3\,s^{-1}$	f
Non-steady-state chamber			
Duration of closure	Exact time of sampling from headspace since start of chamber closure	s	t
Forced diffusion chamber			
Diffusivity	Area-specific effective membrane diffusivity	$m^2\,s^{-1}$	D
Path length	Effective diffusive path length	m	L
Scalar	Single term for conversion of chamber-specific membrane area, diffusivity and path length	$m\,s^{-1}$	G

Table 60.2 Other measurements commonly performed alongside chamber flux measurements

Parameter	Description	Unit	Symbol
Soil temperature	Current temperature of soil, ideally covering a number of depth increments	°C	T_s
Soil moisture	Volumetric or gravimetric water content of soil; normally applied to surface soil layers, but ideally obtained across several depths	$m^3\,m^{-3}$ or $kg\,kg^{-1}$	SWC
Air temperature	Temperature of ambient air	°C	$T_{ambient}$
Water table depth	Depth of water table below soil surface	m	h

60.2 History of Soil Chamber Measurements

Soil CO_2 flux chambers have been used for about 100 years [60.13], and their design has changed with the variety of research and monitoring requirements, analytical capabilities, and the advancement of the understanding of the disturbance that may be created by chambers themselves. The main measurement principles of chambers used today have not changed over many decades, and the basic theory outlined in Sect. 60.3 and models presented in Sect. 60.4 represent refinements on what has been only a small number of successful measurement designs.

However, whilst the principal physical design of soil chambers has not changed fundamentally, methods of determining the flux rates measured with these chambers have, in fact, evolved. In this section, we outline a number of key methods to determine CO_2 concentrations that have been widely used in the past but are now only rarely used.

60.2.1 Offline Sampling and Chemical Absorption

Initial chamber designs follow the current *closed chamber* principle, where a headspace of known volume is created over a specific soil area to trap CO_2 emitted from the soil (Sect. 60.3.1). This *respiration bell* (Fig. 60.2) [60.13] was left in place over a defined period of time (e.g., 10–20 min [60.13] or 1 h [60.17]), and CO_2 concentrations were determined either by extracting a small volume of gas (e.g., 20 mL) from the headspace for determination of CO_2 concentration at the end of this period, or by allowing CO_2 to be absorbed onto a chemical trap throughout the period of chamber closure. The calculation of soil CO_2 flux rates was then simply based on the total amount of CO_2 observed in the headspace, following analogous calculations to those presented in Sect. 60.3.1.

These early measurements provided useful insights into the general dynamics of CO_2 flux and allowed comparative studies of flux rates from different soils and over different measurement periods. However, the static nature of these measurements creates a number of problems associated with the buildup of the CO_2 concentration following chamber closure.

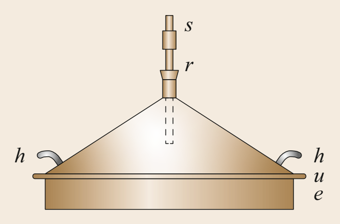

Fig. 60.2 Early model of a closed respiration chamber termed *respiration bell* by *Lundegårdh* in 1926 (after [60.13])

The offline sampling method assumes that the buildup of concentration in the headspace is linear or, in other words, that the rate of CO_2 flux from soil to chamber is constant throughout the period. However, the soil surface flux rate is highly sensitive to changes in the concentration differential between the chamber headspace and air in superficial soil pores. As the headspace volume progressively enriches in CO_2, this differential progressively decreases, leading to a lower rate of net flux of CO_2 from soil to chamber. Over time, also the soil profile beneath the chamber is enriched in CO_2 relative to the natural soil CO_2 profile, leading to lateral diffusion of CO_2 and, hence, an underestimation of CO_2 efflux. Figure 60.3a illustrates the reduction in the concentration gradient from the headspace into the soil profile. Note that the graph is not based on direct measurements but was produced using a 1-D diffusion model. It clearly shows the reduction in concentration difference between headspace and superficial soil pores, as well as within the soil profile (here illustrated for 3 and 5 cm soil depth), resulting in a diminishing diffusion gradient and hence decreasing measured CO_2 flux (Fig. 60.3c). The 1-D model does not account for lateral diffusion in soil pore spaces adjacent to the chamber footprint, which is likely to occur once a lateral gradient has been established. This would further reduce the CO_2 gradients beneath the chamber, as the observed increase in soil pore concentration would be less pronounced owing to the *loss* of CO_2 from soil pores beneath the chamber. Scenarios shown in Fig. 60.3 simulate an initial surface CO_2 flux of $1.5\,\mu mol\,m^{-2}\,s^{-1}$. For a static chamber with continuous CO_2 enrichment, the flux reduces soon after chamber closure (0 min) and continues to drop up until the chamber is opened after 60 min. The spike in soil CO_2 efflux seen after 60 min is a result of the artificially increased CO_2 concentrations in the soil profile. Early measurements of soil CO_2 flux based on prolonged period of concentration enrichment are, therefore, likely to represent underestimates of soil CO_2 efflux.

Closed chamber methods using continuous chemical absorption of CO_2 have the opposite effect on the atmosphere–soil concentration gradient, as the efficient absorption of CO_2 in the headspace would artificially increase the CO_2 concentration differential to soil pore spaces. The impact on the soil CO_2 gradient is much lower compared to chambers with CO_2 enrichment, so that the overall bias from this effect alone is of smaller magnitude (Fig. 60.3b,d). However, there are

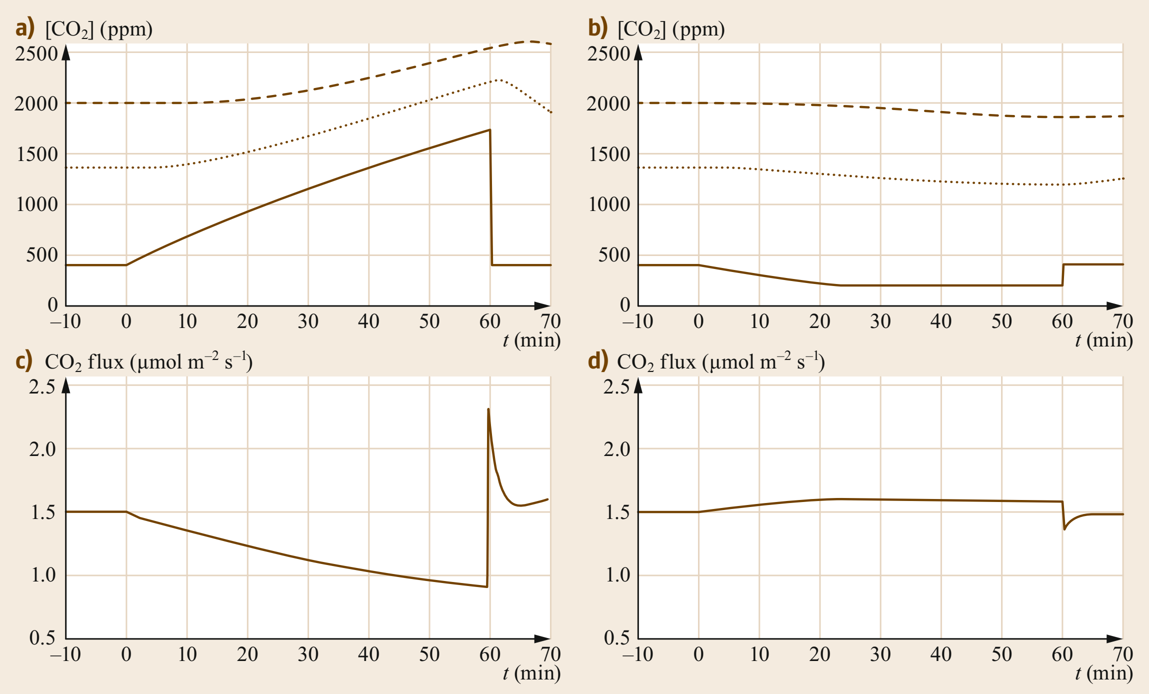

Fig. 60.3a–d Simulated CO_2 concentrations in the chamber headspace (*solid black line*) and soil pores beneath the chamber at 3 cm (*dotted line*) and 5 cm (*dashed line*) soil depth for a closure time of 1 h. **(a)** CO_2 enrichment scenario, **(b)** CO_2 absorption scenario, and **(c,d)** calculated surface CO_2 flux for both scenarios

further uncertainties associated with the efficiency of CO_2 absorption over the period of chamber closure, and additional efforts associated with handling of chemical reagents in the field combined with a more labor intensive analysis of CO_2 concentration determination mean that this method is used very rarely for flux measurements of CO_2 in the field.

60.2.2 Steady-State Flowthrough Chamber Designs (*Open Chambers*)

An early design for continuous soil respiration measurement from a single chamber was proposed in 1953 by drawing ambient air through the headspace of a soil cover to estimate soil CO_2 efflux from the enrichment in CO_2 [60.18]. These early chambers consisted of a frame firmly anchored in the soil, on which a lid was placed to create a chamber headspace. Single chambers of this design were then connected to an infrared gas analyzer (IRGA), with air flowing at a known rate through the chamber, and the difference between ambient air and chamber air recorded (Sect. 60.3). Further development of that technique with multiple chambers sampled sequentially were reported in the late 1960s [60.19–21] to improve spatial coverage and produce a first complete time series of soil CO_2 efflux in forest ecosystems. To avoid prolonged disturbance of the soil environment caused by the presence of chambers, early versions of these steady-state chambers already included *moving chamber* designs, where robotic drives opened and closed chambers between measurement cycles [60.22].

60.2.3 Field-Portable Chambers

Field-deployable IRGAs enabled direct monitoring of CO_2 increase in chamber headspace concentrations. Commercial availability of small IRGA units from the early 1990s facilitated shorter deployment periods and a more robust analysis of CO_2 concentration evolution in headspaces [60.23, 24]. In this chamber design, air is continuously exchanged between the chamber headspace and a portable infrared gas analyzer via tubing or by directly mounting the analyzer on the chamber (Fig. 60.4). This (quasi) continuous monitoring of concentration increments over the deployment period yields data with which assumptions regarding the linearity of the concentration increase can be tested, and potential errors resulting from a diminishing CO_2 diffusion gradient corrected (Sect. 60.3.1). The more portable design of chamber and analyzer and significantly shorter deployment period when compared to the chemical absorption methodology meant that researchers could measure from a larger number of locations with significantly reduced effort. Several off-the-shelf measuring systems have since become available, incorporating much of the advancement provided by the early experimental setups (Sect. 60.4).

60.3 Theory

Gas exchange between soil and atmosphere is mainly driven by the gradient in concentration within the soil profile, where there may be a range of sources of sinks of trace gases. Random movements of molecules lead to a net flux across the soil surface due to concentration differentials between soil layers and across the soil–atmosphere interface. In the absence of turbulent exchange or mass movement of air due to pressure fluctuation caused by wind, the trace gas flux could theoretically be calculated using Fick's law if concentration profiles, effective soil porosity, and diffusion constants in air are known [60.25]. However, the typical heterogeneity in physical structure, as well as organic matter and moisture contents of especially the superficial soil horizons, renders it difficult to predict the actual diffusivity across the soil–atmosphere interface. Furthermore, atmospheric turbulence induced by advection (wind) near the soil surface or pressure fluctuations due to wind gusts results in a *flushing* of superficial soil pores. Such mass movements of air produce a much faster transport of trace gases than diffusion processes and also impact the soils' internal concentration gradients.

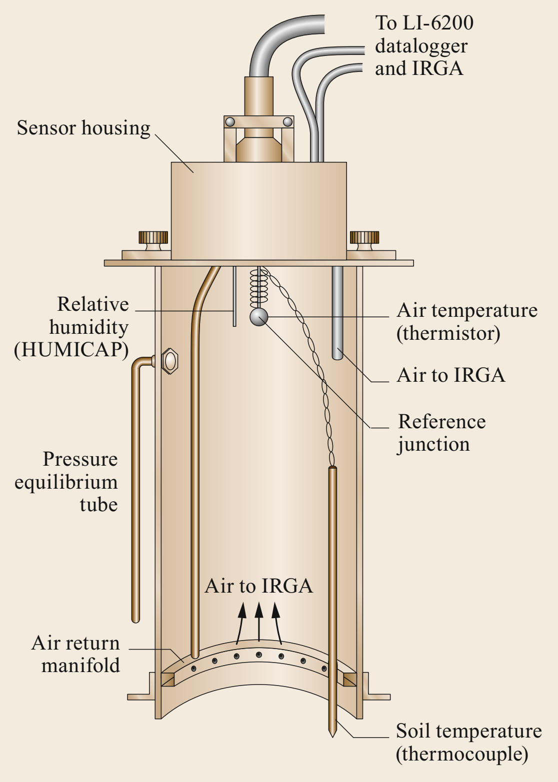

Fig. 60.4 Portable non-steady-state soil CO_2 flux chamber (after [60.23] © John Wiley and Sons)

Besides the fluxes into the chamber headspace, the design of flux chambers must account for the processes driving exchanges of CO_2 *within* chambers. Some chamber models use small fans to minimize the development of boundary layers that would cause the buildup of concentration gradients within chambers as an artefact of chamber placement. Especially in the case of the non-steady-state chambers, where fluxes are calculated based on the changes in concentration over time, an effective mixing of chamber headspace is important. Turbulence caused by fans partly compensates for the absence of the *natural* turbulence caused by wind but has the risk of increasing soil–surface exchanges by artificially *eroding* the soil surface boundary layer and enhancing the flushing of soil pore spaces, resulting in artificially large soil CO_2 efflux estimates [60.9]. Moderation of fan speeds and careful placement of fans to avoid directing airflow directly towards the soil surface can mitigate this risk. Many chamber designs, however, do not include forced air movement by fans and use airflow induced by the circulation of air between analyzers and chamber to create an effective mixing of the chamber headspace (Fig. 60.4).

60.3.1 Mass Flow and Pressure Issues

Pressure changes within the chamber headspace result in mass flow of air in and out of soils [60.26]. Where the chamber itself induces pressure changes, this represents a potentially significant artefact for flux rate measurements [60.27, 28]. Placement of a chamber on the soil, or closure of chamber covers onto a chamber base or collar, are potential situations where a positive pressure within the chamber may push atmospheric air into the soil profile. In situations where the presence of the chamber operator near the chamber causes compression of soil, displacement of air volumes under the measurement area of a chamber would also influence observed chamber fluxes owing to artificial flushing of soil pores. This is likely to be a significant consideration in peatlands or other high-organic soils, where compaction of soil leads to lateral movement of either air or water, hence propagating mass movement and artificial soil–atmosphere gas exchange.

The act of pushing air volumes from the chamber headspace into the superficial soil layers alters the gas concentration profile and is likely to lead to an initially lower exchange of the trace gas, as an artificially low concentration gradient between the uppermost part of the soil column and atmosphere is created. Compaction of soil around chambers is likely to result in the opposite effect, where air is forced from pore spaces beneath the chamber, creating an apparently greater flux than what would occur naturally.

Prolonged chamber deployment (commonly used for the measurement of rarer gases than CO_2) may also lead to a heating of the chamber volume, resulting in an expansion of the air volume and resulting in pressurization of the headspace. Alongside the physical expansion of air following an increase in temperature (following the relationship between temperature and pressure described by the ideal gas law), evaporation of water from soil and plant surfaces can contribute to a slight increase in chamber pressure, whilst also diluting the concentration of trace gases (Sect. 60.3.2).

In contrast to such artificial pressures effects in soil chambers, naturally occurring atmospheric pressure fluctuations can be considered to form part of the inherent gas exchange between soil and atmosphere. However, closing off these fluctuations by the use of a chamber could underestimate flux values.

Most chamber models include small pressure vents that minimize air pressure differentials between ambient and chamber headspace atmospheres (Fig. 60.4). These vents mitigate both pressure artefacts from placement/closure of chambers and continuous wind-induced fluctuations. The design of the vents with small diameters aims to minimize ingress and egress of CO_2, whilst allowing equilibration of pressure differentials by a small volume flow of air.

60.3.2 Concentration Corrections and Flux Calculations

All chamber approaches have to account for changes in partial pressure of other gases that occur during the period of measurement. Evaporation from the soil surface, as well as transpiration by plants present within the chamber, can cause increases in water vapor in the chamber headspace. This addition of water molecules to the mixture of gases making up the chamber air means that the rate of trace gas fluxes can be underestimated (in the case of a net efflux from soil) or overestimated (in the case of a net soil uptake).

It is, therefore, advised to include measurement of water vapor pressure (χ_{H_2O}; Table 60.1) content in both air streams and correct measured CO_2 concentrations accordingly. Many commercial chamber systems can perform such a correction as a factory default, providing e.g., *dry* CO_2 readings.

60.3.3 Non-Steady-State Chambers

Non-steady-state chambers are the most commonly used in the scientific literature. The measuring principle relies on a chamber being placed on the ground to create an effective isolation of a defined airspace (*headspace*) in which gas exchange with the underlying soil surface leads to changes in headspace gas concentrations. These gas concentration changes are then monitored continuously by either having a sensor placed directly in the chamber or by pumping a small volume in a closed loop between chamber headspace and the measurement cell of an analyzer (e.g., nondispersive infrared gas analyzer, cavity ringdown spectrometer). The CO_2 mass flux rate at a given time point during the chamber closure ($F(t)$; in $\mathrm{kg\,m^{-2}\,s^{-1}}$) is calculated from the mass concentration change with time ($\mathrm{d}c/\mathrm{d}t(t)$; in $\mathrm{kg\,m^{-3}\,s^{-1}}$), chamber volume ($V$; in $\mathrm{m^3}$), and chamber area (A; in $\mathrm{m^2}$)

$$F(t) = \frac{\mathrm{d}c}{\mathrm{d}t}(t)\frac{V}{A}\,. \tag{60.1}$$

The mass concentration of the gas of interest $c(t)$ is calculated from the measured fraction of CO_2 in air ($\chi(t)$; in $\mathrm{mol\,mol^{-1}}$), pressure ($p(t)$; in Pa) and temperature ($T(t)$, in K) of the headspace air, molar mass of the gas of interest (M; in $\mathrm{kg\,mol^{-1}}$) and the universal gas constant ($R \approx 8.314\,\mathrm{m^3\,Pa\,K^{-1}\,mol^{-1}}$) [60.29]

$$c(t) = \chi(t)\frac{p(t)}{T(t)}\frac{M}{R}\,. \tag{60.2}$$

Commonly, water vapor evaporates from the soil surface or vegetation (if present) into the chamber headspace during chamber closure. This addition of molecules leads to expansion of the headspace air and dilution of the gas of interest [60.16, 30, 31]. The effect of this dilution on the molecular fraction of the gas of interest can be approximately corrected for if the amount fraction of water vapor $\chi_{H_2O}(t)$ is monitored in the chamber headspace

$$\chi_{\mathrm{corr}}(t) = \chi_{\mathrm{uncorr}}(t)\frac{1-\chi_{H_2O}(t_0)}{1-\chi_{H_2O}(t)}\,, \tag{60.3}$$

where $\chi_{H_2O}(t_0)$ is water vapor amount fraction at the start of chamber closure.

Unfortunately, there is no general agreement about the best time interval for determining $\mathrm{d}c/\mathrm{d}t$ following chamber closure. Traditionally, a linear regression function was fitted to the complete concentration time series recorded during chamber closure, and the slope of that linear function was set equal to $\mathrm{d}c/\mathrm{d}t$. However, various studies demonstrated that the concentration time series often does not develop in a linear way, even over short closure periods [60.32–34]. Whilst linear regressions applied over short periods provide robust estimates, it should be noted that they can underestimate real fluxes by up to 40%, depending on the absolute flux rates [60.33, 35]. There is no consensus about how long exactly a measurement (chamber closure) should last, or which nonlinear regression method is the most appropriate. Software solutions are now available [60.36] that provide diagnostic statistics and initial recommendations for whether nonlinear or linear regression is the most appropriate. They allow users to define custom criteria for a given experimental setting.

Non-steady-state chambers need to open after completing measurement to allow the reequilibration of CO_2 concentrations between soil and atmosphere and to minimize the modification of abiotic conditions through e.g., rainfall exclusion or temperature increases. In order to obtain continuous time series of soil flux measurements, robotic systems that close and open chambers at predetermined intervals have been widely used. As, generally, multiple chambers are measured using a single gas analyzer, switching between different chamber locations is required to enable quasi continuous measurement of flux within a given area. The size of this area is determined mainly by the length of tubing (radius of 10 m, with additional pumps included, up to 20 m) between chambers and CO_2 analyzer, where an efficient exchange of air between headspace and analyzer has to be guaranteed in order to obtain meaningful estimates of concentration change over time. Power draw of robotic drives as well as pumps to circulate air over considerable distances are a major consideration for these systems, and there are usually higher maintenance costs due to the necessity of having moving parts within the chamber design compared to manually operated systems or passive methods (Sect. 60.3.3).

60.3.4 Steady-State Chambers

Steady-state chambers operate by having a continuous flow of air through the headspace. As air passes through the chamber, the CO_2 concentration within the headspace is enriched by soil CO_2 efflux, and air leaving the chamber will over time equilibrate at a constant concentration (assuming constant soil CO_2 efflux) that is determined by the rate at which the headspace atmosphere is turned over by the air stream. Calculation of the soil CO_2 efflux rate, hence, relies on direct measurements of the CO_2 concentration drawn from the chamber headspace (out-flowing concentration, c_o; ppm, or μmol mol^{-1}), the ambient air CO_2 concentration (incoming concentration, c_i; ppm, or μmol mol^{-1}), the flow rate of air through the headspace (f; mol s^{-1}), and the surface area of soil enclosed by the chamber (A_s; m^2)

$$F = f\frac{c_\mathrm{o} - c_\mathrm{i}}{A_\mathrm{s}} \,. \tag{60.4}$$

The flow of air through the chamber headspace is commonly achieved by continuously drawing air from within the headspace and allowing air to enter the headspace passively from the ambient atmosphere. Alternative modes of either pumping air into the chamber, with chamber air exiting the headspace passively [60.25, 37], or creating airflow by simultaneous drawing and pushing of air out of and into the chamber [60.26] have also been trialled but are less common.

As for all chamber methods, a complete seal between chamber headspace and ambient atmosphere is critical. An intentional opening integral to the chamber design to either allow ingress or egress of air (depending on whether air is actively drawn or pushed from/into the chamber), therefore, has to be designed carefully to achieve an effective air seal. This means that the rate at which air flows through the inlet/outlet has to exceed the diffusion speed of CO_2 in air for the range of temperatures under which the chamber operates. The cross-sectional area of the inlet/outlet must, therefore, be dimensioned in accordance with the volumetric airflow rate (f). The critical speed of air flow (a_c) across the cross-sectional area of an inlet has been determined experimentally to be around 50 cm s^{-1} [60.10], and the appropriate inlet area (A_i; cm^2) for a given volumetric flow rate of air through the headspace (f_V; cm^3 s^{-1}) can, hence, be calculated according to

$$A_\mathrm{i} = \frac{f_\mathrm{V}}{a_\mathrm{c}} \,. \tag{60.5}$$

To ensure that no CO_2 is lost through the inlet, this critical speed should be maintained over some distance by the use of an inlet tube of the appropriate diameter. However, it should be noted that any airflow generated by drawing air from the chamber headspace necessarily results in a lower pressure inside the headspace compared to the ambient atmosphere (as this is the principle on which air is drawn into the chamber). The magnitude of this pressure differential is a function of the length and diameter of the inlet tube, as well as the airflow velocity. An excessive length of the inlet tube should be avoided, as a longer inlet tube increases air friction and, hence, the pressure differential between atmosphere and chamber headspace.

In contrast to closed chambers, open chamber designs have the potential to measure continuously, without the need to open and reclose chambers, as steady-state conditions are created within the headspace. A change in F over time is detected through the continuous monitoring of $(c_\mathrm{o}-c_\mathrm{i})$, meaning that a different soil CO_2 efflux rate will result in a new steady-state chamber concentration and, hence, a new concentration differential between soil surface and headspace.

60.3.5 Forced Diffusion Chambers

Forced diffusion (FD) chambers are a specific type of steady-state chamber, which were first described by *Risk* et al. [60.38]. Like for other steady-state chambers, the soil CO_2 efflux rate is calculated based on the difference between the outside atmospheric concentration and the concentration inside the chamber. The main difference is that the FD chamber uses a membrane instead of a pump. The membrane is responsible for maintaining proportionality between chamber air and outside air through molecular diffusion instead of active pumping. In the currently available commercial forced diffusion chambers, a single IRGA measures both atmosphere and chamber concentrations through a switching arrangement. Forced diffusion chambers, therefore, have reduced power demand and better long-term durability compared to robotic chambers.

The factors that control the exhaust rate of a FD chamber and the proportionality between flux and inside air concentration include the area-specific effective membrane diffusivity (D), the effective diffusive path length (L), and surface areas exposed to the soil and air (A_a, A_s). Changing any of these factors alters the proportionality between chamber and atmospheric air, or the concentration retained in the chamber per unit flux. These factors are represented by a single scalar (G), which is established for each FD chamber by calibration on a flux generator [60.39]

$$F = \frac{A_\mathrm{a}}{A_\mathrm{s}}\left(D\frac{c_\mathrm{c}-c_\mathrm{a}}{L}\right) = G\left(c_\mathrm{c}-c_\mathrm{a}\right) . \qquad (60.6)$$

The empirical calibration simplifies the design requirements and mathematical approach for flux calculations. It also validates that the FD chamber measures fluxes accurately. Most other chamber systems are calibrated only for concentration, which means that pump issues, air leaks, or other operational issues are more likely to go unnoticed in those systems.

Modern FD chambers incorporate two membrane-covered cavities within the same structure. The main cavity consists of a chamber that is exposed to the soil at the bottom and in contact with the atmosphere through a membrane. This membrane imposes the diffusional limitation or *forces* it to a specific rate. The secondary cavity is to measure the free atmospheric concentration of the gas, at the same height above ground as the primary chamber membrane. Both cavities should have identical membranes and the same volume-to-surface-area characteristics, so that they respond with identical time constants to changes in atmospheric concentration. Membranes are normally made of a synthetic material that is hydrophobic, impermeable, highly diffusive, and resistant to ultraviolet (UV) degradation.

Ideally, the FD chamber should be designed to retain a minimum level of soil gas (small $c_\mathrm{c}-c_\mathrm{a}$ per unit flux) in order to minimize lateral diffusion [60.40]. However, higher diffusivity is not necessarily better if the FD chamber analyzer or sensor cannot adequately resolve small concentration differences between the cavities. If concentration differences cannot be resolved at flux rates of interest, $c_\mathrm{c}-c_\mathrm{a}$ per unit, the concentration buildup must be increased by decreasing the membrane surface area or by using less diffusive membrane material.

Forced diffusion chambers use less power than other chamber variants, mainly because active pumping is not required. FD autochambers and their sensors can theoretically remain unpowered most of the time and only need to be activated to *grab* concentration values at preprogrammed intervals. FD chambers are also tolerant to long-term analyzer baseline drift, because a single analyzer is used to measure the difference in concentrations between the two cavities. Because FD chambers lack moving parts, maintenance intervals are reduced. However, annual recalibration of chambers is advised, but more frequent calibration may be necessary, for example in environments where biofouling is important. Because they lack moving parts, FD chambers can be used in snow, as long as the snowpack is fresh and highly diffusive, or where special-purpose manufacturer add-on accessories are used. Winter deployments often require a reduction in measurement frequency, to minimize heating and snowmelt, and to conserve battery power when solar charging is at a minimum. Owing to their low power consumption and good reliability, FD chamber systems have been used year-round even under harsh Arctic and Antarctic conditions [60.41, 42]. FD chambers can also be used without modification on floating platforms in studies that aim to contrast terrestrial and aquatic fluxes or on vertical surfaces including trees to quantify bole flux.

60.3.6 Comparison of Measuring Principles

All chamber measurements create some degree of disturbance to the physical environment, affecting the natural flux of gases between soil and atmosphere. The contrasting measuring principles of steady-state and non-steady-state chambers influence different aspects of the headspace environment, relating to e.g., duration of chamber closure or effects of pressure and airflow. Several studies have compared different chambers directly, indicating general biases between the different principles [60.15, 43–45]. For earlier non-steady-state chamber systems, consistent underestimates of known flux rates have been reported. Subsequent changes to chamber designs, for example introducing controlled air vents and improving air flow within chamber headspaces, seem to have eliminated this bias. The most recent comparison study showed that both steady-state and non-steady-state chambers provided estimates close to known flux rates [60.15]. Forced diffusion chambers, however, have not been included in any comprehensive comparison study. Nonetheless, since individual FD chambers are calibrated against known flux rates before deployment, any biases resulting from instruments, chamber geometry, or materials are accounted for in the measured fluxes.

60.4 Devices and Systems

A variety of chamber systems have been built by researchers over the past decades, driving the development of the methodologies outlined above. The considerable volume of existing publications reflects this diversity of devices and measuring setups, in turn reflecting the variety of contexts and research questions being addressed. Here, we outline some of the most commonly used systems with examples of commercially available models. Further development of chamber systems is ongoing and is largely driven by modifications of existing setups or custom-built designs.

The objective of most soil gas flux studies is to better understand the sources and sinks of gases and drivers of flux dynamics across the soil–atmosphere interface. Analyses of the relation of flux rates from chamber measurements with abiotic conditions, such as air or soil temperature, precipitation volumes and frequencies, soil moisture content, or static pressure, are performed regularly, guided mainly by the specific objectives of a given investigation. Many commercially available chamber systems provide at least some of these ancillary measurements as part of the setup. However, as these ancillary measurements are not an integral part of the chamber approach, we do not cover them in any detail here.

60.4.1 Manual Chambers

Portability is an important requirement for soil chambers to enable surveys across wider areas, during which instruments often have to be carried between measurement locations. Infrared gas analyzers (IRGAs) have been used for soil CO_2 flux measurements for many decades now and continue to be widely used. The decrease in size of IRGA units over the years has promoted the development of portable systems, with a number of models now commercially available.

Battery power is a further crucial factor for the use of portable systems in field surveys. Energy consumption, and hence the need to carry sufficient battery power into the field, is driven by the need to pump air between chamber and analyzer as well as auxiliary functions, such as internal fans or chamber closing mechanisms and the thermostatic requirements of the optical bench within the analyzer.

Operation of manual survey chambers is nowadays greatly facilitated by simple routines carried out by analytical units that facilitate flushing of chamber headspaces prior to chamber closure, automatic logging of chamber concentration changes over time, and direct computation of flux rates based on chamber geometry.

The small and relatively lightweight chambers by PP Systems (Amesbury, Massachusetts, USA) are placed directly on the soil surface or on previously installed soil collars to initiate a flux measurement. A choice exists between a smaller opaque chamber for respiration measurements and a larger chamber of transparent materials (enabling net CO_2 exchange) (Fig. 60.5, top). The console containing the infrared gas analyzer provides a numerical and graphical display of CO_2 concentration, and raw data as well as computed fluxes can be stored on an external USB (Universal Serial Bus) flash drive. The relatively simple operation with low power consumption means that battery power of the control unit is sufficient for more than 6 h of continuous flux measurements (assuming about 20 measurements per hour). The unit alone weighs only 1.5 kg (including batteries), with the two types of chambers weighing an additional 1 kg.

Li-Cor Biosciences (Lincoln, Nebraska USA) commercializes a very robust survey chamber setup, with

Fig. 60.5a–c Portable soil respiration chambers used with infrared gas analyzers. **(a)** PP Systems soil chamber (diameter: 10 cm, $V = 1180\,\text{cm}^3$). **(b)** PP Systems canopy chamber (diameter: 14.6 cm, $V = 2430\,\text{cm}^3$). **(c)** Li-Cor survey chamber (diameter: 20 cm, $V = 4840\,\text{cm}^3$). Note that other sizes of chambers are available from these and other manufacturers (images **(a)** and **(b)** reprinted with permission from PP Systems; image reprint with permission of LI-COR Biosciences)

the infrared gas analyzer contained in a rugged hard case and without a physical user interface to protect electronics and gas handling parts (Fig. 60.5, bottom). Survey chambers with a diameter of 10 or 20 cm can be placed either directly on the soil surface or onto matching soil collars prior to flux measurements. An individual measurement is initiated by the system's onboard control, with which the user can either interact directly via wireless devices or an Ethernet/serial cable, or by preprogramming a sequence of measurements at user-specified intervals. To minimize disturbance from chamber placement, the Li-Cor survey chambers have a bellows that operates the closing mechanism to initiate a measurement; CO_2 concentrations are then logged by the analyzer unit and stored along with any auxiliary measurements, and flux rates are computed at the end of measurements. Data are stored in a large internal memory and can be downloaded after field operation. The Li-Cor analyzer unit (Li8100A) in combination with the bellows-based closure mechanism in chambers has relatively high power demands. With a battery providing power for about 2 h of measurements (assuming about 20 measurements per hour), the analyzer unit weighs about 6.7 kg, with the 10 and

Fig. 60.6a–c Portable gas analyzers suitable for combined chamber-based measurements of CH_4, H_2O and CO_2. **(a)** GasScouter^{TM} by Picarro, with attached soil chamber (diameter: 28 cm, $V = 9340\,cm^3$), which has the analytical unit contained in a backpack. (Reprinted with permission of Picarro Inc.) **(b)** Ultra-portable gas analyzer by Los Gatos Research (29.5 × 34 × 12 cm) (reprinted with permission from ABB). **(c)** Li-7810 by Li-Cor (51 × 33 × 18 cm) (image reprint with permission of LI-COR Biosciences)

20 cm chambers weighing a further 1.6 and 2.9 kg, respectively.

Recent advances in laser spectroscopy, and particularly the cavity-ringdown technique, have led to new, portable analyzers capable of measuring CH_4 and H_2O alongside CO_2. The Picarro GasScouter (Picarro, Santa Clara, CA, USA) weighs just over 10 kg and is housed in a backpack case (Fig. 60.6). A soil chamber is available for this analyzer, and battery life enables measurement of up to 8.5 h (according to manufacturer specifications). Using a related technology (cavity-enhanced absorption), two further portable trace gas analyzers have recently become available. The Microportable Greenhouse Gas Analyzer (M-GGA) by Los Gatos Research (San Jose, CA, USA) weighs only around 5.4 kg, which includes a small internal battery that allows operation of up to 2 h. The Li-7810 by Li-Cor (Lincoln, NE, USA) weighs 11.4 kg and like the M-GGA comes in a hard case. All three trace gas analyzers provide onboard data storage and easy interfacing for external data storage or remote downloads. Combining these trace gas analyzers with existing custom-built chambers or commercially available CO_2 flux systems is relatively unproblematic.

60.4.2 Automated Chambers

Continuous soil flux measurements can be carried out using chamber systems from a number of manufacturers. As in the case of portable chambers, the automated chambers can be interfaced with either CO_2 analyzers or other trace gas analyzers. As these systems are typically employed in more permanent setups, portability and energy supply are of less relevance, and larger analyzers with potentially better analytical resolution and greater signal stability can be used. They do, however, require a weather-proof shelter.

Most automated chambers are equipped with moving components to ensure that soil conditions of the chamber footprint (usually contained within a soil collar) are disturbed as little as possible by the presence of the chamber. However, it should be noted that the chambers are likely to have indirect impacts, even when in their *open* position. The physical presence of chamber, support structures, and motor drives can affect the thermal regime through shading or reflectance of solar radiation. The same is true for the rainfall and soil wetting regime, through interception and displacement of nonvertical rain, which can result in artefacts from ad-

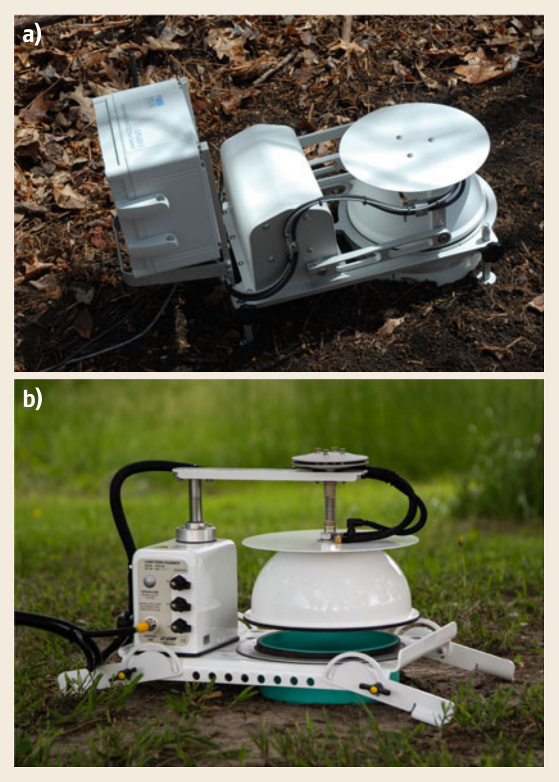

Fig. 60.7a,b Automated long-term chamber models. **(a)** PP Systems (diameter: 20 cm, $V = 2500\,\mathrm{cm}^3$) (image reprinted with permission from PP Systems). **(b)** Li-Cor (diameter: 20 cm, $V = 4080\,\mathrm{cm}^3$) (image reprint with permission of LI-COR Biosciences)

ditional or reduced rain splash and infiltration into the collar area.

Robotic non-steady-state chamber models are available from a number of suppliers; Fig. 60.7 shows two examples. The CFlux-1 model (PP Systems) opens and closes by lifting a dome-shaped chamber vertically and locking it in an open position adjacent to the chamber collar. The gas analyzer is located next to the chamber, so that gas analysis occurs locally with only electricity having to be provided externally. The eosAC model (Eosense, Dartmouth, NS, Canada) has a similar mechanical layout as the CFlux-1 but requires air from the chamber headspace to be pumped to and from a centrally located analyzer via a multiplexed switching unit. This is also the case for the Li-8100A system (Li-Cor). Its chambers open and close in a combined vertical and swing motion, so that the chamber covers in the open position rest at a greater distance from the soil collars than is the case for other systems.

Fig. 60.8 Forced diffusion chamber eosFD by Eosense (diameter: 10.2 cm, 20 cm high) (reprinted with permission from Eosense Inc.)

The maximum length of tubes and power/data cables limits the spatial reach of continuous chambers. Tube length is limited by the associated increase in flow resistance and, hence, by pressure considerations for pumping air between chambers and analyzers or multiplexers. Excessive tube length also increases the time required to flush tube volumes prior to measurements and leads to attenuation of concentrations that may affect the calculation of CO_2 evolution rates. The PP Systems approach of individual gas analyzers for each long-term chamber overcomes these constraints on spatial reach, but the costs per automated chamber are comparatively high because of these individual analyzers.

All automated chambers have moving parts, so their maintenance is an important consideration. Long-term measurements in environments with extreme conditions (high or low temperatures, precipitation, dust) have to be carefully considered because of the increased likelihood of mechanical failures. Appropriate housing particularly for analyzers and power supply are clearly critical for such systems.

Forced diffusion systems provide a recent alternative to the above-mentioned systems (Fig. 60.8).

Using steady-state chambers, FD systems operate well in continuous mode, and their relatively low power consumption means that long-term measurements are easily achieved. Chambers run on extremely low power (average below 1 W for longer deployment) and have onboard data storage. Having no moving parts, FD systems furthermore have a reduced risk of mechanical failure. However, continuous operation of FD chambers at the same location is likely to have substantial impacts on the abiotic environment inside the chamber, as the headspace is likely to heat to temperatures above those of the surroundings and as it excludes rainfall. This limitation can be (partially) overcome by relocating the chambers at regular intervals, so that roving FD chamber systems should have an elevated potential for continuous monitoring in locations with no continuous electricity supply [60.42].

60.4.3 Overview

This section aims to provide an overview of some of the most commonly used chamber-based measuring systems to give a representative sample for users. Table 60.3 summarizes the main advantages and disadvantages of the three main types of measuring systems and reflects a general summary of most common features of the systems available at the time of writing. The most appropriate measuring setup will depend strongly on the specific research question(s). Given a certain research budget, there will often be a clear tradeoff between the spatial and temporal resolution that can be achieved, using portable versus automated systems. In many cases, however, a combination of both systems will be ideal for a comprehensive assessment.

Table 60.3 Advantages and disadvantages of the three main types of systems

Devices	Advantages	Disadvantages
Manual chambers	Few spatial constraints due to low weight & small size Versatile for comparative analyses across ecosystems and treatments	Manual operation Limited by battery power Limited temporal replication
Automated chambers	Low demand on person time High temporal resolution Can be operated in response to specific environmental triggers/events	Significant maintenance demand for continuous operation Risk of mechanical failure Limited in spatial reach Requires secure power supply
Forced diffusion chambers	No spatial limitation Continuous data collection Very low power demand Reduced maintenance requirements due the absence of moving parts	Potential impacts on abiotic and biotic conditions in the case of prolonged placement at the same location

60.5 Specifications

Soil flux chambers are available over a range of sizes (Sect. 60.4), and there is a range of analytical equipment that can be interfaced with these. We here provide an overview of analyzers that are commonly used in soil flux studies and are included in the overview given in Sect. 60.4. Note that the specific information is provided by manufacturers, and variations from stated values may occur depending on, e.g., integration intervals of laser spectrometers or across concentration and temperature ranges. Specification should, therefore, be regarded as indicative only. In this overview, we focus on portable chamber systems, which are of most immediate interest to many researchers. Permanently installed, continuous chamber systems may use these same analyzers, but a wide range of other analyzers is available, as permanent setups typically involve few restrictions on the size and weight of analyzers.

60.6 Quality Control

Estimates of soil–atmosphere gas fluxes based on soil chamber measurements are characterized by the following four major sources of uncertainty:

- Imperfections of the instrumental analysis of the gas concentration (e.g., due to noise, drift, and cross sensitivities).

Table 60.4 Error and temperature ranges for a selection of key instruments used in currently chamber systems to measure soil gas flux. (All specifications from manufacturers' information)

Instrument	Error (precision)	Temperature range (°C)	Manufacturer
Infrared gas Analyzers			
Li-8100	1.5% of reading	−20 to 45	Li-Cor, Lincoln, NE, USA
EGM-5	1% over calibrated range	0 to 50	PP Systems, Amesbury, MA, USA
Laser spectrometers			
GasScouter^{TM}	CO_2: 0.4 ppm CH_4: 3 ppb H_2O: 100 ppm	10 to 45	Picarro, Santa Clara, CA, USA
M-GGA	CO_2: 0.25 ppm CH_4: 1.2 ppb H_2O: 60 ppm	5 to 45	Los Gatos Research, San Jose, CA, USA
Li-7810	CO_2: 0.25 ppm CH_4: 1.5 ppb H_2O: 20 ppm	−25 to 45	Li-Cor, Lincoln, NE, USA
Solid-state sensor (FD chambers)			
Vaisala GMP343	±3 ppm + 1% of reading	−40 to 60	Vaisala, Helsinki, Finland

- Artefacts induced by the chamber method, such as pressure shocks during chamber setting; pressure differences between chamber headspace and ambient air; decreased or increased turbulence strength in the headspace compared to ambient conditions; reduced insolation levels due to the chamber walls; changed air, plant and soil temperatures; changes in the gas concentration gradients between soil and headspace air during chamber closure; leakages through the soil and chamber structure.
- Imperfect sampling of spatial variability in gas fluxes at the relevant scales (centimeters to kilometers).
- Imperfect sampling of temporal variability in gas fluxes at the relevant scales (seconds to years).

These different sources of uncertainty need to be estimated and specified when presenting and interpreting results. The uncertainty thresholds should be defined when planning a study, and the experimental setup should be designed considering the different sources of uncertainty.

60.6.1 Uncertainties in Instrumental Gas Concentration Analysis

The accuracy and precision of the measurements of the molar fraction of the gas of interest, as well as of the headspace air temperature and pressure, and of the gas transport rate in flow-through systems has to be regularly evaluated to assess and minimize uncertainty due to instrumental gas analysis. Systematic errors must be kept small through regular calibration of the instruments involved, and it is important to evaluate drift of gas analyzers in response to temperature and pressure changes. The same is true for cross sensitivities of analyzers between different gases. The effects of water vapor on gas measurements based on absorption spectroscopy are particularly important, because water vapor has many absorption bands, and its concentration typically increases during chamber closure. This is especially true for non-steady-state chambers. The precision of the instruments should be checked regularly across the entire measurement range. A deterioration of precision indicates staining of sensors and/or electronic problems and implies the need for instrument maintenance or repair.

60.6.2 Uncertainties Due to Artefacts by the Non-Steady-State (Closed) Chamber Method

It is very important to minimize the various potential artefacts associated with the closed chamber method through careful chamber design and experiment planning. The functioning of non-steady-state chambers should be tested under controlled conditions at regular intervals. It is necessary that:

- Chambers walls are composed of gas-tight and nonreactive materials.
- The air-tightness of the seals between chamber bases and tops is tested for leakages.
- Chamber bases are sealed well against the soil surface, potentially inserted deep enough into the soil to prevent any mass flow of air between the chamber headspace and the ambient air (where experimental objectives allow).
- The chamber is equipped with a properly dimensioned vent that is open during chamber deployment

and allows propagation of ambient air pressure fluctuations into the chamber [60.32].

- The chamber is equipped with additional closable large-diameter vents that are opened during chamber placement to avoid short-time pressurization of the chamber headspace.
- Turbulent mixing of the headspace air is ensured by installation of appropriately dimensioned fans or, in the case of flowthrough systems, by a properly designed sample intake manifold.
- The change of temperature during chamber closure is recorded and – if necessary – controlled by a cooling system.

Some artefacts due to suboptimal chamber application can be identified by careful evaluation of the time series of gas concentrations during chamber closure. The measurement principle of the closed chamber method assumes that the gas concentration time series during a successful chamber closure experiment can be well described by either a strictly monotonically increasing (net gas release) or a strictly monotonically decreasing (net gas uptake) function. Based on diffusion theory, the monotonically increasing or decreasing functions are expectedly nonlinear and degressive. The relative quality of different regression functions can be compared with the Akaike information criterion [60.46] or tested using an F-test of the residual variances of two potential regression functions [60.47]. A best-fitting function that shows a nonlinear progressive form cannot be explained by diffusion theory, indicating a disturbed chamber experiment that should be flagged for quality control [60.48]. The most important quality control criterion is the standard deviation of the residuals of the best-fitting function, as it provides an estimate of the unexplained variance in the gas concentration time series during chamber closure. A standard deviation of the residuals for the best-fitting function higher than a critical threshold level indicates technical errors or other problematic artefacts, which should be flagged for quality control. By contrast, the coefficient of determination, R^2, cannot be recommended as a quality control criterion, as it inherently discriminates against lower fluxes [60.33].

60.6.3 Uncertainties Due to Spatial Variability

Soils are characterized by a pronounced spatial heterogeneity on the scales of centimeters up to many kilometers [60.49]. The higher the spatial variability of soils within the investigated area of interest, the greater the uncertainty of the estimated mean of the fluxes due to sampling variability $u_{\text{mean,space}}$. Under the assumption that the sampled population is normally distributed, $u_{\text{mean,space}}$ can be estimated as

$$u_{\text{mean,space}} = t_{\alpha/2,n-1}\frac{s}{\sqrt{n}}\,, \qquad (60.7)$$

where s is the sample standard deviation, n is the sample size, and $t_{\alpha/2,n-1}$ is the upper $(1-\alpha/2)$ quantile of the Student's t-distribution, and α is the significance level. A pilot study should be performed for estimating s and assessing the distance between sample plots that is enough for spatial interdependence (e.g., by a semivariogram, e.g., [60.50]), which is needed for an unbiased estimation of the population variance by s.

The necessary sample size n_{min} to estimate a mean flux within a specified margin of uncertainty d at a confidence level α can be estimated by finding the lowest value of n for which the following inequality is true

$$\frac{\sqrt{n}}{t_{\alpha/2,n-1}} \geq \frac{s}{d}\,. \qquad (60.8)$$

Since the number of spatial replicates in typical soil chamber measurement campaigns is severely limited by resources and logistical constraints, these are prone to considerable margins of error due to suboptimal sampling in space (e.g., [60.51, 52]). With large uncertainties due to small sample sizes, effect sizes (i.e., means or differences between means from different areas) must be large to be detected at usually accepted significance levels (e.g., $\alpha \leq 0.05$) [60.53].

60.6.4 Uncertainties Due to Temporal Variability

Soil gas fluxes are highly variable through time. Temporal variability occurs on scales of seconds to years. Chamber flux measurements are discrete samples in time with a specified temporal resolution. Chamber closure times can vary from 15 s [60.54] to about an hour [60.55]. Chamber closure intervals at a specific measurement spot can vary from hours for automatic chamber systems [60.55] to weeks for manual chamber campaigns [60.56]. Depending on the research question of the study, the sampling design must account for diurnal cycles, meteorological changes on the synoptic scale, seasonal cycles, and inter-annual variability. For unbiased gas balances, sampling must not be restricted to certain environmental conditions, e.g., only summer, only daytime, or only times without precipitation [60.57]. A low sampling frequency can lead to high uncertainty of seasonal or annual gas-exchange balances [60.58, 59].

Since chamber measurements cannot provide continuous time series of flux measurements, smaller and larger gaps need to be filled by models. The uncertainty of seasonal or annual cumulative fluxes due to temporal variability is typically dominated by the ability of the models to simulate the true fluxes [60.60, 61]. Model performance is characterized by residuals between simulated and measured data. These should be evaluated in both the time and frequency domain [60.62]. Monte Carlo simulations are useful to assess the uncertainty of cumulative fluxes due to the uncertainty in the model predictions used for gap filling [60.63].

60.7 Maintenance

In order to obtain reliable flux estimates, chambers and associated analytical equipment require maintenance. Exact intervals for maintenance are strongly dependent on the application, but Table 60.5 provides a general overview of typical maintenance schedules.

Table 60.5 Servicing schedule for contrasting chamber systems

	Manual chambers	Automated chambers	Forced diffusion
Weekly	Tubes are free of dust, condensation or obstructions, all electrical and gas connections sound		N/A
	Fans (where present) working	Check physical condition, no obstruction in closing mechanisms	
Monthly	Check zero and span of analyzers		
	If used consistently in dusty environments, check filters	Check physical condition and if deployed over long periods, either relocate or check seal with soil is intact	
Annually	Send analyzer for service and calibration		Send entire chamber setup to manufacturer for recalibration
	Pump replacement (potentially)		
		Full service of all moving parts	

60.8 Application

Soil gas flux chambers have been used in a wide variety of settings, where they may measure a number of different trace gases and serve a range of purposes. Whilst it is beyond the scope of this chapter to cover the full range of chamber applications over the past decades, we use a small number of examples here to illustrate the applicability of soil flux chambers. The examples were selected to cover the key chamber types outlined in Sect. 60.3 and address aspects of continuous monitoring, experimental manipulation, and challenges of remote operation.

60.8.1 Ecosystem Flux Components

Chambers have been widely used in order to quantify constituent fluxes from different parts of ecosystems. Methods such as the eddy-covariance technique (Chap. 55) provide net fluxes between ecosystems and the atmosphere integrated over time (usually 30 min) and space. However, researchers generally require a more detailed understanding of the flux contributions from different areas within the *flux footprint* of the eddy-covariance setup (Chap. 55). Knowledge of the relative contributions of, e.g., vegetation versus soil versus open water, contrasting vegetation types/covers, distinct (micro)topographic units are critical in order to understand the drivers of the fluxes from these contrasting areas and provide a way to independently validate net ecosystem fluxes. It also allows a more detailed understanding of contributing fluxes, such as the separation of CO_2 assimilation and respiration by canopy and understorey vegetation and respiration from soil, which is not possible by eddy covariance alone.

Analyses of fluxes from within the footprint area of eddy-covariance towers are typically conducted using manual chambers in distinct measurement campaigns [60.33, 64–66]. This enables the measurement of fluxes across the entire flux footprint area, which is typically larger than what an automated flux system with permanently installed chambers can accomplish. Such campaigns should aim to capture a wide range of flux situations, i.e., resolve diurnal as well as seasonal patterns. The exact number of measurement points required depends on the nature of the footprint area, i.e., the multitude of different surface covers, and spatial variability within these units. Ideally, all relevant surface cover types are sampled to allow an upscaling of contributing flux estimates at any given period using the weighted areal representation of the respective covers.

Whilst manual chamber measurements have the benefit of a wider spatial reach, they require the presence of an experimenter within the footprint of the eddy-covariance measurement, possibly affecting the flux estimate within that particular time interval. Depending on the magnitude of ecosystem fluxes and the size of the footprint, this disturbance may be significant for the net ecosystem flux estimates, and a direct comparison of fluxes obtained by the two techniques may not be possible. Most studies attempt an area-weighted average of fluxes within footprint areas that is then compared to representative flux averages that are not necessarily obtained simultaneously but based on comparable conditions (in terms of abiotic drivers of fluxes). Continuous measurements using automated chambers have also been used to develop a more detailed understanding of the contribution from soils or even subcomponents within the soil to ecosystem carbon exchange (Sect. 60.8.2) [60.67, 68].

60.8.2 Long-Term Monitoring of Soil Gas Flux

Continuous measurements of soil–atmosphere gas exchange enable powerful investigations into the drivers of gas fluxes as well as their temporal dynamics over short (intraday) to long intervals (interannual). Automated systems with multiple chambers (both steady-state and non-steady-state), can give up to (half-)hourly soil CO_2 efflux readings and have been powerful in disentangling influences of temperature and soil moisture, as well as diurnal and seasonal flux dynamics. The wealth of data generated by continuous measurements (subject to appropriate quality checks) allows detailed analysis of, e.g., temperature responses under contrasting moisture regimes or during different parts of the growing season [60.69].

In manipulative field experiments, continuous soil flux measurements can reveal further details, for example, on the interaction of biotic and abiotic drivers of gas fluxes. Studies in a boreal black spruce forest [60.68] and a temperate oak forest [60.67] illustrate compellingly how the allocation of carbon by plants to the soil via root and mycorrhizal networks differs between seasons. As both studies were carried out within the footprint of an above-canopy eddy-covariance tower, the continuous data further enabled a detailed analysis of the relationship between soil flux and total ecosystem dynamics, revealing a link between C assimilation by the canopy and magnitude of soil fluxes.

Long-term chamber systems can be interfaced with a range of gas analyzers to provide continuous soil–atmosphere gas exchange for trace gases other than CO_2. For example, by integrating a methane analyzer into a measuring setup for soil CO_2 efflux, it was possible to resolve short-term dynamics of methane uptake by forest soil [60.70]. Apart from a known relationship with soil moisture, these measurements revealed novel insights into the diurnal fluctuation of methane oxidation flux in response to small changes in background methane concentration above the forest floor.

60.8.3 Gas Exchange in Remote Locations

Accessibility to field sites and availability of grid power have been key factors in the selection of long-term observation sites. This has created a strong bias towards areas easily accessed by road and well-equipped research sites. For Arctic areas, this bias is extreme, given the much sparser population and, hence, lower density of road and power infrastructure. As an illustration, about 31% of all Arctic studies focused on climate change (including many flux studies) originate from measurements within 50 km of just two Arctic research sites (Toolik Lake, Alaska, and Abisko, Sweden) [60.71]. There is, therefore, a real need to obtain more data from more remote and less accessible areas. The portability of analyzers and chamber systems has enabled researchers to obtain soil flux measurements from a wide range of locations, but this is limited to distinct, infrequent measuring campaigns.

Whilst this has so far been mostly limited to CO_2 flux systems, advances in analyzer design have led to more frequent measurements also of other trace gases (Sect. 60.4). For continuous measurements in remote locations, moving chamber designs associated with air pumps between chambers and analyzers are limited by power availability. Forced diffusion chambers offer a new opportunity to continuously monitor CO_2 flux in remote locations. This is illustrated by a 1-year record obtained by permanently installed FD chambers in the dry valleys of Antarctica [60.42]. Whilst the steady-state measurement in nonmoving chambers creates some problems in relation to precipitation and organic matter entering the soil environment, this study was able to identify specific abiotic conditions during which microbial activity led to soil CO_2 efflux. The dry and cold nature of the study system facilitated the use of FD chambers, which may be prone to greater artefacts when deployed continuously in other ecosystems.

60.9 Future Developments

Chamber measurements of all trace gases form an important part of gas exchange studies. They can resolve small spatial scales and are adaptable to specific settings with regards to, e.g., microtopography, vegetation cover, or landscape features that larger scale flux approaches, such as eddy covariance, cannot address. Therefore, chamber measurements will continue to play an important role in future investigations.

The scientific literature is rich in contrasting designs of flux chambers, and there are many applications besides soil respiration measurements that have driven their original development. Recent advances in the detection of important atmospheric trace gases have led to ever-smaller analyzers capable of resolving small concentration changes with good accuracy and precision. Gas flux measurements that were historically severely limited by the requirement of using offline sample collection and a-posteriori analyses of samples in the laboratory can now be carried out using in-situ analyzers, enabling fast and more mobile measuring setups. We anticipate this trend to continue, and more gases, as well as isotopic ratios of trace gases, to become detectable by flux chambers operated on portable or automated devices. The development of chambers has led to a great level of sophistication, so that current models can operate at minimal disturbance of the soil environment. Further advances, e.g., in materials used or in chamber geometry for specific tasks, are likely to occur in the future, but the general measuring principles described in this chapter will most likely continue to be the basis of any chamber flux measurement.

60.10 Further Readings

- E.A. Davidson, K. Savage, L.V. Verchot, R. Navarro: Minimizing artefacts and biases in chamber-based measurements of soil respiration, Agric. For. Meteorol. **113**, 21–23 (2000)
- J. Pumpanen, P. Kolari, H. Ilvesniemi, K. Minkkinen, T. Vesala, S. Niinistö, A. Lohila, T. Larmola, M. Morero, M. Pihlatie, I. Janssens, J.C. Yuste, J.M. Grünzweig, S. Reth, J.-A. Subke, K. Savage, W. Kutsch, G. Østreng, W. Ziegler, P. Anthoni, A. Lindroth, P. Hari: Comparison of different chamber techniques for measuring soil CO_2 efflux, Agric. For. Meteorol. **123**(3/4) 159–176 (2004)
- W. Kutsch, M. Bahn, A. Heinemeyer (Eds.): *Soil Carbon Dynamics: An Integrated Methodology* (Cambridge Univ. Press, Cambridge (2009)
- A.R. Pedersen, S.O. Petersen, K. Schelde: A comprehensive approach to soil-atmosphere trace-gas flux estimation with static chambers, Eur. J. Soil Sci. **61**(6) 888–902 (2010)

References

60.1 J.A. Subke, I. Inglima, M.F. Cotrufo: Trends and methodological impacts in soil CO_2 efflux partitioning: A metaanalytical review, Glob. Change Biol. **12**(6), 921–943 (2006)

60.2 B. Bond-Lamberty, A. Thomson: A global database of soil respiration data, Biogeosciences **7**(6), 1915–1926 (2010)

60.3 S.D. Bridgham, H. Cadillo-Quiroz, J.K. Keller, Q. Zhuang: Methane emissions from wetlands: Biogeochemical, microbial, and modeling perspectives from local to global scales, Glob. Change Biol. **19**(5), 1325–1346 (2013)

60.4 L. Liu, T.L. Greaver: A review of nitrogen enrichment effects on three biogenic GHGs: The CO_2 sink may be largely offset by stimulated N_2O and CH_4 emission, Ecol. Lett. **12**(10), 1103–1117 (2009)

60.5 A.J. Thomson, G. Giannopoulos, J. Pretty, E.M. Baggs, D.J. Richardson: Biological sources and sinks of nitrous oxide and strategies to mitigate emissions, Philos. Trans. R. Soc. B **367**(1593), 1157–1168 (2012)

60.6 J. Pumpanen, B. Longdoz, W.L. Kutsch: Field measurements of soil respiration: Principles and constraints, potentials and limitations of different methods. In: *Soil Carbon Dynamics: An Integrated Methodology*, ed. by W. Kutsch, M. Bahn, A. Heinemeyer (Cambridge Univ. Press, Cambridge 2009) pp. 16–33

60.7 G.P. Livingston, G.L. Hutchinson: Enclosure-based measurement of trace gas exchange: Applications and sources of error. In: *Biogenic Trace Gases: Measuring Emissions from Soil and Water*, ed. by P.A. Matson, R.C. Harriss (Blackwell Science Ltd., Oxford 1995) pp. 14–51

60.8 D. Hooper, Z. Cardon, F. Chapin, M. Durant: Corrected calculations for soil and ecosystem measurements of CO_2 flux using the LI-COR 6200 portable photosynthesis system, Oecologia **132**(1), 1–11 (2002)

60.9 V. Le Dantec, D. Epron, E. Dufrêne: Soil CO_2 efflux in a beech forest: Comparison of two closed dynamic systems, Plant Soil **214**(1/2), 125–132 (1999)

60.10 M. Rayment, P. Jarvis: An improved open chamber system for measuring soil CO_2 effluxes in the field, J. Geophys. Res. Atmos. **102**(D24), 28779–28784 (1997)

60.11 B. Widen, A. Lindroth: A calibration system for soil carbon dioxide efflux measurement chambers: Description and application, Soil Sci, Soc. Am. J. **67**(1), 327–334 (2003)

60.12 E. Takle, W. Massman, J. Brandle, R. Schmidt, X. Zhou, I. Litvina, R. Garcia, G. Doyle, C. Rice: Influence of high-frequency ambient pressure pumping on carbon dioxide efflux from soil, Agric. For. Meteorol. **124**(3/4), 193–206 (2004)

60.13 H. Lundegårdh: Carbon dioxide evolution of soil and crop growth, Soil Sci. **23**(6), 417–453 (1927)

60.14 F. Bornemann: *Kohlensäure und Pflanzenwachstum*, 2nd edn. (P. Parey, Berlin 1923)

60.15 J. Pumpanen, P. Kolari, H. Ilvesniemi, K. Minkkinen, T. Vesala, S. Niinistö, A. Lohila, T. Larmola, M. Morero, M. Pihlatie, I. Janssens, J.C. Yuste, J.M. Grünzweig, S. Reth, J.-A. Subke, K. Savage, W. Kutsch, G. Østreng, W. Ziegler, P. Anthoni, A. Lindroth, P. Hari: Comparison of different chamber techniques for measuring soil CO_2 efflux, Agric. For. Meteorol. **123**(3/4), 159–176 (2004)

60.16 P. Rochette, G.L. Hutchinson: Measurement of soil respiration in situ: Chamber techniques. In: *Micrometeorology in Agricultural Systems*, Agronomy Monographs, Vol. 47, ed. by J.L. Hatfield, J.M. Baker (ASA, CSSA, SSSA, Madison 2005) pp. 247–286

60.17 M. Witkamp: Rates of carbon dioxide evolution from forest floor, Ecology **47**(3), 492–494 (1966)

60.18 H. Koepf: Die Verwendung des Ultrarotabsorptionsschreibers (URAS) für die kontinuierliche Registrierung der Bodenatmung im Freiland, Landwirtsch. Forsch. **5**, 54–62 (1953)

60.19 W. Reiners: Carbon dioxide evolution from floor of three Minnesota forests, Ecology **49**(3), 471–483 (1968)

60.20 M. Witkamp, M. Frank: Evolution of CO_2 from litter, humus, and subsoil of a pine stand, Pedobiologia **9**(5/6), 358–365 (1969)

60.21 N. Edwards, P. Sollins: Continuous measurement of carbon-dioxide evolution from partitioned forest floor components, Ecology **54**(2), 406–412 (1973)

60.22 N. Edwards: Moving chamber design for measuring soil respiration rates, Oikos **25**(1), 97–101 (1974)

60.23 J. Norman, R. Garcia, S. Verma: Soil surface CO_2 fluxes and the carbon budget of a grassland, J. Geophys. Res. Atmos. **97**(D17), 18845–18853 (1992)

60.24 M. Blanke: Soil respiration in an apple orchard, Environ. Exp. Bot. **36**(3), 339–348 (1996)

60.25 E. DeJong, R. Redmann, E. Ripley: Comparison of methods to measure soil respiration, Soil Sci. **127**(5), 300–306 (1979)

60.26 C. Fang, J. Moncrieff: An improved dynamic chamber technique for measuring CO_2 efflux from the surface of soil, Funct. Ecol. **10**(2), 297–305 (1996)

60.27 E.A. Davidson, K. Savage, L.V. Verchot, R. Navarro: Minimizing artifacts and biases in chamber-based measurements of soil respiration, Agric. For. Meteorol. **113**(1–4), 21–37 (2002)

60.28 C. Fang, J. Moncrieff: An open-top chamber for measuring soil respiration and the influence of pressure difference on CO_2 efflux measurement, Funct. Ecol. **12**(2), 319–325 (1998)

60.29 NIST: Fundamental Physical Constants, available via https://physics.nist.gov/cgi-bin/cuu/Value?r, Accessed 23 July 2021

60.30 J. Welles, T. Demetriades-Shah, D. McDermitt: Considerations for measuring ground CO_2 effluxes with chambers, Chem. Geol. **177**(1/2), 3–13 (2001)

60.31 O. Perez-Priego, A. Lopez-Ballesteros, E.P. Sanchez-Canete, P. Serrano-Ortiz, L. Kutzbach, F. Domingo, W. Eugster, A.S. Kowalski: Analysing uncertainties in the calculation of fluxes using whole-plant chambers: Random and systematic errors, Plant Soil **393**(1/2), 229–244 (2015)

60.32 G. Hutchinson, A. Mosier: Improved soil cover method for field measurement of nitrous-oxide fluxes, Soil Sci. Soc. Am. J. **45**(2), 311–316 (1981)

60.33 L. Kutzbach, J. Schneider, T. Sachs, M. Giebels, H. Nykanen, N.J. Shurpali, P.J. Martikainen, J. Alm, M. Wilmking: CO_2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression, Biogeosciences **4**(6), 1005–1025 (2007)

60.34 M.K. Pihlatie, J.R. Christiansen, H. Aaltonen, J.F.J. Korhonen, A. Nordbo, T. Rasilo, G. Benanti, M. Giebels, M. Helmy, J. Sheehy, S. Jones, R. Juszczak, R. Klefoth, R. Lobo-do-Vale, A.P. Rosa, P. Schreiber, D. Serça, S. Vicca, B. Wolf, J. Pumpanen: Comparison of static chambers to measure CH_4 emissions from soils, Agric. For. Meteorol. **171**, 124–136 (2013)

60.35 A.R. Pedersen, S.O. Petersen, K. Schelde: A comprehensive approach to soil-atmosphere trace-gas flux estimation with static chambers, Eur. J. Soil Sci. **61**(6), 888–902 (2010)

60.36 A.R. Pedersen: Package 'HMR' – Flux Estimation with Static Chamber Data, https://cran.r-project.org/web/packages/HMR/HMR.pdf (2017), Accessed 23 July 2021

60.37 E. Kanemasu, W. Powers, J. Sij: Field chamber measurements of CO_2 flux from soil surface, Soil Sci. **118**(4), 233–237 (1974)

60.38 D. Risk, N. Nickerson, C. Creelman, G. McArthur, J. Owens: Forced diffusion soil flux: A new technique for continuous monitoring of soil gas efflux, Agric. For. Meteorol. **151**(12), 1622–1631 (2011)

60.39 J. Martin, P. Bolstad, J. Norman: A carbon dioxide flux generator for testing infrared gas analyzer-based soil respiration systems, Soil Sci. Soc. Am. J. **68**(2), 514–518 (2004)

60.40 C. Creelman, N. Nickerson, D. Risk: Quantifying lateral diffusion error in soil carbon dioxide respiration estimates using numerical modeling, Soil Sci. Soc. Am. J. **77**(3), 699–708 (2013)

60.41 Y. Kim, S. Park, B. Lee, D. Risk: Continuous measurement of soil carbon efflux with forced diffusion (FD) chambers in a tundra ecosystem of Alaska, Sci. Total Environ. **566**, 175–184 (2016)

60.42 D. Risk, C.K. Lee, C. MacIntyre, S.C. Cary: First year-round record of Antarctic dry valley soil CO_2 flux, Soil Biol. Biochem. **66**, 193–196 (2013)

60.43 I.A. Janssens, A.S. Kowalski, B. Longdoz, R. Ceulemans: Assessing forest soil CO_2 efflux: An in situ comparison of four techniques, Tree Physiol. **20**, 23–32 (2000)

60.44 J. Norman, C. Kucharik, S. Gower, D. Baldocchi, P. Crill, M. Rayment, K. Savage, R. Striegl: A comparison of six methods for measuring soil-surface carbon dioxide fluxes, J. Geophys. Res. Atmos. **102**(D24), 28771–28777 (1997)

60.45 F. Gao, S. Yates: Laboratory study of closed and dynamic flux chambers: Experimental results and implications for field application, J. Geophys. Res. Atmos. **103**(D20), 26115–26125 (1998)

60.46 H. Akaike: New look at statistical-model identification, IEEE Trans. Autom. Control **19**(6), 716–723 (1974)

60.47 R.A. Fisher: On a distribution yielding the error functions of several well known statistics. In: *Proc. Int. Congr. Math., Toronto*, Vol. 2 (Univ. Toronto Press, Toronto 1924) pp. 805–813

60.48 C.M. Görres, L. Kutzbach, L. Elsgaard: Comparative modeling of annual CO_2 flux of temperate peat soils under permanent grassland management, Agric. Ecosyst. Environ. **186**, 64–76 (2014)

60.49 M. Herbst, L. Bornemann, A. Graf, G. Welp, H. Vereecken, W. Amelung: A geostatistical approach to the field-scale pattern of heterotrophic soil CO_2 emission using covariates, Biogeochemistry **111**(1–3), 377–392 (2012)

60.50 E. Leon, R. Vargas, S. Bullock, E. Lopez, A.R. Panosso, N. La Scala Jr.: Hot spots, hot moments, and spatio-temporal controls on soil CO_2 efflux in a water-limited ecosystem, Soil Biol. Biochem. **77**, 12–21 (2014)

60.51 M. Herbst, N. Prolingheuer, A. Graf, J.A. Huisman, L. Weihermueller, J. Vanderborght: Characterization and understanding of bare soil respiration spatial variability at plot scale, Vadose Zone J. **8**(3), 762–771 (2009)

60.52 D.R. Chadwick, L. Cardenas, T.H. Misselbrook, K.A. Smith, R.M. Rees, C.J. Watson, K.L. Mcgeough, J.R. Williams, J.M. Cloy, R.E. Thorman, M.S. Dhanoa: Optimizing chamber methods for measuring nitrous oxide emissions from plot-based agricultural experiments, Eur. J. Soil Sci. **65**(2), 295–307 (2014)

60.53 J.C.F. de Winter: Using the student's t-test with extremely small sample sizes, Pract. Assess. Res. Eval. **18**, Article 10 (2013)

60.54 R. Angell, T. Svejcar: A chamber design for measuring net CO_2 exchange on rangeland, J. Range Manag. **52**(1), 27–31 (1999)

60.55 S.G. Morris, S.W.L. Kimber, P. Grace, L. Van Zwieten: Improving the statistical preparation for measuring soil N_2O flux by closed chamber, Sci. Total Environ. **465**, 166–172 (2013)

60.56 M. Vanselow-Algan, S.R. Schmidt, M. Greven, C. Fiencke, L. Kutzbach, E.-M. Pfeiffer: High methane emissions dominated annual greenhouse gas balances 30 years after bog rewetting, Biogeosciences **12**(14), 4361–4371 (2015)

60.57 M. Ryan, B. Law: Interpreting, measuring, and modeling soil respiration, Biogeochemistry **73**(1), 3–27 (2005)

60.58 T. Parkin, T. Kaspar: Temporal variability of soil carbon dioxide flux: Effect of sampling frequency on cumulative carbon loss estimation, Soil Sci. Soc. Am. J. **68**(4), 1234–1241 (2004)

60.59 K. Savage, E.A. Davidson, A.D. Richardson: A conceptual and practical approach to data quality and analysis procedures for high-frequency soil respiration measurements, Funct. Ecol. **22**(6), 1000–1007 (2008)

60.60 A.D. Richardson, B.H. Braswell, D.Y. Hollinger, P. Burman, E.A. Davidson, R.S. Evans, L.B. Flanagan, J.W. Munger, K. Savage, S.P. Urbanski, S.C. Wofsy: Comparing simple respiration models for eddy flux and dynamic chamber data, Agric. For. Meteorol. **141**(2–4), 219–234 (2006)

60.61 V. Huth, S. Vaidya, M. Hoffmann, N. Jurisch, A. Guenther, L. Gundlach, U. Hagemann, L. Elsgaard, J. Augustin: Divergent NEE balances from manual-chamber CO_2 fluxes linked to different measurement and gap-filling strategies: A source for uncertainty of estimated terrestrial C sources and sinks?, J. Plant Nutr. Soil Sci. **180**(3), 302–315 (2017)

60.62 R. Vargas, M.S. Carbone, M. Reichstein, D.D. Baldocchi: Frontiers and challenges in soil respiration research: From measurements to model-data integration, Biogeochemistry **102**(1–3), 1–13 (2011)

60.63 A. Knohl, A.R.B. Soe, W.L. Kutsch, M. Goeckede, N. Buchmann: Representative estimates of soil and ecosystem respiration in an old beech forest, Plant Soil **302**(1/2), 189–202 (2008)

60.64 J.A. Subke, J.D. Tenhunen: Direct measurements of CO_2 flux below a spruce forest canopy, Agric. For. Meteorol. **126**(1/2), 157–168 (2004)

60.65 M.C. Myklebust, L.E. Hipps, R.J. Ryel: Comparison of eddy covariance, chamber, and gradient methods of measuring soil CO_2 efflux in an annual semi-arid grass, *Bromus tectorum*, Agric. For. Meteorol. **148**(11), 1894–1907 (2008)

60.66 J.M. Wang, J.G. Murphy, J.A. Geddes, C.L. Winsborough, N. Basiliko, S.C. Thomas: Methane fluxes measured by eddy covariance and static chamber techniques at a temperate forest in central Ontario, Canada, Biogeosciences **10**(6), 4371–4382 (2013)

60.67 A. Heinemeyer, M. Wilkinson, R. Vargas, J.-A. Subke, E. Casella, J.I.L. Morison, P. Ineson: Exploring the "overflow tap" theory: Linking forest soil CO_2 fluxes and individual mycorrhizosphere components to photosynthesis, Biogeosciences **9**, 79–95 (2012)

60.68 D. Gaumont-Guay, T.A. Black, A.G. Barr, R.S. Jassal, Z. Nesic: Biophysical controls on rhizospheric and heterotrophic components of soil respiration in a boreal black spruce stand, Tree Physiol. **28**(2), 161–171 (2008)

60.69 J.A. Subke, M. Reichstein, J.D. Tenhunen: Explaining temporal variation in soil CO_2 efflux in a mature spruce forest in Southern Germany, Soil Biol. Biochem. **35**(11), 1467–1483 (2003)

60.70 J.A. Subke, C.S. Moody, T.C. Hill, N. Voke, S. Toet, P. Ineson, Y. Teh: Rhizosphere activity and atmospheric methane concentrations drive variations of methane fluxes in a temperate forest soil, Soil Biol. Biochem. **116**, 323–332 (2018)

60.71 D.B. Metcalfe, T.D.G. Hermans, J. Ahlstrand, M. Becker, M. Berggren, R.G. Bjork, M.P. Bjorkman, D. Blok, N. Chaudhary, C. Chisholm, A.T. Classen, N.J. Hasselquist, M. Jonsson, J.A. Kristensen, B.B. Kumordzi, H. Lee, J.R. Mayor, J. Prevey, K. Pantazatou, J. Rousk, R.A. Sponseller, M.K. Sundqvist, J. Tang, J. Uddling, G. Wallin, W. Zhang, A. Ahlstrom, D.E. Tenenbaum, A.M. Abdi: Patchy field sampling biases understanding of climate change impacts across the Arctic, Nat. Ecol. Evol. **2**(9), 1443–1448 (2018)

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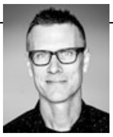

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