

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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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 $\overline{\alpha'c'}$ via normalization of the latter by the standard deviations of the individual time series, σ_α and σ_c ,

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

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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2.2.3 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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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; Mission 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 N_2O 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 CH_4 and N_2O 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 CO_2 fluxes are measured with eddy covariance, but CH_4 and/or N_2O 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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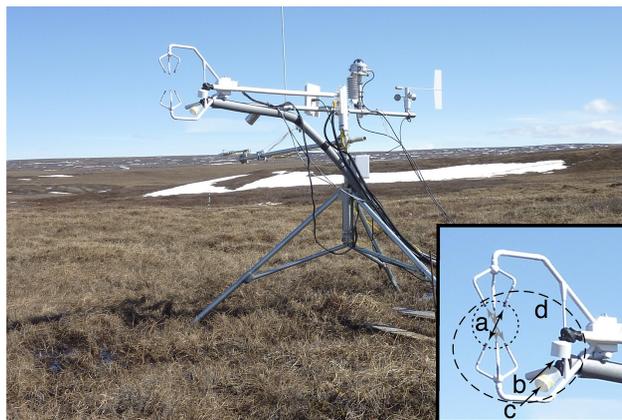
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Figure 1. Example of an eddy covariance flux system in the low Arctic, Toolik Field Station, Alaska. The inset shows the ultrasonic anemometer's sensor head **(a)** with two inlets of tubes leading air to **(b)** an enclosed-path CO_2 and H_2O analyser, 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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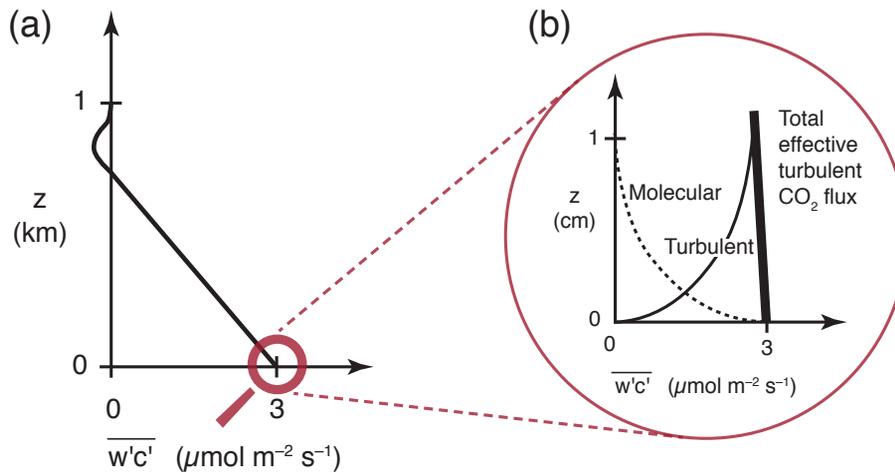
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Figure 2. Idealized vertical profile of CO_2 flux **(a)** during daytime under convective, well-mixed atmospheric conditions over bare organic soil with a respiration flux of $3 \mu\text{mol m}^{-2} \text{s}^{-1}$ at the ground surface. **(b)** The zoom indicates how the molecular flux from the soil is incorporated in the turbulent flux near the ground surface to yield total effective turbulent CO_2 flux. Modified and adapted to CO_2 after Stull (1988).

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