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НОВЫЕ МЕТОДЫ И РЕЗУЛЬТАТЫ ИССЛЕДОВАНИЙ ЛАНДШАФТОВ В ЕВРОПЕ, ЦЕНТРАЛЬНОЙ АЗИИ И СИБИРИ

Монография в 5 томах

Том I Ландшафты в XXI веке: анализ состояния, основные процессы и концепции исследований

**В содружестве с Академией почвенного плодородия
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Монография содержит информацию о самых современных методологиях и результатах в ландшафтных исследованиях. Она может быть использована в качестве руководства для исследователей, преподавателей, студентов и всех, кого интересует тема ландшафтной науки и смежных дисциплин. Монография является особо ценной информационной базой для лиц, принимающих решения на различных уровнях, от местных до международных органов по принятию решений. Приведенная в монографии информация представляет собой современный уровень ландшафтной науки в очень краткой форме.

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This monograph shall inform you about up to date methodologies and recent results in landscape research. It is intended as a guide for researchers, teachers, students, decision makers, stakeholders interested in the topic of landscape science and related disciplines. It provides information basis for decision makers at various levels, from local up to international decision bodies, representing the top level of landscape science in a very short form.

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Chapter I/51: QUANTIFICATION OF CARBON LOSSES FROM ORGANIC SOILS
Глава I/51: Количественная оценка потерь углерода из органических почв

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ABSTRACT. Worldwide, organic soils store vast amounts of soil organic carbon, but drainage for agriculture, forestry and peat extraction has destroyed many of these valuable ecosystems and turned them from carbon sinks into carbon sources to the atmosphere. Even if an undisturbed peatlands is not threatened by drainage for economic utilization, climate change and increased nitrogen deposition might still influence carbon fluxes and species composition due to a change of hydro-meteorological conditions and nutrient supply. To understand ecosystem dynamics and to evaluate strategies for successful carbon dioxide (CO_2) emission reduction, reliable measurements of carbon fluxes are required. Here, we give a brief literature overview as well as describe and compare the two most commonly used methods for measuring fluxes of CO_2 and methane: the eddy-covariance technique and the closed-chamber method. Besides, we briefly explain further components of the carbon balance such as dissolved organic carbon.

Резюме. Во всем мире органические почвы хранят огромное количество органического углерода, но дренаж в сельском хозяйстве, лесоводстве и при добыче торфа разрушил многие из этих ценных экосистем и превратил их из поглотителей углерода в источники углерода для атмосферы. Даже если ненарушенным торфяникам не угрожает дренаж для их хозяйственного использования, то изменение климата и повышенное осаждение азота могут по-прежнему влиять на потоки углерода и видовой состав из-за изменения гидрометеорологических условий и поставок питательных веществ. Для понимания динамики экосистем и оценки стратегии успешного сокращения выбросов двуокиси углерода (CO_2) требуются надежные методы измерения потоков углерода. Приведен краткий обзор литературы, а также описание и сравнение двух наиболее часто используемых методов измерения потоков CO_2 и метана: метод вихревой ковариации и метод замкнутой камеры. Кроме того, дано краткое объяснение дополнительных компонентов углеродного баланса - таких как растворенный органический углерод.

KEYWORDS: flux measurement, biosphere-atmosphere exchange, eddy covariance, carbon dioxide, methane, dissolved organic carbon, peatland, bog, fen
Ключевые слова: измерение потока, обмен биосферной атмосферой, вихревая ковариация, углекислый газ, метан, растворимый органический углерод, Болото, трясина, топь

INTRODUCTION

Worldwide, peatlands store vast amounts of soil organic carbon derived from the incomplete decomposition of peat-forming plant species such as *Sphagnum* spp. or *Carex* spp. [1]. Thus, they had a cooling effect on the climate during the Holocene [2]. However, peatlands have been drained for decades to centuries for agriculture, forestry and peat extraction, which causes high emissions of carbon dioxide (CO_2) and subsidence of the land surface [3,4]. For example, drained grasslands on organic soils in Germany emit on average 756 g CO_2-C m^{-2} yr^{-1} [4]. Furthermore, drainage causes nutrient export to downstream water bodies [5,6] and the loss of valuable biodiversity [6,7,8]. Carbon can also be emitted as methane (CH_4) and exported as dissolved organic carbon (DOC). Natural peatlands are usually a source of CH_4, while emissions from drained sites are negligible [3,4,6]. DOC export strongly depends on hydrology, but usually increases with drainage [6,9]. Besides drainage, peatlands are threatened by atmospheric nitrogen (N) deposition [10] and climate change [11]. Groundwater level, peat properties (N, pH), meteorological parameters and vegetation composition are important drivers of CO_2 and CH_4 fluxes [4,10,12]. To understand processes also under climate change conditions and to evaluate emission reduction strategies, reliable data is needed. Here, we describe the two most commonly used approaches for the quantification of CO_2 and CH_4 fluxes, and also briefly introduce to methods for the determination of further components of the carbon balance.

COMPONENTS OF THE CARBON BALANCE

Ecosystems take up CO_2 by photosynthesis (GPP: gross primary production) and release CO_2 by plant and microbial respiration, i.e. the mineralization of peat (R_{eco}: ecosystem respiration). The balance of these terms is the net ecosystem exchange (NEE):

$$NEE = GPP + R_{eco} \qquad (1)$$

According to the atmospheric sign convention, fluxes from the ecosystem to the atmosphere are positive numbers (= source) and *vice versa*. GPP depends, among others, on the plant species, the development stage of the vegetation, and photosynthetic active radiation (PAR). R_{eco} is also influenced by the vegetation, but even more so by temperature, soil moisture and soil properties. Effects of environmental conditions depend on the temporal scale: for example, hourly variation of R_{eco} is mainly driven by temperature, but annual and inter-site variability e.g. by the groundwater level [4,10,12]. To derive the C balance, export of biomass (harvest), import of organic fertilizers, losses of dissolved organic carbon (DOC) and methane fluxes have to be additionally considered:

$$\text{C-balance} = \text{NEE} - \text{C-Import} + \text{C-Export} + \text{DOC} + CH_4\text{-C} \quad (2)$$

To quantify the greenhouse gas balance, nitrous oxide (N_2O) and CH_4 have to be considered according to their respective global warming potential.

MEASURING THE CARBON EXCHANGE BETWEEN BIOSPHERE AND ATMOSPHERE USING THE EDDY-COVARIANCE TECHNIQUE

Eddy-covariance (EC) towers and their associated meteorological measurements offer an opportunity to quantify carbon, water, and energy fluxes across a variety of climate zones and vegetation types. EC has become a reliable and popular method and is currently the preferred approach to measure continuously exchanges of CO_2, CH_4, water vapor and sensible heat between ecosystems and the atmosphere over time scales of hours to decades, thereby enabling the evaluation of seasonal and inter-annual variability in these exchanges and the elucidation of their climatic controls [14,14,15].

Key components of an EC system are a three-dimensional sonic anemometer to measure wind velocities, direction, and sonic temperature and a fast response open, enclosed or closed-path infrared gas analyzer (IRGA) for measurements of CO_2, CH_4, and water vapor molar densities. IRGA and sonic anemometer are usually installed on a tower with the measurement height being a few meters above the vegetation canopy [Figure 1].

The EC approach determines the vertical flux F_c of a trace gas in the air as the covariance of the instantaneous vertical wind w and the gas concentration c at a given point:

$$F_c = \sum_{i=1}^{n} [w(t) - \overline{w}] * [c(t+\tau) - \overline{c}] \quad (3)$$

$w(t)$ and $c(t)$ are the instantaneous values of vertical wind and scalar concentration (sampling frequency is usually 10 or 20 Hz), and the overbars indicate the mean over a suitable flux integration interval, which is commonly set to 30 minutes. In closed-path systems, the time lag τ is introduced to correct for the delay between sampling and detection/recording of the trace gas concentration due to the residence time in the sampling tube and in the analyzer.

The area from which the detected eddies originate is described probabilistically and called a flux footprint. The flux footprint area is dynamic in size and shape, changing with wind direction, thermal stability and measurement height, and has a gradual border.

The effect of sensor separation, finite sampling length, sonic path averaging, as well as other instrumental limitations, affect frequency response of the measurement system and may need a co-spectral correction, especially noticeable with closed-path instruments and at low heights below 1 to 1.5 m. A number of other data quality procedures and correction steps [16,17] depending on site and system characteristics may need to be applied. Nowadays, these are conveniently implemented in EC software packages such as EddyPro^{TM} or EddyUH [17], which are widely used across the micrometeorological community. In a nutshell [see also Table 1], the EC method

- quantifies gas exchange rates by directly measuring movement of gases in the atmosphere,
- requires turbulent flow, with winds generally above 0.5 m/s,

- requires state-of-the-art fast instruments,
- and is the most direct and defensible way to measure exchange fluxes.

Figure 1 – Eddy covariance tower (left) at a semi-natural peatland [10] and a transparent chamber connected to a portable analyzer for the measurement of NEE at a grassland site [12].

The methodology has been successfully applied when investigating the C exchange from ecosystems on organic soils, one of which is the study by Hurkuck et al. [10]. The authors found that the site – a semi-natural, temperate bog ecosystem in Northwest Germany where the whole region is dominated by intensive agricultural land use with total (wet and dry) atmospheric N deposition being about 25 kg N ha^{-1} yr^{-1} – was a small net CO_2 sink during all three years of investigation ranging from -9 to -73 g C m^{-2} yr^{-1}. R_{eco} and GPP were found to be temperature and light-dependent, but there were only weak correlations between CO_2 exchange and water level despite large inter-annual and seasonal variability.

FLUX MEASUREMENTS: CHAMBER METHOD

At the plot scale, flux measurements can be conducted with manual non-steady state chambers [4, 12, 19, Figure 1]. R_{eco} is measured with opaque chambers and NEE with transparent chambers. Chambers are placed on permanent frames inserted into the peat, vented for pressure equilibration, and – in the case of transparent chambers – ventilated and cooled. Boardwalks need to be installed to prevent ebullition events triggered by the measurement procedure. Measurement campaigns generally take place every two to four weeks and cover a diurnal cycle from before sunrise until maximum soil temperature. Within one campaign, each plot is visited several times with both chamber types. CO_2 concentrations are recorded in the field with a portable IRGA [Figure 1]. CO_2 fluxes for each single measurement which typically lasts for two to four minutes are calculated by linear regression. Next, response functions for R_{eco} and GPP (calculated according to Eq. 1) are fitted to the CO_2 fluxes of each campaign. Most frequently, R_{eco} is fitted as a function of temperature [20] and GPP as a function of PAR [21]. Finally, annual budgets are assembled from the response functions and continuously recorded temperature and PAR data [12,19].

CH_4 and N_2O flux measurements are conducted with the opaque chambers (at least every 2-3 weeks). Chambers are closed for around one hour and 4-5 gas samples are collected in headspace vials which are analyzed by gas chromatography in the laboratory. From this data, fluxes are calculated linearly or non-linearly [12]. Annual values might be calculated either by linear interpolation or as a function of environmental data (e.g. groundwater level). As EC measurements of CH_4 and N_2O are expensive, relatively new and usually demand power supply, manual measurements of CH_4 and N_2O are frequently combined with EC measurements of CO_2. Automatic chambers (“autochambers”) are an alternative to manual chambers, but expensive and technically challenging especially for CO_2.

MEASUREMENT OF FURTHER COMPONENTS OF THE CARBON BALANCE

At sites used for agriculture or forestry, the input and export of organic carbon has to be taken into account (Eq. 2). This is relatively straightforward for agricultural sites where the amount and C content of fertilizers and harvest can easily be measured [6]. However, the allocation of C fluxes in forests is more complex. The determination of DOC losses is methodologically challenging as this requires a quantification of the recharge or runoff at a scale consistent with the flux measurements.

Table 1 - Comparison of the eddy covariance technique and the chamber method: √ appropriate, 0 – applicable depending on circumstances or with limitations, **-** not feasible/not recommended. Both methods require complex post-processing procedures [12,16,17,18,19].

Field of application	**Eddy covariance**	**Chambers**
Plot scale experiments, large number of treatments, questions on small scale variability (< 1 m²)	-	√
Field scale investigations (1-100 ha, depending on measurement height and atmospheric stability)	√	-
Fluxes of vegetation species or communities	0 (scale-dependent)	√
Tall vegetation (especially forests)	√	-
High temporal resolution, continuous measurements	√	- (autochambers: 0)
Remote locations without power supply	0	√ (autochambers: -)

If the hydrological catchment and the eddy footprint match reasonably well, DOC losses can be measured at the catchment outlet. As such integration over a catchment rarely fits to the scale of plot-scale measurement, DOC could alternatively be determined in the soil or groundwater (for a comparison of different techniques see [6]). This needs to be combined with modelling the water balance, ideally based on actual soil hydrological data (e.g. tension, moisture). In terms of percentage of the C balance, DOC tends to be especially important in undisturbed peatlands with low NEE, while absolute values of DOC concentrations and losses are frequently higher in drained peatlands [3,6,9].

Finally, to gain thorough understanding of CO_2, CH_4 and DOC data, environmental variables such as e.g. groundwater level, moisture, temperature and precipitation, plant properties (vegetation species and cover, leaf area index) and soil properties (pH, C, N, bulk density, degree of humification) are necessary (monitoring details: [6]) and need to be planned as carefully as the flux measurements in any experimental setup.

CONCLUSIONS

1. Quantifying the full carbon balance of a peatland is complex and requires the combination of different techniques originating from different disciplines.
2. The “ideal” method depends on the research questions.
3. To understand flux data, environmental and vegetation data is absolutely necessary.

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