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Eddy covariance for soil processes

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Eddy covariance for quantifying trace gas fluxes from soils

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Abstract

Soils are highly complex physical and biological systems, and hence measuring soil gas exchange fluxes with high accuracy and adequate spatial representativity remains a challenge. A technique which has become increasingly popular is the eddy covariance (EC) method. This method takes advantage of the fact that surface fluxes are mixed into the near-surface atmosphere via turbulence. As a consequence, measurement with an EC system can be done at some distance above the surface, providing accurate and spatially integrated flux density estimates. In this paper we provide a basic overview targeting at scientists who are not familiar with the EC method. This reviews gives examples of successful deployments from a wide variety of ecosystems. The primary focus is on the three major greenhouse gases carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Several limitations to the application of EC systems exist, requiring a careful experimental design, which we discuss in detail. Thereby we group these experiments into two main classes: (1) manipulative experiments, and (2) survey-type experiments. Recommendations and examples of successful studies using various approaches, including the combination of EC flux measurements with online measurements of stable isotopes are given. We conclude that EC should not be considered a substitution of traditional flux measurements, but an addition to the latter. The greatest strength of EC measurements in soil science are (1) their uninterrupted continuous measurement of gas concentrations and fluxes that also can capture short-term bursts of fluxes that easily could be missed by other methods; and (2) the spatial integration covering the ecosystem scale (several m² to ha), thereby integrating over small-scale heterogeneity in the soil.

1 Introduction

Soils are highly complex physical and biological systems which have been challenging scientists who study soil processes in situ. Even simple soils that purely consist

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of quartz sand, exhibit a heterogeneity that leaves experimental scientists with an impressively large uncertainty when measuring gas fluxes from the soil to the atmosphere under controlled conditions (Gao et al., 1998a, b; Pumpanen et al., 2004; Pihlatie et al., 2013).

Thus, in addition to well established techniques to measure soil–atmosphere exchange processes, the technical advances to measure turbulent gas fluxes in the atmosphere above the soil surface with the eddy covariance (EC) method has been enthusiastically adopted even in soil process investigations. In this review we will provide the basic background why atmospheric flux measurements can provide sensitive, accurate, and timely quantitative information on soil processes that are otherwise difficult to measure with traditional techniques. At the same time we will discuss the limitations of the eddy covariance technique in soil process research studies and provide suggestions, how to design field experiments when using the eddy covariance technique. Finally, we highlight potential future applications and developments.

2 How it works

The basic concept of the eddy covariance method is the measurement of a turbulent flux in the near-surface atmosphere above an ecosystem and therefore also above the soil surface. The measurements follow a systematic sampling approach where air parcels moving past a wind velocity sensor combined with a gas concentration sensor or inlet of relatively small dimension are sampled with a sufficiently high time resolution to resolve all – or almost all – turbulent transport motions that turbulently move the entity of interest up and down in the atmosphere (Baldocchi and Meyers, 1998). To be more precise, the movement is chaotic and three-dimensional (3-D), where the vertical movements of air is of highest interest for soil scientists because this is the direction in which a gas produced in the soil can escape the soil towards the atmosphere. Similarly, the corresponding flux can be in the opposite direction (downwards towards the ground surface) if a gas in the atmosphere is taken up by the soil.

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The key to understanding, how eddy covariance flux measurements work and why a measurement in the atmosphere can be used to quantify a flux from the soil that has the soil surface as it's reference, is to understand the basics of atmospheric turbulence (Sect. 2.1) and how the point measurement made in the atmosphere relates to the soil surface (footprint concept, Sect. 3). The starting point is the point measurement made by an eddy covariance sensor set (Fig. 1). In reality, this "point" is a small volume (Fig. 1d), and the question is: how can the quantitative information of the 3-D turbulent flux measured in such a small volume be used as a representative spatial average estimate of the soil surface flux density of a specific trace gas?

Because the turbulent flux is directly measured by EC, as compared to inferential methods, where the flux is deduced from e.g. the change of concentration over time, it is important to understand which assumptions are actually made if such a (direct) point flux measurement is interpreted as the (inferential) flux density of a representative soil surface upwind of the EC sensors.

2.1 The basics of atmospheric turbulence

Without a minimum understanding of turbulent motion in the near-surface atmosphere it remains "black magic" to use eddy covariance for flux measurements in soil sciences. First of all, inside the soil there is no turbulent atmosphere, and hence students studying soil sciences generally are not made familiar with atmospheric turbulence. Here we provide a minimum insight into the few aspects of atmospheric turbulence that are the starting point for novices in eddy covariance. Although there are very good books, such as e.g. Wyngaard (2010) or Aubinet et al. (2012), they are either targeting atmospheric and fluid dynamics scientists or are strongly focusing on forest ecosystems. This is particularly the case since most active scientists who measure CO₂ fluxes have started to do so in forest ecosystems. In such settings, the special role of a voluminous plant canopy with often decoupled atmospheric conditions inside the canopy from what is measured above, poses special challenges that are not treated here, but can be found e.g. in Foken et al. (2012). Our brief summary aims at providing the basics of

atmospheric turbulence that is necessary to understand the eddy covariance flux concept when measuring fluxes from an exposed soil (e.g. over a ploughed or harvested crop field) or a soil with short-statured vegetation.

In atmospheric science the theoretical conditions at a measurement point can be expressed by the mass conservation equation for the gas of interest (Eq. 1). For momentum, the conservation equation is known as the Navier–Stokes equation, for scalars such as gas concentrations the term advection–diffusion equation is also used. Equation (1) is already a simplified version of such an equation. We did not include a molecular diffusion term, since diffusion of gases in a turbulent atmosphere is primarily driven by turbulent and not by molecular diffusion. The ratio between the two is on the order of 5000 (Oke, 1987), and thus at least during daytime molecular diffusion in the atmosphere can safely be neglected:

$$\frac{\partial \bar{c}}{\partial t} = \underbrace{S_{o_c}}_{\text{Source term:}} - \underbrace{\left(\frac{\partial}{\partial x} \overline{u\bar{c}} + \frac{\partial}{\partial y} \overline{v\bar{c}} + \frac{\partial}{\partial z} \overline{w\bar{c}} \right)}_{\text{Change in concentration due to:}} - \underbrace{\left(\frac{\partial}{\partial x} \overline{u'c'} + \frac{\partial}{\partial y} \overline{v'c'} + \frac{\partial}{\partial z} \overline{w'c'} \right)}_{\text{Change in concentration due to:}} - \underbrace{S_{i_c}}_{\text{Sink term:}} \quad (1)$$

Change in concentration

Source term:

- respiration
- emission
- chemistry

Change in concentration due to:

- horizontal
- vertical

} advection

Change in concentration due to:

- horizontal
- vertical

} flux divergence

Sink term:

- uptake
- deposition
- chemistry

with c representing the concentration of the gas of interest, t time, u and v are the horizontal wind speed components in x and y direction, respectively, w is the vertical wind speed (z direction). S_{o_c} and S_{i_c} denote the local source and sink terms for c , respectively.

Equation (1) describes how the concentration (c) changes over time (t) inside an imaginary small volume of air (see example in Fig. 1d). Due to physical mass conservation considerations, this temporal change of concentration $\partial \bar{c} / \partial t$ must have a reason, given on the right hand side of the equation. As Eq. (1) shows, the changes of c are strongly driven by the 3-D movements, the so-called eddies (turbulent whirls) leading to short-term fluctuations in all three wind speed components. Due to the fact that

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eddy covariance measurements are chaotic (nonlinear) time series measurements, an attempt to linearize the system helps both the understanding of the concept and the calculations. Following the decomposition concept by Reynolds (1895), each turbulently varying variable is decomposed into a mean component (denoted with an overbar, as in \bar{c}) and an instantaneous deviation from that mean (denoted by a prime, such as in c'). A single measurement c hence equals $\bar{c} + c'$. In micrometeorology and ecosystem sciences an averaging period of 30 min has become the standard, but depending on the research questions addressed, the averaging is also done at shorter or longer time intervals (Lenschow et al., 1994).

In principle, Eq. (1) is quite simple and straight forward: the right hand side states that the gas of interest (expressed by c) is transported in all three directions of space (x , y , z), and if there are source and sink terms (S_{o_c} and S_{i_c}) the concentration of c in the air volume can further change due to these. Following Reynolds (1895), all transport terms in Eq. (1) – which are the product of a wind vector component multiplied with c – are split in two parts, one which groups the means (e.g. $\overline{u\bar{c}}$), and one which groups the turbulent deviations (e.g. $\overline{w'c'}$). Technically, the terms $\overline{u'c'}$, $\overline{v'c'}$ and $\overline{w'c'}$ are statistical covariances, which have given this micrometeorological measurement technique the name “eddy covariance”. Older literature often used the term “eddy correlation”. Both are correct, and the correlation $r_{\alpha,c}$ is related to the covariance $\overline{a'c'}$ via normalization of the latter by the standard deviations of the individual time series, σ_α and σ_c ,

$$r_{\alpha,c} = \frac{\overline{a'c'}}{\sigma_\alpha \sigma_c}. \quad (2)$$

As long as all transport terms in Eq. (1) do not change in space (i.e., $\partial/\partial x$, $\partial/\partial y$ and $\partial/\partial z$ are zero in all cases), then there is no change in \bar{c} over time, unless a local source or sink is active. For the volume shown in Fig. 1d it is safe to assume that CO_2 (used here as an example) is neither taken up nor produced inside this volume, and the air stream used by the gas analyzer is so small that it can be ignored as a potential CO_2 sink. In the case of chemically reactive gases such as NO_2 , O_3 , NO ,

etc., this is of course not necessarily true and needs to be taken into account. Here we restrict ourselves to the case of chemically inert gases, such as CO_2 , CH_4 and N_2O , for which $S_{O_c} = 0$ and $S_{I_c} = 0$ inside the air volume measured by eddy covariance. Still, this assumption alone does not yet allow us to quantify the soil surface flux via eddy covariance measurements. A series of simplifying assumptions must be made and are further explained in the following section.

2.2 Simplifying assumptions to be made

Although we can quantify all transport terms in Eq. (1), we cannot quantify the divergence of these quantities in x , y and z direction with only one single EC system. Hence, a set of assumptions – as in any other flux measurement method, although experimentalists tend to forget about such assumptions – must be made to allow us to quantify surface fluxes with one single eddy covariance system as shown in Fig. 1.

2.2.1 Assumption of stationarity of the turbulence field

Although we may obtain a technically perfect measurement for the sample volume (Fig. 1d), relating this measurement to a surface area is only possible if we can make a space-for-time substitution approach known also as Taylor's frozen turbulence field hypothesis (see Stull, 1988, for an in-depth discussion). In simple words: under ideal conditions the turbulence field is stationary in such a way that we would get exactly the same readings no matter where we placed our EC system around the location of interest. Under such conditions, the horizontal advection terms ($\frac{\partial}{\partial x} \overline{u'c}$ and $\frac{\partial}{\partial y} \overline{v'c}$) become zero, and also the horizontal flux divergence terms ($\frac{\partial}{\partial x} \overline{u'c'}$ and $\frac{\partial}{\partial y} \overline{v'c'}$) become zero. If this is the case, then also vertical advection ($\frac{\partial}{\partial z} \overline{w'c}$) can be neglected.

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2.2.2 Assumption of negligible horizontal flux divergence

On perfectly flat and homogeneous ground the assumption of stationary turbulence also implies that $\overline{u'c'}$ and $\overline{v'c'}$ measured at a given height above the ground (the EC measurement height) should not vary in space. Hence, the horizontal flux divergence terms ($\frac{\partial}{\partial x}\overline{u'c'}$ and $\frac{\partial}{\partial y}\overline{v'c'}$) also become negligible.

With these assumptions, Eq. (1) expressed for the EC measurement height can be greatly simplified to

$$\frac{\partial \bar{c}}{\partial t} = -\frac{\partial}{\partial z}\overline{w'c'}, \quad (3)$$

with the negative sign indicating the convention that turbulent fluxes directed from the atmosphere towards the soil surface are negative. In simple words, Eq. (3) shows that if the term $\overline{w'c'}$ decreases with height, then \bar{c} increases over time, and if $\overline{w'c'}$ does not change with height, then $\partial \bar{c} / \partial t = 0$. The vertical flux divergence term $\frac{\partial}{\partial z}\overline{w'c'}$ remains in the equation due to the simple fact that the soil surface is a discontinuity in the system where turbulent motion dominates all gaseous transport in the atmosphere, but in the soil pores only laminar (nonturbulent) flow and hence molecular diffusion can occur. If we simplify Eq. (1) for the soil surface where turbulence vanishes, using the same simplifying assumptions as for Eq. (3), then we are left with

$$\frac{\partial \bar{c}}{\partial t} = S_{o_c} - S_{i_c} = Q_c, \quad (4)$$

where Q_c is the net flux of component c (in units of c per unit air volume and per unit time, e.g. $\mu\text{mol m}^{-3} \text{s}^{-1}$) at the soil surface. This is not yet the flux density, F_c , which is the flux per unit surface area. Thus, to yield F_c from an EC system, Eq. (1) must be integrated from the ground surface ($z = 0$) up to the EC height z_{ec} .

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2.2.3 Assumption about vertical concentration profile

If $\partial \bar{c} / \partial t$ differs at the soil surface (not inside the soil volume, but just above the physical soil surface which is difficult to define in field research) from the value obtained at the EC measurement height, then a profile measurement of concentrations is recommended.

5 In practice, however, over soils and short-statured vegetation it is safe to assume that $\partial \bar{c} / \partial t \approx \text{const}$ for $0 < z \leq z_{\text{ec}}$, and hence

$$F_c = \int_0^{z_{\text{ec}}} Q_c = \int_0^{z_{\text{ec}}} \frac{\partial \overline{w'c'}}{\partial z} dz \approx \overline{w'c'}_{z_{\text{ec}}}. \quad (5)$$

Figure 2 adopted from Stull (1988) illustrates this aspect very nicely: in the lowest centimeter above the ground the molecular flux that dominates the gas flux inside the soil volume is incorporated into the turbulent flux in the atmosphere in such a way, that a single EC system at some distance above the ground is able to accurately quantify the gas exchange F_c at the soil surface.

2.3 Importance of measurement height

In principle, the lower the measurement height above the ground, the easier it is to assume that between the ground surface and EC measurement height there are no confounding processes distorting the flux measurements. Due to the size of the sensors (Fig. 1d) and their response times and sampling intervals, it is however necessary to keep a distance from the ground surface such that no relevant eddy sizes are missed by the EC system. An additional reason may also be that the lower the measurement height, the smaller the footprint area represented by such a measurement (Sect. 3). If we however measure at greater height, our approximations made to yield Eq. (5) may become problematic: within the atmospheric boundary layer, which is the layer of air touching the soil surface and which is mixed by atmospheric turbulence, a given flux density F_c at ground surface almost linearly decreases with height until the flux

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vanishes at around inversion height. In Fig. 2a this inversion height is drawn at 1 km height above the ground surface, a typical value for daytime conditions. In a desert or semi-arid region, the height may be higher, and under cloudy conditions or at night it can be substantially lower. If we assume that EC flux measurements are accurate to $\pm 20\%$, unless special, restrictive data filtering is applied (e.g., Foken and Wichura, 1996), then it would be challenging to resolve the vertical gradient with normal EC instruments within the lowest 10–20% of the actual atmospheric boundary layer. If its height is 1000 m, then a 10 m tall tower would still measure 99% of the expected flux. Contrastingly, if e.g. at night the boundary layer is only 20 m, then the 10 m tower most likely only sees around 50% of the surface flux. Using a measurement height of 2 m, however, brings the measurements back to the range of experimental uncertainty.

Of most concern is, that the assumptions made above to simplify Eq. (1) are challenged by nocturnal atmospheric conditions, both over flat ground, where a meandering low-level jet may lead to intermittent turbulence (Mahrt, 2014) or by stagnant air pooling in valleys and topographic depressions in nonlevel terrain. Aubinet et al. (2012) address all these general issues with eddy covariance measurements in specific systems.

3 Flux footprint

Eddy covariance measurements have the great advantage that they can be performed in a noninvasive and nondestructive way. Only a minor disturbance is needed for placing a tripod or tower at a field site, but since the sensors measure the turbulent flux in the atmosphere, their measurements are in the vast majority of cases unrelated to the position of the tripod or tower itself, but reflect the surface conditions of a so-called “footprint area” upwind of the sensor.

Under the simplifying assumptions made in Sect. 2.2 it is possible to relate the point measurement obtained from eddy covariance to an upwind surface area that influences the measurements. To estimate the area of the flux footprint a wide variety of models is used. The most detailed information can be gained by inverse models. These models

invert the wind field and the computer model collects gas molecules artificially emitted by an EC system when they hit the ground. From such information a weighting function can be derived to estimate the percentage of influence of a given square meter to the overall flux measurement.

5 A statistical representation of such a footprint area estimated with the footprint model by Kljun et al. (2004) is shown in Fig. 3 for a grassland site in Switzerland. For each 30 min averaging interval covering a total time period of 2 years of measurements (mostly 2006 and 2007; see Zeeman et al., 2010) such calculations were performed and then were aggregated to obtain a statistical representation of the footprint area.

10 This example shows conditions that are quite typical for many localities: due to larger scale meteorological conditions, wind directions are not randomly distributed and show the typical diel variations, which is up-valley during daytime and down-valley during nighttime in mountain areas and the mountain foreland (example in Fig. 3). Similar patterns can be observed in locations near large water bodies: wind blowing from the

15 sea during daytime and from land during the night. This behavior is not a question of how flat the ground is, but where the relevant contrasts in surface energy fluxes are found. Also contrasts between irrigated and nonirrigated, or between vegetated and nonvegetated surfaces lead to predefined wind directions (“farm breeze”, e.g., Zhong and Doran, 1995) and need to be accounted for if such areas are of research interest.

20 The disadvantage of the noninvasive and nondestructive nature of EC flux measurements is that nobody can clearly identify the boundaries of the footprint in the real landscape. This makes the concept difficult to understand for researchers who are used to work with more traditional techniques such as chambers, where anybody can clearly see which part of the surface area is covered by the chamber – and hence contributes

25 to the measurements.

Moreover, the flux footprint of an eddy covariance system changes in size as atmospheric stability changes with the diel cycle. During the night, when the cold air pools in the low and flat parts of the landscape and soil surface temperatures are lowest, the flux footprint is relatively large. During daytime solar radiation heats the soil surface,

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makes the atmosphere unstable and convective, and thus the footprint can shrink to a few meters squared, depending on measurement height of the EC system.

Still, the problem is mostly not that “the eddy covariance method fails”, the issue is that even if the eddy covariance point measurement is of high quality, under such conditions there is no simple way to relate that measurement to the true flux density at the soil surface, leading to rejection of these data.

4 Experimental approaches

The understanding of the footprint concept of atmospheric measurements in general, and of eddy covariance flux measurements in particular, is essential for the establishment of feasible field experiments (see Sect. 4.2). The low predictability of wind direction and turbulence, in combination with the relatively large dimensions of the footprint area and its temporal variability normally do not allow for small-scale measurements in conventional factorial designs of manipulative experiments. However, for ecosystem-scale survey type experiments eddy covariance systems have proved their quality and usefulness. The decision for a specific experimental design is strongly related to the research question and processes that are addressed. Hence, we first provide a short overview over the key processes that have been investigated with the use of eddy covariance flux measurements, followed by a more general classification of approaches and experimental designs.

4.1 Measuring net fluxes of trace gases

Due to the fact that the eddy covariance technique is commonly applied to understand the ecosystem-scale processes it is crucial to understand that this technique is only capable of measuring a net flux of a specific greenhouse gas. That is, the difference between two or more counteracting gross fluxes is measured. In this review we primarily focus on CO₂, CH₄ and N₂O. For these, a basic knowledge of the soil processes

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involved in the exchange of a trace gas is needed to correctly interpret eddy covariance fluxes. Only few specific experimental set-ups allow measurements of a gross flux component such as soil respiration. Examples are *in-canopy (or below-canopy) eddy covariance setups* (Meyers and Baldocchi, 1993; Baldocchi and Vogel, 1996; Baldocchi et al., 1997; Blanken et al., 1998; Law et al., 1999; Pihlatie et al., 2005; Misson et al., 2007; Mammarella et al., 2010; Emmel et al., 2014) and/or measurements at sites that do not include any active above-ground vegetation, such as deserts (Leuning et al., 1982; Wohlfahrt et al., 2008; Bowling et al., 2010; Liu et al., 2012), or sites with a snow cover (Aurela et al., 2002; Röser et al., 2002; Lohila et al., 2007a; Reba et al., 2009; Björkman et al., 2010; Merbold et al., 2012, 2013).

While the processes leading to carbon dioxide (CO_2) losses from soils are rather widely investigated and well understood, it remains more complex to identify and understand all the processes that lead to methane (CH_4) and nitrous oxide (N_2O) fluxes, amongst other trace gases. A brief summary of the major processes involved in CO_2 , CH_4 and N_2O production or consumption will be provided in the following paragraphs.

4.1.1 CO_2 fluxes

Two counteracting processes, respiration and photosynthesis drive the net ecosystem exchange of CO_2 (NEE_{CO_2}). Both processes can easily be distinguished by the fact that photosynthesis is only active during the day, whereas respiration dominates the net flux measurements in the dark. But respiration is also active during the day, and some discussion has been focusing on the question, whether respiration fluxes are higher during the day due to higher (soil) temperatures during the day as compared to night, or whether daytime respiration rates should actually be lower than at night due to the so-called Kok effect of light inhibition of plant respiration (e.g., Atkin et al., 2000).

The most common approach to study soil CO_2 production processes during the day is to extrapolate nighttime measurements using a regression approach based on major driving variables, such as soil temperature and soil moisture (Lloyd and Taylor, 1994; Reichstein et al., 2005; Coleman and Jenkinson, 2008). Doing so ignores the possible

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light inhibition effect of plant respiration during the day, but for soil scientists interested in CO_2 production from the soil this may not be of concern. Another approach is the partitioning the net flux of CO_2 via daytime measurements and a light-response curve approach (Gilmanov et al., 2003; Yi et al., 2004; Gilmanov et al., 2007; Desai et al., 2008; Lasslop et al., 2010). Still, it is noteworthy that measured ecosystem respiration consists of several contributing sub-processes, and hence measurements can not directly be linked to the soil only (i.e., to below-ground processes). The major components of ecosystem respiration measured by eddy covariance are autotrophic respiration (CO_2 originating from plants as a by-product of photosynthesis) and soil respiration. The latter consists of several sub-terms such as heterotrophic respiration (namely basal and litter respiration) and the mycorrhizosphere respiration, which again consists of root respiration, rhizomicrobial respiration and mycorrhizal respiration. Details on each of these processes, driver variables, and their relative contribution to the net flux of CO_2 from the soil have been studied in detail across many ecosystems (e.g., Hogberg and Hogberg, 2002; Bhupinderpal-Singh et al., 2003; Moyano et al., 2007; Gaumont-Guay et al., 2008).

4.1.2 CH_4 and N_2O fluxes

The clear distinction of one gross process during a specific time period remains challenging for CO_2 and may even be impossible for CH_4 and N_2O fluxes (Butterbach-Bahl et al., 2013; Denmead, 2008). While again two counteracting processes are responsible for the net exchange of CH_4 , namely methanogenesis (production of CH_4) and methanotrophy (consumption of CH_4) resulting in the net ecosystem exchange of CH_4 (NEE_{CH_4}) a multitude of soil processes are involved in the production and consumption of N_2O ($\text{NEE}_{\text{N}_2\text{O}}$). The most commonly observed processes contributing to $\text{NEE}_{\text{N}_2\text{O}}$ are nitrification, denitrification, and nitrifier denitrification (Butterbach-Bahl et al., 2013). While uptake of N_2O by soils has been observed in several studies (Flechard et al., 2005; Hörtnagl et al., 2014) and this has clearly been evaluated as a relevant term in the net flux of N_2O between the soil and the atmosphere (Chapuis-Lardy et al., 2007),

the involved soil processes remain unknown. A complete overview of currently known N₂O soil processes has recently been given by Butterbach-Bahl et al. (2013).

The application of the eddy covariance technique to study soil processes leading to net exchange of CH₄ and N₂O can be based on two objectives. Some researchers are specifically interested in the variation of a specific trace gas flux over longer time periods – often termed “monitoring”. Such observations are most frequently carried out in forest ecosystems and are often combined with traditional techniques (Gaumont-Guay et al., 2008; Giasson et al., 2013).

4.1.3 Deployments in different ecosystem types

Besides specific case studies in *forests* (e.g. Pilegaard et al., 2003; Pihlatie et al., 2005; Eugster et al., 2007), investigations were also carried out in *grasslands* (Scanlon and Kiely, 2003; Leahy et al., 2004; Neftel et al., 2007; Soussana et al., 2007; Zeeman et al., 2010), *croplands* including rice paddies (Skiba et al., 1996; Alberto et al., 2009; Smith et al., 2010; Du and Liu, 2013), *savannas* (Hanan et al., 1996; Williams et al., 2004; Xu and Baldocchi, 2004; Xu et al., 2004; Hutley et al., 2005; Kutsch et al., 2008; Archibald et al., 2009; Merbold et al., 2009; Bruemmer et al., 2009; Eamus et al., 2013), *peatlands* (Lafleur et al., 2001; Lund et al., 2010; Brown et al., 2014), *landfills* (Rinne et al., 2005; Lohila et al., 2007b; McDermitt et al., 2011; Schroth et al., 2012), and *arctic tundra ecosystems* (Walker et al., 1998; Vourlitis and Oechel, 1999; Corradi et al., 2005; Eugster et al., 2005; Wille et al., 2008; Sachs et al., 2008; Grant et al., 2011). Only very recently researchers have started to also extend eddy covariance measurements to ever more challenging and less widespread ecosystem types, such as *mangroves* (Barr et al., 2012; Jha et al., 2014), *deserts* (Honrath et al., 2002; Liu et al., 2012; Li et al., 2014), *intertidal flats* (Polsenaere et al., 2012) and *screenhouses* (Tanny et al., 2006).

However, only few of these studies include observations of more than a single or two trace gases measured by eddy covariance. The typical configuration is that CO₂ fluxes are measured with eddy covariance, but CH₄ and/or N₂O fluxes are based on traditional

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techniques, often due to costs and logistical constraints. Fully integrative studies using the eddy covariance technique are still rare (bioenergy plantation: Zona et al. (2013), permanent grassland: Leahy et al. (2004), Hörtnagl et al. (2014) and Merbold et al. (2014)).

4.2 Experimental designs

Experimental designs can be grouped into two categories:

- *Manipulative experiments*: The standard approach used in laboratories under controlled conditions, where all confounding factors are kept constant, and only the factors of interest are varied in one or more treatments that are compared against a control.
- *Survey-type experiments*: Experiments, that are aware of the fact that time is a special variable that cannot be controlled and hence a long enough measurement in time and/or an adequate coverage of spatial variability are used to gather the quantitative flux data to answer a specific research question.

The following overview identifies the possibilities and limitations to use the eddy covariance technique to address specific research questions.

4.2.1 Manipulative experiments using eddy covariance

Manipulative experiments are the classical experimental approach used in laboratory studies. A typical design of such an experiment involves a control and at least one treatment. In order to investigate the effect of the treatment, the experimental set-up is made in a way that allows to control all factors of interest that may influence the response variable, e.g. a greenhouse gas flux. Although in principle it would be possible to use eddy covariance under indoor conditions in large halls with artificially created turbulence inside them, the logistical investment would be so great that no truly manipulative experiment under fully controlled conditions has been carried out so far. At

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most, turbulence measurements were done in a wind tunnel or shadehouse (Tanny et al., 2006), but in such a configuration the largest eddies that exist are those of the size of the containment, which is orders of magnitude smaller than large eddies in the turbulent outdoor environment.

Thus, the experiments with eddy covariance instrumentation are generally restricted to outdoor conditions, which limits the possibility to control environmental factors. Due to the high costs of the equipment it is normally not realistic to design full factorial experiments with more than one factor and with multiple levels. On the other hand, one can take advantage of the fact that eddy covariance integrates flux measurements over several spatial and temporal scales and hence may provide the more realistic approach to quantify the combined effects of manipulations. Good examples are *paired sites* studies, where eddy covariance towers are placed in similar environments where many of the environmental conditions are similar, but others are in contrast, such that this contrast corresponds to an experimental treatment. For example, Ammann et al. (2007, 2009) established two adequately sized fields next to each other, so that two different levels of agricultural management intensities could be studied via direct inter-comparison of two flux tower time series. Similarly, Amiro (2001) and Kowalski et al. (2004) compared a regenerating forest stand after disturbance with an undisturbed control stand.

Another successful approach is to use natural gradients or “treatments” such as in the study by Rocha and Shaver (2011) who established three eddy covariance towers in an area where a huge tundra fire in northern Alaska has left its trace in the landscape: one tower was placed on the most severely burnt surface, a second one was placed on a moderately burnt surface where the fire only destroyed the surface plant material but not the surface soil layer, and the third tower was placed next to the burnt area as a control (“unburnt”). Similarly, chronosequences after forest management (Kowalski et al., 2004; Humphreys et al., 2006; Schwalm et al., 2007; Peichl et al., 2010; Coursolle et al., 2012; Payeur-Poirier et al., 2012) or forest fires (Röser et al., 2002; Beringer

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et al., 2003) as well as thaw lake cycles in the Arctic (Sturtevant and Oechel, 2013) have been explored using the experimental concept of manipulative experiments.

The key issue for success with such experimental designs is the synchronous measurements of two or more eddy covariance towers. Due to the huge variability in atmospheric weather conditions, it is always much more difficult to find significant differences between sites that do not cover the same time period, than if the time periods coincide and statistical testing for differences can be made using the paired-samples approach. Due to serial autocorrelation in time series data and spatial autocorrelation between sites, a correction is needed in all statistical testing (e.g., Legendre and Legendre, 1998; Wilks, 2006).

Such a correction takes care of the fact that eddy covariance data heavily oversample the process of interest. This is not specific to EC measurements, but to any regularly spaced time series of measurements. Hence, the number of independent data points in a time series tends to be much lower than the actual number of data records. All statistical tests, however, assume that data are randomly drawn from an ensemble, and are independent of each other. Following Wilks (2006) the true number of independent data points n' in a time series with n regularly spaced data points can be determined using the lag-1 autocorrelation ρ_1 (Wilks, 2006),

$$n' \cong n \frac{1 - \rho_1}{1 + \rho_1}, \quad (6)$$

and statistical testing is then done using n' instead of n to compute the test statistics. As an example, if a measurement at time t depends to 90 % on what was measured during the previous time step in a way that $\rho_1^2 = 0.9$, then a time series with $n = 1000$ data points actually contains $n' \approx 26$ independent data points, and all tests for differences become less significant than if serial autocorrelation is forgotten to be corrected for.

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4.2.2 Survey-type experiments using eddy covariance

Manipulative experiments are typically limited to paired-site studies, and hence the most widespread experimental approach seen in the scientific activities employing EC measurements is rather conforming to a survey-type approach. Even if a specific research group is only focusing on one single site, sooner or later the wish for comparison with other sites measuring the same gas fluxes arises. Since such comparisons were not planned a priori when the experimental design was established, such comparisons do not normally conform to the rather strict control mechanisms employed in manipulative experiments.

Namely, if measurements from different sites and different years should be compared, then the data analysis is most successful with a survey-based approach, using natural gradients and contrasts of environmental variables and ecosystem parameters that were measured or estimated in addition to EC flux measurements. Often, the first step is to relate near-surface measurements to remote sensing products using regression analysis, be it simple linear or multivariate and nonlinear approaches. The goal is to find functional relationships that in the ideal case can be used as time-for-space substitutions to translate the information content of a time series to what a snapshot of the spatial distribution would reveal, had it been possible to take such a snapshot.

Aircraft flux measurements directly aim at providing a spatial survey of fluxes. By carefully considering the spatio-temporal variability of fluxes and using increasingly elaborate computer models to interpolate aircraft flux measurements in space and time, it is now possible to assess spatial variability of soil effluxes over larger regions (e.g. Desjardins et al., 1995; Zulueta et al., 2013; Hiller et al., 2014). This comes at the expense of a relatively coarse spatial resolution due to the measurement height of such an aircraft (see Sect. 2.3), and the time constraints for such flights, which are most likely only possible during daytime hours.

Roving towers (also mobile towers, portable towers) are an approach to assess spatial variability of soil surface fluxes by placing a tower on different surfaces for a few

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days or weeks at each location (Eugster et al., 1997; Billesbach et al., 2004). While a few days are generally already helpful for assessing surface energy fluxes, the use of roving towers for CO₂ fluxes is more challenging due to the phenology and seasonal variations in these fluxes (Eugster et al., 1997). The first successful deployment of roving towers as replicated measurements of CO₂ fluxes on four arable plots using only two EC towers was reported by Davis et al. (2010). Such innovative experimental concepts will most likely see further developments and applications in the future, but will always remain a compromise between a permanent tower and a full spatial flux survey as can be done with an aircraft.

In general, the greatest strength of EC measurements over other techniques is the continuous measurements at a high temporal resolution. This may not be the most essential point for CO₂ flux measurements which tend to be quite predictable based on simple light response and respiration models (see Sect. 4.1.1). Contrastingly, effluxes of CH₄ and N₂O are not necessarily resulting from continuous processes, but may appear in bursts (Fig. 4), from temporally active hot spots, or in response to short-term events (e.g. first precipitation after a drought period). Such cases can be captured via the systematic time-series measurements of EC systems, and substantial fluxes may result from such periods, which are not easily captured by a standard chamber measurement approach. Table 1 provides an overview over advantages and disadvantages of EC flux measurements in comparison to conventional chamber flux measurements.

5 Future directions and challenges

To gain further insights into soil processes via EC data and overcome some of the previously mentioned challenges when applying this technique, several approaches have shown to be promising. To understand the differences between plot-scale versus landscape-scale trace gas emissions the combination of EC with traditional techniques has shown great potential. Only with such a combination is it possible to investigate individual processes and to obtain an accurate net flux estimate for the entire ecosystem.

Chambers can be used to assess specific topographic effects and therefore providing essential information on the small-scale variability of trace gas fluxes, while eddy covariance measurements integrate over larger scales.

5 Examples focusing on CO₂ are presented by Norman et al. (1997), Lavigne et al. (1997), Janssens et al. (2000), and Merbold et al. (2011). Combined CH₄ flux measurements were carried out by Parmentier et al. (2011) and Zhang et al. (2012), and N₂O was assessed by Christensen et al. (1996) and Laville et al. (1999).

10 Another way forward in understanding soil processes is the combination of eddy covariance measurements with state-of-the-art isotope measurements (Chun-Ta et al., 2003; Sturm et al., 2012). Stable isotopes have been shown to provide a powerful tools to identify hot-spots of consumption and production of trace gases in the soil, leading to more complete understanding of interacting soil process at larger scales.

15 Besides the fact of identifying source processes (Baggs, 2008) an additional advantage when combining both techniques, EC and isotope measurements, is the potential of partitioning net fluxes into the contributing gross components (Ogee et al., 2003; Knohl and Buchmann, 2005; Baggs, 2008). Still, studies combining online measurements of isotopologues and EC remain rare and have in most cases focused on CO₂ only (Saleska et al., 2006; Wehr et al., 2013). Studies focusing on N₂O and CH₄ are likely to become available in the near future. Particularly with the development of new
20 laser absorption spectrometers capable of measuring the isotopic signatures of carbon, nitrogen and oxygen in methane and nitrous oxide (Mohn et al., 2008, 2013; McManus et al., 2010) new insights into soil processes producing these trace gases become possible (Wolf et al., 2014).

25 Another promising approach to study soil processes using EC data across ecosystems are research infrastructures. Such measurement networks provide ecosystem greenhouse gas flux data that has so far only partly been elaborated to study soil processes (Sanderman et al., 2003). Data originating from such networks (e.g., ICOS: Integrated Carbon Observatory System in Europe, and NEON: National Ecological Observatory Network in the USA, respectively) will provide standardized flux data of trace

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gases at different spatial scales (EC data and chamber) that will be publicly available and ready to be investigated. The great advantage of such networks is the twofold: (1) they cover a wide range of ecosystems, and (2) they provide ancillary data, which are essential for the interpretation of flux measurements.

Besides data driven approaches, combining the eddy covariance technique with modeling approaches to reliably estimate the contribution of heterogeneously distributed source and sinks of specific trace gases to the net flux can be achieved (Goeckede et al., 2006; Massman and Ibrom, 2008; Vesala et al., 2008) and thereby allowing the setup of eddy covariance towers in more complex environments (e.g., small-scale multicrop systems as often used on organic farms). Furthermore applications of EC towers within or below the canopy as well as at ecosystem edges (Rogiers et al., 2005; Kirton et al., 2009) bear great potential in studying soil processes at the ecosystem scale. Still, each application in heterogeneous terrain involve complex micrometeorological conditions and need a careful interpretation of the data collected.

6 Conclusions

The eddy covariance method is a micrometeorological technique to quantify surface flux densities of many trace gases produced by soil organisms or taken up by soils and the vegetation. The EC method's main advantage compared to other methods is its spatial scale of integration, ranging from several meters squared to a hectare and more, depending on measurement height, and its temporal coverage that includes all turbulent time scales that are relevant for trace gas mixing in the near-surface atmosphere from fractions of seconds to a typical 30 min averaging interval and longer.

Still, the method is not yet at a level where the uninitiated scientist can simply buy a system off the shelf, install it, and be happy with the data streaming in. In contrast to conventional meteorological measurements (e.g., air temperature), for which robust, reliable sensors exist that are easy to use and maintain, present-day eddy covariance flux systems still require a fair share of technical and micrometeorological knowledge

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to operate them reliably and satisfactorily under field conditions and over longer time periods.

In practice, this method substantially enlarges the soil scientist's toolbox and does not necessarily replace any of the existing traditional methods. Thus, the EC method is preferably used in combination with other techniques and methods that fill the gap where eddy covariance flux measurements are not helpful. The key issues to keep in mind to succeed with eddy covariance flux measurements is an adequate design of field experiments that rather should conform to paired-site and survey-type investigations, whereas its application in fully manipulative factorial designs with small spatial treatment units remains a challenge to be solved with future developments. As eddy covariance systems may drop in costliness both in investment and maintenance, it can be envisaged that EC systems could be deployed by the dozens in the near future, which would be required for full factorial manipulative experiments with several treatments that also include replications.

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References

- Alberto, M. C. R., Wassmann, R., Hirano, T., Miyata, A., Kumar, A., Padre, A., and Amante, M.: CO₂/heat fluxes in rice fields: Comparative assessment of flooded and non-flooded fields in the Philippines, *Agr. Forest Meteorol.*, 149, 1737–1750, 2009. 555
- Amiro, B. D.: Paired-tower measurements of carbon and energy fluxes following disturbance in the boreal forest, *Global Change Biol.*, 7, 253–268, 2001. 557

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Ammann, C., Flechard, C. R., Leifeld, J., Neftel, A., and Fuhrer, J.: The carbon budget of newly established temperate grassland depends on management intensity, *Agriculture, Ecosystems and Environment*, 121, 5–20, 2007. 557

Ammann, C., Spirig, C., Leifeld, J., and Neftel, A.: Assessment of the nitrogen and carbon budget of two managed temperate grassland fields, *Agriculture, Ecosystems and Environment*, 133, 150–162, doi:10.1016/j.agee.2009.05.006, 2009. 557

Archibald, S. A., Kirton, A., van der Merwe, M. R., Scholes, R. J., Williams, C. A., and Hanan, N.: Drivers of inter-annual variability in Net Ecosystem Exchange in a semi-arid savanna ecosystem, *South Africa, Biogeosciences*, 6, 251–266, doi:10.5194/bg-6-251-2009, 2009. 555

Atkin, O. K., Millar, A. H., Gardeström, P., and Day, D. A.: Photosynthesis, carbohydrate Metabolism and respiration in leaves of higher plants, vol. 9 of *Advances in Photosynthesis*, chap. 7, 153–175, Kluwer, The Netherlands, 2000. 553

Aubinet, M., Vesala, T., and Papale, D., eds.: *Eddy Covariance – A Practical Guide to Measurement and Data Analysis*, Springer, Dordrecht Heidelberg London New York, doi:10.1007/978-94-007-2351-1, 449 pp., 2012. 544, 550

Aurela, M., Laurila, T., and Tuovinen, J. P.: Annual CO₂ balance of a subarctic fen in northern Europe: Importance of the wintertime efflux, *J. Geophys. Res.*, 107, 4607, doi:10.1029/2002JD002055, 2002. 553

Baggs, E. M.: A review of stable isotope techniques for N₂O source partitioning in soils: recent progress, remaining challenges and future considerations, *Rapid Commun. Mass Spectrom.*, 22, 1664–1672, 2008. 561

Baldocchi, D. and Meyers, T.: On using eco-physiological, micrometeorological and biogeochemical theory to evaluate carbon dioxide, water vapor and trace gas fluxes over vegetation: a perspective, *Agr. Forest Meteorol.*, 90, 1–25, 1998. 543

Baldocchi, D. D. and Vogel, C. A.: Energy and CO₂ flux densities above and below a temperate broad-leaved forest and a boreal pine forest, *Tree Physiol.*, 16, 5–16, doi:10.1093/treephys/16.1-2.5, 1996. 553

Baldocchi, D. D., Vogel, C. A., and Hall, B.: Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest, *Agr. Forest Meteorol.*, 83, 147–170, doi:10.1016/S0168-1923(96)02335-0, 1997. 553

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Barr, J. G., Engel, V., Smith, T. J., and Fuentes, J. D.: Hurricane disturbance and recovery of energy balance, CO₂ fluxes and canopy structure in a mangrove forest of the Florida Everglades, *Agr. Forest Meteorol.*, 153, 54–66, 2012. 555

Beringer, J., Hutley, L. B., Tapper, N. J., Coutts, A., Kerley, A., and O'Grady, A. P.: Fire impacts on surface heat, moisture and carbon fluxes from a tropical savanna in northern Australia, *Int. J. Wildland Fire*, 12, 333–340, 2003. 557

Bhupinderpal-Singh, Nordgren, A., Ottosson L fvenius, M., H gberg, M. N., Mellander, P.-E., and H gberg, P.: Tree Root and Soil Heterotrophic Respiration as Revealed by Girdling of Boreal Scots Pine Forest: Extending Observations Beyond the First Year, *Plant Cell Environ.*, 26, 1287–1296, 2003. 554

Billesbach, D. P., Fischer, M. L., Torn, M. S., and Berry, J. A.: A portable eddy covariance system for the measurement of ecosystem–atmosphere exchange of CO₂, water vapor, and energy, *J. Atmos. Ocean. Technol.*, 21, 639–650, 2004. 560

Bj rkman, M. P., Morgner, E., Bj rk, R. G., Cooper, E. J., Elberling, B., and Klemedtsson, L.: A comparison of annual and seasonal carbon dioxide effluxes between sub-Arctic Sweden and High-Arctic Svalbard, *Polar Research*, 29, 75–84, 2010. 553

Blanken, P. D., Black, T. A., Neumann, H. H., den Hartog, G., Yang, P. C., Nesic, Z., Staebler, R., Chen, W., and Novak, M. D.: Turbulent flux measurements above and below the overstory of a boreal aspen forest, *Bound.-Lay. Meteorol.*, 89, 109–140, 1998. 553

Bowling, D. R., Bethers-Marchetti, S., Lunch, C. K., Grote, E. E., and Belnap, J.: Carbon, water, and energy fluxes in a semiarid cold desert grassland during and following multiyear drought, *J. Geophys. Res.*, 115, G04026, doi:10.1029/2010JG001322, 2010. 553

Brown, M. G., Humphreys, E. R., Moore, T. R., Roulet, N. T., and Lafleur, P. M.: Evidence for a nonmonotonic relationship between ecosystem-scale peatland methane emissions and water table depth, *J. Geophys. Res.*, 119, 826–835, 2014. 555

Bruemmer, C., Papen, H., Wassmann, R., and Brueggemann, N.: Fluxes of CH₄ and CO₂ from soil and termite mounds in south Sudanian savanna of Burkina Faso (West Africa), *Global Biogeochem. Cy.*, 23, GB1001, doi:10.1029/2008GB003237, 2009. 555

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., and Zechmeister-Boltenstern, S.: Nitrous oxide emissions from soils: how well do we understand the processes and their controls?, *Philos. Trans. Roy. Soc. B*, 368, 20130122, doi:10.1098/rstb.2013.0122, 2013. 554, 555

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- Christensen, S., Ambus, P., Arah, J. R. M., Clayton, H., Galle, B., Griffith, D. W. T., Hargreaves, K. J., Klemmedtsson, L., Lind, A. M., Maag, M., Scott, A., Skiba, U., Smith, K. A., Welling, M., and Wienhold, F. G.: Nitrous oxide emission from an agricultural field: Comparison between measurements by flux chamber and micrometeorological techniques, *Atmos. Environ.*, 30, 4183–4190, 1996. 561
- Chun-Ta, L., Schauer, A. J., Owensby, C., Ham, J. M., and Ehleringer, J. R.: Isotopic air sampling in a tallgrass prairie to partition net ecosystem CO₂ exchange, *J. Geophys. Res.*, 108, ACL4–1–14, 2003. 561
- Coleman, K. and Jenkinson, D. S.: A model for the turnover of carbon in soil: Model description and windows users guide, Tech. rep., Rothamsted Research, Harpenden, Herts (U.K.), ISBN 0-951-4456-8-5, 29 pp., 2008. 553
- Corradi, C., Kolle, O., Walter, K., Zimov, S. A., and Schulze, E.-D.: Carbon dioxide and methane exchange of a north-east Siberian tussock tundra, *Global Change Biol.*, 11, 1910–1925, doi:10.1111/j.1365-2486.2005.01023.x, 2005. 555
- Coursolle, C., Margolis, H. A., Giasson, M. A., Bernier, P. Y., Amiro, B. D., Arain, M. A., Barr, A. G., Black, T. A., Goulden, M. L., McCaughey, J. H., Chen, J. M., Dunn, A. L., Grant, R. F., and Lafleur, P. M.: Influence of stand age on the magnitude and seasonality of carbon fluxes in Canadian forests, *Agr. Forest Meteorol.*, 165, 136–148, 2012. 557
- Davis, P. A., Brown, J. C., Saunders, M., Lanigan, G., Wright, E., Fortune, T., Burke, J., Connolly, J., Jones, M., and Osborne, B.: Assessing the effects of agricultural management practices on carbon fluxes: Spatial variation and the need for replicated estimates of Net Ecosystem Exchange, *Agr. Forest Meteorol.*, 150, 564–574, doi:10.1016/j.agrformet.2010.01.021, 2010. 560
- Denmead, O. T.: Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere, *Plant Soil*, 309, 5–24, doi:10.1007/s11104-008-9599-z, 2008. 554
- Desai, A. R., Richardson, A. D., Moffat, A. M., Kattge, J., Hollinger, D. Y., Barr, A., Falge, E., Noormets, A., Papale, D., Reichstein, M., and Stauch, V. J.: Cross-site evaluation of eddy covariance GPP and RE decomposition techniques, *Agr. Forest Meteorol.*, 148, 821–838, doi:10.1016/j.agrformet.2007.11.012, 2008. 554

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- Desjardins, R. L., MacPherson, J. I., Neumann, H., den Hartog, G., and Schuepp, P. H.: Flux estimates of latent and sensible heat, carbon dioxide, and ozone using an aircraft-tower combination, *Atmos. Environ.*, 29, 3147–3158, doi:10.1016/1352-2310(95)00007-L, 1995. 559
- 5 Du, Q. and Liu, H.: Seven years of carbon dioxide exchange over a degraded grassland and a cropland with maize ecosystems in a semiarid area of China, *Agriculture, Ecosystems Environment*, 173, 1–12, 2013. 555
- Eamus, D., Cleverly, J., Boulain, N., Grant, N., Faux, R., and Villalobos-Vega, R.: Carbon and water fluxes in an arid-zone Acacia savanna woodland: An analyses of seasonal patterns and responses to rainfall events, *Agr. Forest Meteorol.*, 182, 225–238, 2013. 555
- 10 Emmel, C., Paul-Limoges, E., Bowler, R., Black, T. A., and Christen, A.: Vertical distribution of carbon dioxide sources and sinks in a recovering mountain pine beetle-attacked lodgepole pine stand, *Agr. Forest Meteorol.*, 195, 108–122, 2014. 553
- Eugster, W., McFadden, J. P., and Chapin III, F. S.: A comparative approach to regional variation in surface fluxes using mobile eddy correlation towers, *Bound.-Lay. Meteorol.*, 85, 293–307, 1997. 560
- 15 Eugster, W., McFadden, J. P., and Chapin III, F. S.: Differences in surface roughness, energy, and CO₂ fluxes in two moist tundra vegetation types, Kuparuk Watershed, Alaska, USA, *Arctic, Antarctic Alpine Res.*, 37, 61–67, 2005. 555
- 20 Eugster, W., Zeyer, K., Zeeman, M., Michna, P., Zingg, A., Buchmann, N., and Emmenegger, L.: Methodical study of nitrous oxide eddy covariance measurements using quantum cascade laser spectrometry over a Swiss forest, *Biogeosciences*, 4, 927–939, doi:10.5194/bg-4-927-2007, 2007. 555
- Flechard, C. R., Neftel, A., Jocher, M., Ammann, C., and Fuhrer, J.: Bi-directional soil/atmosphere N₂O exchange over two mown grassland systems with contrasting management practices, *Global Change Biol.*, 11, 2114–2127, 2005. 554
- 25 Foken, T. and Wichura, B.: Tools for Quality Assessment of Surface-Based Flux Measurements, *Agric. Forest Meteorol.*, 78, 83–105, 1996. 550
- Foken, T., Aubinet, M., and Leuning, R.: The eddy covariance method, chap. 1, pp. 365–376, doi:10.1007/978-94-007-2351-1_1, 449 pp., 2012. 544
- 30 Gao, F., Jin, Y., and Yates, S. R.: Simulation of enclosure-based methods for measuring gas emissions from soil to the atmosphere, *J. Geophys. Res.*, 103, 26127–26136, 1998a. 543

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- Gao, F., Yates, S. R., and Jin, Y.: Laboratory study of closed and dynamic flux chambers: Experimental results and implications for field applications, *J. Geophys. Res.*, 103, 26115–26125, 1998b. 543
- 5 Gaumont-Guay, D., Black, T. A., Barr, A. G., Jassal, R. S., and Nestic, Z.: Biophysical controls on rhizospheric and heterotrophic components of soil respiration in a boreal black spruce stand, *Tree Physiol.*, 28, 161–171, 2008. 554, 555
- Giasson, M. A., Ellison, A. M., Bowden, R. D., Crill, P. M., Davidson, E. A., Drake, J. E., Frey, S. D., Hadley, J. L., Lavine, M., Melillo, J. M., Munger, J. W., Nadelhoffer, K. J., Nicoll, L., Ollinger, S. V., Savage, K. E., Steudler, P. A., Tang, J., Varner, R. K., Wofsy, S. C., Foster, 10 D. R., and Finzi, A. C.: Soil respiration in a northeastern US temperate forest: a 22-year synthesis, *Ecosphere*, 4, UNSP 140, 2013. 555
- Gilmanov, T. G., Verma, S. B., Sims, P. L., Meyers, T. P., Bradford, J. A., Bourba, G. G., and Suyker, A. E.: Gross Primary Production and Light Response Parameters for Four Southern Plains Ecosystems Estimated Using Long-term CO₂-flux Tower Measurements, *Global Biogeochem. Cy.*, 17, 1071, doi:10.1029/2002GB002023, 2003. 554
- 15 Gilmanov, T. G., Soussana, J. F., Aires, L., Allard, V., Ammann, C., Balzarolo, M., Barcza, Z., Bernhofer, C., Campbell, C. L., Cernusca, A., Cescatti, A., Clifton-Brown, J., Dirks, B. O. M., Dore, S., Eugster, W., Fuhrer, J., Gimeno, C., Gruenwald, T., Haszpra, L., Hensen, A., Ibrom, A., Jacobs, A. F. G., Jones, M. B., Lanigan, G., Laurila, T., Lohila, A., Manca, G., Marcolla, B., Nagy, Z., Pilegaard, K., Pinter, K., Pio, C., Raschi, A., Rogiers, N., Sanz, M. J., Stefani, P., 20 Sutton, M., Tuba, Z., Valentini, R., Williams, M. L., and Wohlfahrt, G.: Partitioning European grassland net ecosystem CO₂ exchange into gross primary productivity and ecosystem respiration using light response function analysis, *Agriculture Ecosyst. Environ.*, 121, 93–120, 2007. 554
- 25 Goeckede, M., Markkanen, T., Hasager, C. B., and Foken, T.: Update of a footprint-based approach for the characterisation of complex measurement sites, *Bound.-Lay. Meteorol.*, 118, 635–655, 2006. 562
- Grant, R. F., Humphreys, E. R., Lafleur, P. M., and Dimitrov, D. D.: Ecological controls on net ecosystem productivity of a mesic arctic tundra under current and future climates, *J. Geophys. Res.*, 116, G01031, doi:10.1029/2010JG001555, 2011. 555
- 30 Hanan, N. P., Elbers, J. A., Kabat, P., Dolman, A. J., and deBruin, H. A. R.: CO₂ flux and photosynthesis of a Sahelian savanna during HAPEX-Sahel, *Phys. Chem. Earth*, 21, 135–141, 1996. 555

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- Hiller, R. V., Neiningner, B., Brunner, D., Gerbig, C., Bretscher, D., Künzle, T., Buchmann, N., and Eugster, W.: Aircraft-based CH₄ flux estimates for validation of emissions from an agriculturally dominated area in Switzerland, *J. Geophys. Res.*, 119, 1–14, doi:10.1002/2013JD020918, 2014. 559
- 5 Hogberg, M. N. and Hogberg, P.: Extramatrical ectomycorrhizal mycelium contributes one-third of microbial biomass and produces, together with associated roots, half the dissolved organic carbon in a forest soil, *New Phytologist*, 154, 791–795, 2002. 554
- Honrath, R. E., Lu, Y., Peterson, M. C., Dibb, J. E., Arsenault, M. A., Cullen, N. J., and Steffen, K.: Vertical fluxes of NO_x, HONO, and HNO₃ above the snowpack at Summit, Greenland, *Atmos. Environ.*, 36, 2629–2640, 2002. 555
- 10 Hörtnagl, L., Bamberger, I., Graus, M., Ruuskanen, T. M., Schnitzhofer, R., Walser, M., Unterberger, A., Hansel, A., and Wohlfahrt, G.: Acetaldehyde exchange above a managed temperate mountain grassland, *Atmos. Chem. Phys.*, 14, 5369–5391, doi:10.5194/acp-14-5369-2014, 2014. 554, 556
- 15 Humphreys, E. R., Black, T. A., Morgenstern, K., Cai, T., Drewitt, G. B., Nestic, Z., and Trofymow, J. A.: Carbon dioxide fluxes in coastal Douglas-fir stands at different stages of development after clearcut harvesting, *Agr. Forest Meteorol.*, 140, 6–22, 2006. 557
- Hutley, L. B., Leuning, R., Beringer, J., and Cleugh, H. A.: The utility of the eddy covariance techniques as a tool in carbon accounting: tropical savanna as a case study, *Austr. J. Botany*, 20 53, 663–675, 2005. 555
- Janssens, I. A., Kowalski, A. S., Longdoz, B., and Ceulemans, R.: Assessing forest soil CO₂ efflux: an in situ comparison of four techniques, *Tree Physiol.*, 20, 23–32, 2000. 561
- Jha, C. S., Rodda, S. R., Thumaty, K. C., Raha, A. K., and Dadhwal, V. K.: Eddy covariance based methane flux in Sundarbans mangroves, India, *J. Earth Syst. Sci.*, 123, 1089–1096, 25 2014. 555
- Kirton, A., Scholes, B., Verstraete, M., Archibald, S., Mennell, K., and Asner, G.: Detailed structural characterisation of the Savanna flux site at Skukuza, South Africa, *IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2009)*, 1–5, 437–440, 2009. 562
- Kljun, N., Calanca, P., Rotach, M. W., and Schmid, H. P.: A simple parameterisation for flux footprint predictions, *Bound.-Lay. Meteorol.*, 112, 503–523, 2004. 551
- 30 Knohl, A. and Buchmann, N.: Partitioning the net CO₂ flux of a deciduous forest into respiration and assimilation using stable carbon isotopes, *Global Biogeochem. Cy.*, 19, GB4008, doi:10.1029/2004GB002301, doi:10.1029/2004GB002301, 2005. 561

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- Kowalski, A. S., Loustau, D., Berbigier, P., Manca, G., Tedeschi, V., Borghetti, M., Valentini, R., Kolari, P., Berninger, F., Rannik, Ü., Hari, P., Rayment, M., Mencuccini, M., Moncrieff, J., and Grace, J.: Paired comparisons of carbon exchange between undisturbed and re-generating stands in four managed forests in Europe, *Global Change Biol.*, 10, 1707–1723, doi:10.1111/j.1365-2486.2004.00846.x, 2004. 557
- Kutsch, W. L., Hörmann, G., and Kappen, L.: Carbon and energy balances of different ecosystems and ecosystem complexes at the Bornhöved lake District, in: *Ecosystem organization of a complex landscape*, edited by: Fränzle, O., Kappen, L., and Blume, H.-P., *Ecological Studies 202*, Springer Verlag, Berlin Heidelberg, 2008. 555
- Lafleur, P. M., Roulet, N. T., and Admiral, S. W.: Annual cycle of CO₂ exchange at a bog peatland, *J. Geophys. Res.*, 106, 3071–3081, 2001. 555
- Lasslop, G., Reichstein, M., Papale, D., Richardson, A. D., Arneeth, A., Barr, A., Stoy, P., and Wohlfahrt, G.: Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation, *Global Change Biol.*, 16, 187–208, doi:10.1111/j.1365-2486.2009.02041.x, 2010. 554
- Lavigne, M. B., Ryan, M. G., Anderson, D. E., Baldocchi, D. D., Crill, P. M., Fitzjarrald, D. R., Goulden, M. L., Gower, S. T., Massheder, J. M., McCaughey, J. H., Rayment, M., and Striegl, R. G.: Comparing nocturnal eddy covariance measurements to estimates of ecosystem respiration made by scaling chamber measurements at six coniferous boreal sites, *J. Geophys. Res.*, 102, 28977–28985, 1997. 561
- Laville, P., Jambert, C., Cellier, P., and Delmas, R.: Nitrous oxide fluxes from a fertilised maize crop using micrometeorological and chamber methods, *Agr. Forest Meteorol.*, 96, 19–38, 1999. 561
- Law, B., Baldocchi, D., and Anthoni, P.: Below-canopy and soil CO₂ fluxes in a ponderosa pine forest, *Agr. Forest Meteorol.*, 94, 171–188, 1999. 553
- Leahy, P., Kiely, G., and Scanlon, T. M.: Managed grasslands: A greenhouse gas sink or source?, *Geophys. Res. Lett.*, 31, L20507, doi:10.1029/2004GL021161, 2004. 555, 556
- Legendre, P. and Legendre, L.: *Numerical Ecology*, no. 20 in *Developments in Environmental Modeling*, Elsevier, Amsterdam, 2nd Edn., 853 pp., 1998. 558
- Lenschow, D. H., Mann, J., and Kristensen, L.: How long is long enough when measuring fluxes and other turbulence statistics?, *J. Atmos. Ocean. Technol.*, 11, 661–673, 1994. 546

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- Leuning, R., Denmead, O. T., Lang, A. R. G., and Ohtaki, E.: Effects of heat and water vapor transport on eddy covariance measurement of CO₂ fluxes, *Bound.-Lay. Meteorol.*, 23, 209–222, 1982. 553
- Li, L., Chen, X., van der Tol, C., Luo, G., and Su, Z.: Growing season net ecosystem CO₂ exchange of two desert ecosystems with alkaline soils in Kazakhstan, *Ecology Evolution*, 4, 14–26, 2014. 555
- Liu, R., Li, Y., and Wang, Q.-X.: Variations in water and CO₂ fluxes over a saline desert in western China, *Hydrol. Process.*, 26, 513–522, 2012. 553, 555
- Lloyd, J. and Taylor, J. A.: On the temperature dependence of soil respiration, *Functional Ecology*, 8, 315–332, 1994. 553
- Lohila, A., Aurela, M., Regina, K., Tuovinen, J.-P., and Laurila, T.: Wintertime CO₂ exchange in a boreal agricultural peat soil, *Tellus B*, 59, 860–873, 2007a. 553
- Lohila, A., Laurila, T., Tuovinen, J.-P., Aurela, M., Hatakka, J., Thum, T., Pihlatie, M., Rinne, J., and Vesala, T.: Micrometeorological measurements of methane and carbon dioxide fluxes at a municipal landfill, *Environ. Sci. Technol.*, 41, 2717–2722, doi:10.1021/es061631h, 2007b. 555
- Lund, M., Lafleur, P. M., Roulet, N. T., Lindroth, A., Christensen, T. R., Aurela, M., Chojnicki, B. H., Flanagan, L. B., Humphreys, E. R., Laurila, T., Oechel, W. C., Olejnik, J., Rinne, J., Schubert, P., and Nilsson, M. B.: Variability in exchange of CO₂ across 12 northern peatland and tundra sites, *Global Change Biol.*, 16, 2436–2448, 2010. 555
- Mahrt, L.: Stably stratified atmospheric boundary layers, *Annu. Rev. Fluid Mech.*, 46, 23–45, doi:10.1146/annurev-fluid-010313-141354, 2014. 550
- Mammarella, I., Werle, P., Pihlatie, M., Eugster, W., Haapanala, S., Kiese, R., Markkanen, T., Rannik, Ü., and Vesala, T.: A case study of eddy covariance flux of N₂O measured within forest ecosystems: quality control and flux error analysis, *Biogeosciences*, 7, 427–440, doi:10.5194/bg-7-427-2010, 2010. 553
- Massman, W. J. and Ibrom, A.: Attenuation of concentration fluctuations of water vapor and other trace gases in turbulent tube flow, *Atmos. Chem. Phys.*, 8, 6245–6259, doi:10.5194/acp-8-6245-2008, 2008. 562
- McDermitt, D., Burba, G., Xu, L., Anderson, T., Komissarov, A., Riensche, B., Schedlbauer, J., Starr, G., Zona, D., Oechel, W., Oberbauer, S., and Hastings, S.: A new low-power, open-path instrument for measuring methane flux by eddy covariance, *Appl. Phys. B*, 102, 391–405, doi:10.1007/s00340-010-4307-0, 2011. 555

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- McManus, J. B., Zahniser, M. S., Nelson, D. D., Shorter, J. H., Herndon, S., Wood, E., and Wehr, R.: Application of quantum cascade lasers to high-precision atmospheric trace gas measurements, *Optical Engineering*, 49, 111124, doi:10.1117/1.3498782, 2010. 561
- Merbold, L., Ardö, J., Arneth, A., Scholes, R. J., Nouvellon, Y., de Grandcourt, A., Archibald, S., Bonnefond, J. M., Boulain, N., Brueggemann, N., Bruemmer, C., Cappelaere, B., Ceschia, E., El-Khidir, H. A. M., El-Tahir, B. A., Falk, U., Lloyd, J., Kergoat, L., Le Dantec, V., Mougín, E., Muchinda, M., Mukelabai, M. M., Ramier, D., Rouspard, O., Timouk, F., Veenendaal, E. M., and Kutsch, W. L.: Precipitation as driver of carbon fluxes in 11 African ecosystems, *Biogeosciences*, 6, 1027–1041, doi:10.5194/bg-6-1027-2009, 2009. 555
- Merbold, L., Ziegler, W., Mukelabai, M. M., and Kutsch, W. L.: Spatial and temporal variation of CO₂ efflux along a disturbance gradient in a *miombo* woodland in Western Zambia, *Biogeosciences*, 8, 147–164, doi:10.5194/bg-8-147-2011, 2011. 561
- Merbold, L., Rogiers, N., and Eugster, W.: Winter CO₂ fluxes in a sub-alpine grassland in relation to snow cover, radiation and temperature, *Biogeochemistry*, 111, 287–302, doi:10.1007/s10533-011-9647-2, 2012. 553
- Merbold, L., Steinlin, C., and Hagedorn, F.: Winter greenhouse gas fluxes (CO₂, CH₄ and N₂O) from a subalpine grassland, *Biogeosciences*, 10, 3185–3203, doi:10.5194/bg-10-3185-2013, 2013. 553
- Merbold, L., Eugster, W., Stieger, J., Zahniser, M., Nelson, D., and Buchmann, N.: Greenhouse gas budget (CO₂, CH₄ and N₂O) of intensively managed grassland following restoration, *Global Change Biol.*, 20, 1913–1928, doi:10.1111/gcb.12518, 2014. 556
- Meyers, T. P. and Baldocchi, D. D.: Trace gas exchange above the floor of a deciduous forest – 2: SO₂ and O₃ deposition, *J. Geophys. Res.*, 98, 12631–12638, 1993. 553
- Misson, L., Baldocchi, D. D., Black, T. A., Blanken, P. D., Brunet, Y., Yuste, J. C., Dorsey, J. R., Falk, M., Granier, A., Irvine, M. R., Jarosz, N., Lamaud, E., Launiainen, S., Law, B. E., Longdoz, B., Loustau, D., McKay, M., Paw, K. T., Vesala, T., Vickers, D., Wilson, K. B., and Goldstein, A. H.: Partitioning forest carbon fluxes with overstory and understory eddy-covariance measurements: A synthesis based on FLUXNET data, *Agr. Forest Meteorol.*, 144, 14–31, 2007. 553
- Mohn, J., Zeeman, M. J., Werner, R. A., Eugster, W., and Emmenegger, L.: Continuous field measurements of δ¹³C-CO₂ and trace gases by FTIR spectroscopy, *Isotopes in Environmental and Health Studies*, 44, 241–251, doi:10.1080/10256010802309731, 2008. 561

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1, 541–583, 2014

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- Mohn, J., Steinlin, C., Merbold, L., Emmenegger, L., and Hagedorn, F.: N₂O emissions and source processes in snow-covered soils in the Swiss Alps, *Isotopes Environ. Health Studies*, 49, 520–531, 2013. 561
- Moyano, F. E., Kutsch, W. L., and Schulze, E. D.: Response of mycorrhizal, rhizosphere and soil basal respiration to temperature and photosynthesis in a barley field, *Soil Biol. Biochem.*, 39, 843–853, 2007. 554
- Neftel, A., Flechard, C., Amman, C., Conen, F., Emmenegger, L., and Zeyer, K.: Experimental assessment of N₂O background fluxes in grassland systems, *Tellus*, 59B, 470–482, 2007. 555
- Norman, J., Kucharik, C., Gower, S., Baldocchi, D., Crill, P., Rayment, M., Savage, K., and Striegl, R.: A comparison of six methods for measuring soil-surface carbon dioxide fluxes, *J. Geophys. Res.*, 102, 28771–28777, 1997. 561
- Ogee, J., Peylin, P., Ciais, P., Bariac, T., Brunet, Y., Berbigier, P., Roche, C., Richard, P., Bardoux, G., and Bonnefond, J. M.: Partitioning net ecosystem carbon exchange into net assimilation and respiration using (CO₂)-C-13 measurements: A cost-effective sampling strategy, *Global Biogeochem. Cy.*, 17, 1070, doi:10.1029/2002GB001995, 2003. 561
- Oke, T. R.: *Boundary Layer Climates*, Methuen, London, New York, 2nd Edn., 435 pp., 1987. 545
- Parmentier, F. J. W., van Huissteden, J., Kip, N., Op den Camp, H. J. M., Jetten, M. S. M., Maximov, T. C., and Dolman, A. J.: The role of endophytic methane-oxidizing bacteria in submerged *Sphagnum* in determining methane emissions of Northeastern Siberian tundra, *Biogeosciences*, 8, 1267–1278, doi:10.5194/bg-8-1267-2011, 2011. 561
- Payeur-Poirier, J.-L., Coursolle, C., Margolis, H. A., and Giasson, M.-A.: CO₂ fluxes of a boreal black spruce chronosequence in eastern North America, *Agr. Forest Meteorol.*, 153, 94–105, 2012. 557
- Peichl, M., Brodeur, J. J., Khomik, M., and Arain, M. A.: Biometric and eddy-covariance based estimates of carbon fluxes in an age-sequence of temperate pine forests, *Agr. Forest Meteorol.*, 150, 952–965, 2010. 557
- Pihlatie, M., Rinne, J., Ambus, P., Pilegaard, K., Dorsey, J. R., Rannik, Ü., Markkanen, T., Launiainen, S., and Vesala, T.: Nitrous oxide emissions from a beech forest floor measured by eddy covariance and soil enclosure techniques, *Biogeosciences*, 2, 377–387, doi:10.5194/bg-2-377-2005, 2005. 553, 555

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- Pihlatie, M. K., Riis Christiansen, J., Aaltonen, H., Korhonen, J. F. J., Nordbo, A., Rasilo, T., Benanti, G., Giebels, M., Helmy, M., Sheehy, J., Jones, S., Juszczak, R., Klefoth, R., do Valem, R. L., Rosa, A. P., Schreiber, P., Serca, D., Vicca, S., Wolf, B., and Pumpanen, J.: Comparison of static chambers to measure CH₄ emissions from soils, *Agr. Forest Meteorol.*, 171, 124–136, doi:10.1016/j.agrformet.2012.11.008, 2013. 543
- Pilegaard, K., Mikkelsen, T. N., Beier, C., Jensen, N. O., Ambus, P., and Ro-Poulsen, H.: Field measurements of atmosphere–biosphere interactions in a Danish beech forest, *Boreal Environ. Res.*, 8, 315–333, 2003. 555
- Polsenaere, P., Lamaud, E., Lafon, V., Bonnefond, J.-M., Bretel, P., Delille, B., Deborde, J., Loustau, D., and Abril, G.: Spatial and temporal CO₂ exchanges measured by Eddy Covariance over a temperate intertidal flat and their relationships to net ecosystem production, *Biogeosciences*, 9, 249–268, doi:10.5194/bg-9-249-2012, 2012. 555
- Pumpanen, J., Kolari, P., Ilvesniemi, H., Minkkinen, K., Vesala, T., Lohila, S. N. A., Larmola, T., Morero, M., Pihlatie, M., Janssens, I., Yuste, J. C., Grünzweig, J. M., Reth, S., Subke, J.-A., Savage, K., Kutsch, W., Ostreng, G., Ziegler, W., Anthoni, P., Lindroth, A., and Hari, P.: Comparison of different chamber techniques for measuring soil CO₂ efflux, *Agr. Forest Meteorol.*, 123, 159–176, doi:10.1016/j.agrformet.2003.12.001, 2004. 543
- Reba, M. L., Link, T. E., Marks, D., and Pomeroy, J.: An assessment of corrections for eddy covariance measured turbulent fluxes over snow in mountain environments, *Water Resour. Res.*, 45, W00D38, doi:10.1029/2008WR007045, 2009. 553
- Reichstein, M., Subke, J. A., Angeli, A. C., and Tenhunen, J. D.: Does the temperature sensitivity of decomposition of soil organic matter depend upon water content, soil horizon, or incubation time?, *Global Change Biol.*, 11, 1754–1767, 2005. 553
- Reynolds, O.: On the dynamical theory of incompressible viscous fluids and the determination of the criterion, *Phil. Trans. R. Soc. A*, 186, 123–164, 1895. 546
- Rinne, J., Pihlatie, M., Lohila, A., Thum, T., Aurela, M., Tuovinen, J. P., Laurila, T., and Vesala, T.: Nitrous oxide emissions from a municipal landfill, *Environ. Sci. Technol.*, 39, 7790–7793, 2005. 555
- Rocha, A. V. and Shaver, G. R.: Burn severity influences postfire CO₂ exchange in arctic tundra, *Ecol. Appl.*, 21, 477–489, doi:10.1890/10-0255.1, 2011. 557
- Rogiers, N., Eugster, W., Furger, M., and Siegwolf, R.: Effect of land management on ecosystem carbon fluxes at a subalpine grassland site in the Swiss Alps, *Theor. Appl. Climatol.*, 80, 187–203, 2005. 562

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Röser, C., Montagnani, L., Schulze, E.-D., Mollicone, D., Kolle, O., Meroni, M., Papale, D., Marchesini, L. B., Federici, S., and Valentini, R.: Net CO₂ exchange rates in three different successional stages of the “dark taiga” of central Siberia, *Tellus*, 54B, 642–654, 2002. 553, 557

5 Sachs, T., Wille, C., Boike, J., and Kutzbach, L.: Environmental controls on ecosystem-scale CH₄ emission from polygonal tundra in the Lena River Delta, Siberia, *J. Geophys. Res.*, 113, G00A03, doi:10.1029/2007JG000505, 2008. 555

Saleska, S. R., Shorter, J. H., Herndon, S., Jimenez, J. L., McManaus, B., Nelson, D., Munger, J. W., and Zahniser, M.: What are the instrumentation requirements for measuring the isotopic composition of net ecosystem exchange of CO₂ using eddy covariance methods?, *Isotopes Environ. Health Studies*, 42, 115–133, doi:10.1080/10256010600672959, 2006. 561

10 Sanderman, J., Amundson, R. G., and Baldocchi, D. D.: Application of eddy covariance measurements to the temperature dependence of soil organic matter mean residence time, *Global Biogeochem. Cy.*, 17, 1061, doi:10.1029/2001GB001833, 2003. 561

15 Scanlon, T. M. and Kiely, G.: Ecosystem-scale Measurements of Nitrous Oxide Fluxes for an Intensely Grazed, Fertilized Grassland, *Geophys. Res. Lett.*, 30, 1852–1855, doi:10.1029/2003GL017454, 2003. 555

Schroth, M. H., Eugster, W., Gómez, K. E., Gonzalez-Gil, G., Niklaus, P. A., and Oester, P.: Above- and below-ground methane fluxes and methanotrophic activity in a landfill-cover soil, *Waste Management*, 5, 879–889, doi:10.1016/j.wasman.2011.11.003, 2012. 555, 583

20 Schwalm, C. R., Black, T. A., Morgenstern, K., and Humphreys, E. R.: A method for deriving net primary productivity and component respiratory fluxes from tower-based eddy covariance data: a case study using a 17-year data record from a Douglas-fir chronosequence, *Global Change Biol.*, 13, 370–385, 2007. 557

25 Skiba, U., Hargreaves, K. J., Beverland, I. J., Oneill, D. H., Fowler, D., and Moncrieff, J. B.: Measurement of field scale N₂O emission fluxes from a wheat crop using micrometeorological techniques, *Plant and Soil*, 181, 139–144, 1996. 555

Smith, P., Lanigan, G., Kutsch, W. L., Buchmann, N., Eugster, W., Aubinet, M., Ceschia, E., Béziat, P., Yeluripati, J. B., Osborne, B., Moors, E. J., Brut, A., Wattenbach, M., Saunders, M., and Jones, M.: Measurements necessary for assessing the net ecosystem carbon budget of croplands, *Agriculture Ecosyst. Environ.*, 139, 302–315, doi:10.1016/j.agee.2010.04.004, 2010. 555

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- Soussana, J. F., Allard, V., Pilegaard, K., Ambus, P., Ammann, C., Campbell, C., Ceschia, E., Clifton-Brown, J., Czobel, S., Domingues, R., Flechard, C., Fuhrer, J., Hensen, A., Horvath, L., Jones, M., Kasper, G., Martin, C., Nagy, Z., Neftel, A., Raschi, A., Baronti, S., Rees, R. M., Skiba, U., Stefani, P., Manca, G., Sutton, M., Tuba, Z., and Valentini, R.: Full accounting of the greenhouse gas (CO₂, N₂O, CH₄) budget of nine European grassland sites, *Agriculture Ecosyst. Environ.*, 121, 121–134, 2007. 555
- Stull, R. B.: *An Introduction to Boundary Layer Meteorology*, Kluwer, Dordrecht, 666 pp., 1988. 547, 549, 581
- Sturm, P., Eugster, W., and Knohl, A.: Eddy covariance measurements of CO₂ isotopologues with a quantum cascade laser absorption spectrometer, *Agr. Forest Meteorol.*, 152, 73–82, doi:10.1016/j.agrformet.2011.09.007, 2012. 561
- Sturtevant, C. S. and Oechel, W. C.: Spatial variation in landscape-level CO₂ and CH₄ fluxes from arctic coastal tundra: influence from vegetation, wetness, and the thaw lake cycle, *Global Change Biol.*, 19, 2853–2866, 2013. 558
- Tanny, J., Liu, H., and Cohen, S.: Airflow characteristics, energy balance and eddy covariance measurements in a banana screenhouse, *Agr. Forest Meteorol.*, 139, 105–118, 2006. 555, 557
- Vesala, T., Kljun, N., Rannik, Ü., Rinne, J., Sogachev, A., Markkanen, T., Sabelfeld, K., Foken, T., and Leclerc, M. Y.: Flux and concentration footprint modelling: State of the art, *Environ. Pollut.*, 152, 653–666, 2008. 562
- Vourlitis, G. L. and Oechel, W. C.: Eddy covariance measurements of CO₂ and energy fluxes of an Alaskan tussock tundra ecosystem, *Ecology*, 80, 686–701, 1999. 555
- Walker, D. A., Auerbach, N. A., Bockheim, J. G., F. S. Chapin, I., Eugster, W., King, J. Y., McFadden, J. P., Michaelson, G. J., Nelson, F. E., Oechel, W. C., Ping, C. L., Reeburgh, W. S., Regli, S., Shiklomanov, N. I., and Vourlitis, G. L.: Energy and Trace-gas Fluxes Across a Soil pH Boundary in the Arctic, *Nature*, 394, 469–472, 1998. 555
- Wehr, R., Munger, J. W., Nelson, D. D., McManus, J. B., Zahniser, M. S., Wofsy, S. C., and Saleska, S. R.: Long-term eddy covariance measurements of the isotopic composition of the ecosystem-atmosphere exchange of CO₂ in a temperate forest, *Agr. Forest Meteorol.*, 181, 69–84, 2013. 561
- Wilks, D. S.: *Statistical Methods in the Atmospheric Sciences*, vol. 91 of *International Geophysical Series*, Academic Press, San Diego, 2nd Edn., 627 pp., 2006. 558

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- Wille, C., Kutzbach, L., Sachs, T., Wagner, D., and Pfeiffer, E.-M.: Methane emission from Siberian arctic polygonal tundra: eddy covariance measurements and modeling, *Global Change Biol.*, 14, 1395–1408, doi:10.1111/j.1365-2486.2008.01586.x, 2008. 555
- Williams, D. G., Cable, W., Hultine, K., Hoedjes, J. C. B., Yopez, E. A., Simonneaux, V., Er-Raki, S., Boulet, G., de Bruin, H. A. R., Chehbouni, A., Harthogensis, O. K., and Timouk, F.: Evapotranspiration components determined by stable isotope, sap flow and eddy covariance techniques, *Agr. Forest Meteorol.*, 125, 241–258, 2004. 555
- Wohlfahrt, G., Fenstermaker, L. F., and Arnone, John A., I.: Large annual net ecosystem CO₂ uptake of a Mojave Desert ecosystem, *Global Change Biol.*, 14, 1475–1487, 2008. 553
- Wolf, B., Merbold, L., Decock, C., Tuzson, B., Harris, E., Six, J., Emmenegger, L., and Mohn, J.: First on-line isotopic characterization of N₂O emitted from intensively managed grassland, submitted, 2014. 561
- Wyngaard, J. C.: *Turbulence in the Atmosphere*, Cambridge University Press, iISBN 978-0-521-88769-4, 2010. 544
- Xu, L. K. and Baldocchi, D. D.: Seasonal variation in carbon dioxide exchange over a Mediterranean annual grassland in California, *Agr. Forest Meteorol.*, 123, 79–96, 2004. 555
- Xu, L. K., Baldocchi, D. D., and Tang, J. W.: How soil moisture, rain pulses, and growth alter the response of ecosystem respiration to temperature, *Global Biogeochem. Cy.*, 18, GB4002, doi:10.1029/2004GB002281, 2004. 555
- Yi, C. X., Li, R. Z., Bakwin, P. S., Desai, A., Ricciuto, D. M., Burns, S. P., Turnipseed, A. A., Wofsy, S. C., Munger, J. W., Wilson, K., and Monson, R. K.: A nonparametric method for separating photosynthesis and respiration components in CO₂ flux measurements, *Geophys. Res. Lett.*, 31, L17107, doi:10.1029/2004GL020490, 2004. 554
- Zeeman, M. J., Hiller, R., Gilgen, A. K., Michna, P., Plüss, P., Buchmann, N., and Eugster, W.: Management and climate impacts on net CO₂ fluxes and carbon budgets of three grasslands along an elevational gradient in Switzerland, *Agr. Forest Meteorol.*, 150, 519–530, doi:10.1016/j.agrformet.2010.01.011, 2010. 551, 555, 582
- Zhang, Y., Sachs, T., Li, C., and Boike, J.: Upscaling methane fluxes from closed chambers to eddy covariance based on a permafrost biogeochemistry integrated model, *Global Change Biol.*, 18, 1428–1440, doi:10.1111/j.1365-2486.2011.02587.x, 2012. 561
- Zhong, S. and Doran, J. C.: A Modeling Study of the Effects of Inhomogeneous Surface Fluxes on Boundary-Layer Properties, *J. Atmos. Sci.*, 52, 3129–3142, 1995. 551

- Zona, D., Janssens, I. A., Aubinet, M., Gioli, B., Vicca, S., Fichot, R., and Ceulemans, R.: Fluxes of the greenhouse gases (CO₂, CH₄ and N₂O) above a short-rotation poplar plantation after conversion from agricultural land, *Agr. Forest Meteorol.*, 169, 100–110, 2013. 556
- 5 Zulueta, R. C., Oechel, W. C., Verfaillie, J. G., and Hastings, S. J.: Aircraft regional-scale flux measurements over complex landscapes of mangroves, desert, and marine ecosystems of Magdalena Bay, Mexico, *J. Atmos. Ocean. Technol.*, 30, 1266–1294, 2013. 559

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1, 541–583, 2014

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Table 1. Overview of the major characteristics of traditional chamber systems and the eddy covariance method to measure trace gas fluxes.

Aspect	Traditional chambers	Eddy covariance
Spatial representativity	Small: few cm ² to < 10 m ² ; identification of small scale heterogeneity possible	Large: few m ² (bare soil) to several ha (tall forest), ecosystem-scale integration
Temporal coverage	Low: with manual chambers (e.g. daily, weekly, monthly); moderate: with automatic chambers (hourly, daily)	High: e.g. 30 min flux value for weeks, months, years
Measurement type	Indirect: flux is calculated via the concentration increase over time during chamber closure	Direct: flux is measured as the covariance of changes in turbulence and gas concentration
Instrument costs	Moderate: for manual chambers and analysis of the gas sample via gas chromatography; moderate/high: for automatic chambers which are either connected to a gas chromatograph or a gas analyzer (e.g. infrared gas analyzer or laser absorption spectrometer)	Moderate: for the scaffolding or a tripod; high for instruments capable of measuring turbulence (sonic anemometers) and gas concentrations (infrared gas analyzers, laser absorption spectrometers) at high temporal resolution (typically 20 Hz)
Maintenance costs (technical)	Low: for manual chambers moderate: for automatic chambers as well as for carrier gases etc. within a gas chromatography set-ups	Moderate: for replacing small technical devices and calibration gases, high: in case of sensor replacement
Maintenance costs (labour)	High: due to regular sample collection in the field and permanent lab personal to run e.g. a gas chromatograph	Moderate: due remote maintenance and less field activities
Computing requirements	Low: flux calculation is based on few data points and can be script based	Moderate/high: due to high frequency data (> 10 Hz) and often data covering > 1 year
Pre-existing knowledge	Moderate: basic principles of gas diffusion and calculation of differences in concentration over time	Substantial: basics in micrometeorology, turbulent flows, atmospheric stability, etc.



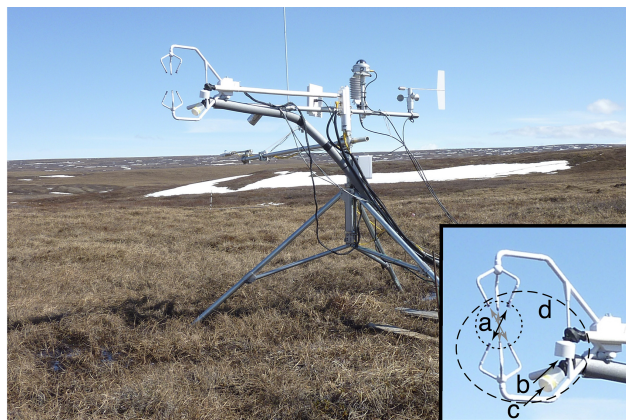
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Figure 1. Example of an eddy covariance flux system in the low Arctic, Toolik Field Station, Alaska. The inset shows the ultrasonic anemometer's sensor head **(a)** with two inlets of tubes leading air to **(b)** an enclosed-path CO_2 and H_2O analyser, and **(c)** to a closed-path CH_4 analyser. The ultrasonic anemometer has three pairs of sensors (pairs shown by arrows), in a configuration that allows to measure the 3-dimensional wind vector in the air volume indicated by **(a)**. Due to sensor separation between wind vector and gas concentration measurements, the eddy covariance “point” measurement is representing a somewhat larger volume of air indicated by **(d)**.

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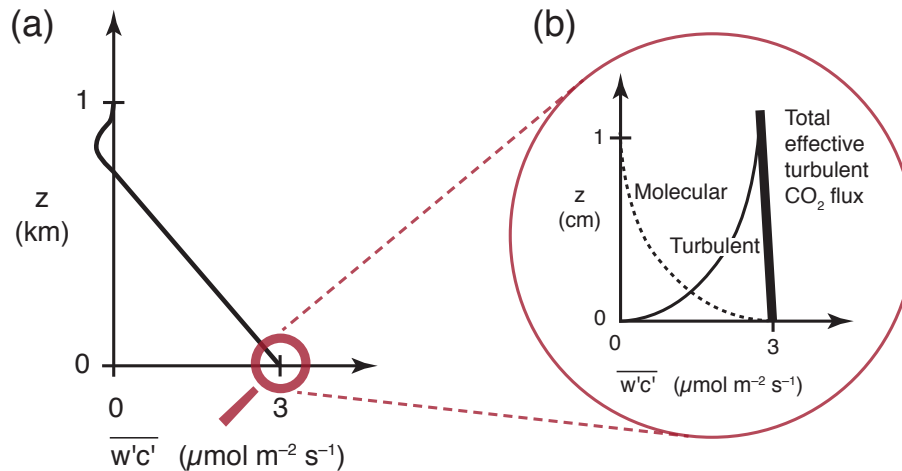
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Figure 2. Idealized vertical profile of CO₂ flux **(a)** during daytime under convective, well-mixed atmospheric conditions over bare organic soil with a respiration flux of $3 \mu\text{mol m}^{-2} \text{s}^{-1}$ at the ground surface. **(b)** The zoom indicates how the molecular flux from the soil is incorporated in the turbulent flux near the ground surface to yield total effective turbulent CO₂ flux. Modified and adapted to CO₂ after Stull (1988).

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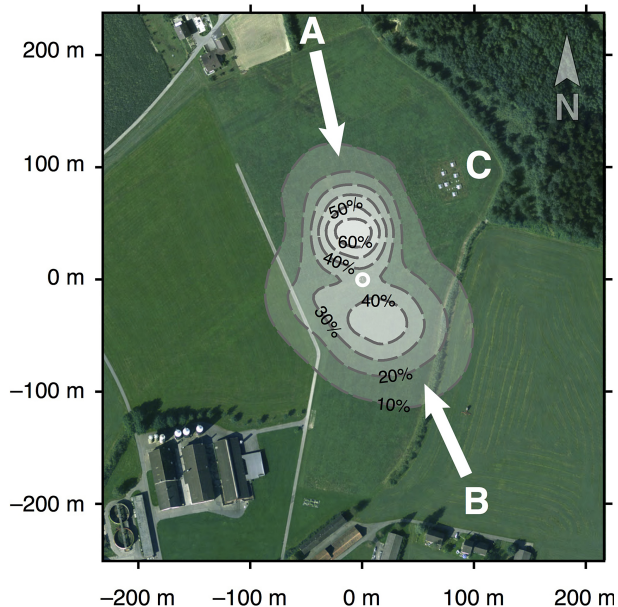


Figure 3. Example of a footprint calculation for the CH-Cha grassland site, Switzerland. Footprint calculations from Zeeman et al. (2010) placed on orthoimage ©2014 swisstopo (JD100042). The footprint shows the typical two-lobe pattern associated with diurnal up-valley winds **(a)** and nocturnal down-valley winds **(b)**. Experimental treatments **(c)** are placed close to the eddy covariance system (round circle) but outside the main footprint area to minimize disturbance.

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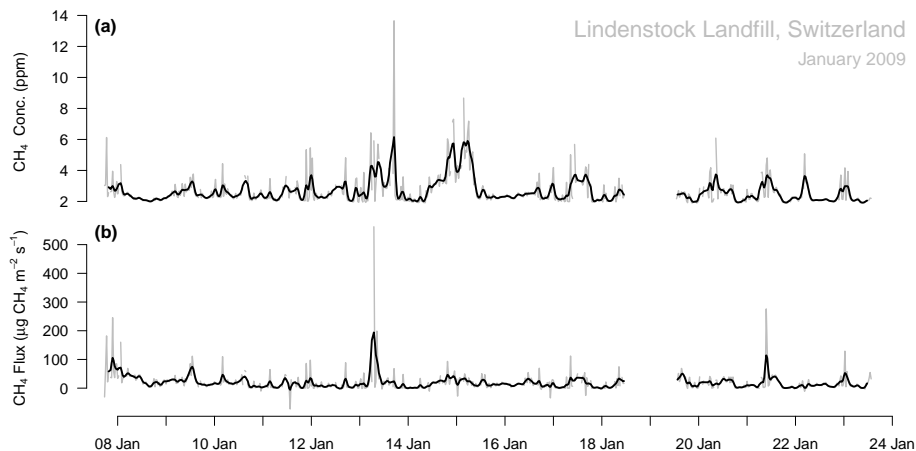
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Figure 4. Example of episodic CH₄ flux peaks from a landfill site in Switzerland during winter with snow cover (following the period reported by Schroth et al. (2012)). **(a)** CH₄ concentration and **(b)** CH₄ flux. Thin gray lines show 30 min averages, and bold black line is the running average using a 4.5 h Gaussian filter. The instruments were carefully checked \approx 4 h after the significant flux peak on 13 January 2009.

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