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Combining eddy-covariance and chamber measurements to determine the methane budget from a small, heterogeneous urban floodplain wetland park

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ABSTRACT

Methane (CH_4) emissions and carbon uptake in temperate freshwater wetlands act in opposing directions in the context of global radiative forcing. Large uncertainties exist for the rates of CH_4 emissions making it difficult to determine the extent that CH_4 emissions counteract the carbon sequestration of wetlands. Urban temperate wetlands are typically small and feature highly heterogeneous land cover, posing an additional challenge to determining their CH_4 budget.

The data analysis approach we introduce here combines two different CH_4 flux measurement techniques to overcome scale and heterogeneity problems and determine the overall CH_4 budget of a small, heterogeneous, urban wetland landscape. Temporally intermittent point measurements from non-steady-state chambers provided information about patch-level heterogeneity of fluxes, while continuous, high temporal resolution flux measurements using the eddy-covariance (EC) technique provided information about the temporal dynamics of the fluxes. Patch-level scaling parameterization was developed from the chamber data to scale eddy covariance data to a 'fixed-frame', which corrects for variability in the spatial coverage of the eddy covariance observation footprint at any single point in time. By combining two measurement techniques at different scales, we addressed shortcomings of both techniques with respect to heterogeneous wetland sites.

We determined that fluxes observed by the two methods are statistically similar in magnitude when brought to the same temporal and spatial scale. We also found that open-water and macrophyte-covered areas of the wetland followed similar phenological cycles and emitted nearly equivalent levels of CH_4 for much of the year. However, vegetated wetland areas regularly exhibited a stronger late-summer emission peak, possibly due to CH_4 transport through mature vegetation vascular systems. Normalizing the eddy covariance data to a fixed-frame allowed us to determine the seasonal CH_4 budget of each patch and the overall site. Overall, the macrophyte areas had the largest CH_4 fluxes followed by the open water areas.

Uncertainties in the final CH_4 budget included spatial heterogeneity of CH_4 fluxes, the tower footprint, measurement in the data to be scaled, and gap-filling. Of these, the spatial placement of the chambers provided the largest source of uncertainty in CH_4 estimates. This reinforces the need to utilize site-level measurements when estimating CH_4 fluxes from wetlands as opposed to using only up-scaled point measurements.

1. Introduction

In the late 1980′s, the United States government set a goal of 'no net loss' of wetlands to preserve their ecological services. The net result has been the creation of new or the restoration of existing wetlands to mitigate the destruction or damage of natural wetlands due to human activities (US-EPA, 2012). Required mitigation activities are determined by quantifying the ecological services provided by the natural wetland. To date, structural hydrogeomorphic and biological indicators are employed to estimate functional ecosystem services (Mack et al., 2004). The overall climatological effects of wetlands are not yet well understood, and therefore are not

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currently considered when determining the qualities of replacement wetlands. Wetlands are strong sinks of carbon dioxide (CO_2) (Hommeltenberg et al., 2014a; Mitsch et al., 2013, 2014; Schäfer et al., 2014; Waletzko and Mitsch, 2013). However, wetlands are also the largest natural source of methane (CH_4) worldwide (IPCC, 2013), and are a powerful source of nitrous oxide (N_2O), another strong greenhouse gas (GHG). The balance of these GHGs determines the net climatological effect of a wetland. In part, the lack of climatological understanding stems from the larger uncertainty in the global wetland CH_4 budget (IPCC, 2013). Traditionally, the quantification of CH_4 emissions from wetlands has been difficult for several reasons. Perhaps chief among these is the heterogeneity of land cover in wetlands and the relatively small scale at which the different patch types are distributed (on the order of meters). This is further complicated by the interactions between biotic and abiotic ecosystem components that govern CH_4 production and transport within each patch.

Currently, the foremost techniques for measuring CH_4 emissions are the eddy covariance (EC) and the closed chamber methods. The eddy covariance method observes turbulent GHG fluxes (Baldocchi et al., 1988) for monitoring trace gas flux dynamics at a landscape level. Eddy covariance towers have become a common approach for monitoring CH_4 emissions from temperate wetlands (Baldocchi et al., 2012; Forbrich et al., 2011; Hatala et al., 2012a,b; Hommeltenberg et al., 2014a,b; Long et al., 2010; Morin et al., 2014a; Wang et al., 2013). High-frequency EC measurements are collected continuously, capturing diurnal and seasonal dynamics. However, the sensors atop EC towers observe CH_4 dynamics from a constantly shifting footprint area (Hsieh et al., 2000; Kljun et al., 2015). The location and size of the surface area that contributes to fluxes observed at the tower top (at a certain height above and downwind from the sources) is determined by wind speed, wind direction, friction velocity, and surface heat flux (among other factors) (Detto et al., 2006). This is rarely a concern for EC towers placed in homogenous terrain as all source terrain is assumed to have uniform fluxes. However, in heterogeneous environments, or when EC measurements are conducted from tall towers or airborne platforms, which result in a very large footprint, a footprint-weighted approach for downscaling flux measurements to the patch level was previously demonstrated for environmental fluxes of CO_2 and energy (Hutjes et al., 2010; Maurer et al., 2013; Metzger et al., 2013; Ogunjemiyo et al., 2003; Wang et al., 2006). Similarly, footprint-weighted approaches were utilized to downscale patch-level model results or chamber measurements in order to compare them with instantaneous EC measurements (Budishchev et al., 2014; Frasson et al., 2015).

Wetlands are frequently composed of a tight mosaic of land cover types (often referred to as microsites or patch types), such as open water, obligate and facultative wetland plant species (macrophytes), grasslands, dry land (uplands), and temporarily flooded (bottomland) forests. Furthermore, the length scale of homogeneity in wetlands is short, and the CH_4 fluxes associated with each patch type can differ by orders of magnitude (Nahlik and Mitsch, 2010; Sha et al., 2011). In heterogeneous landscapes with strong patch-level variability in flux rates, the apparent temporal dynamics of the observed flux may, therefore, not only be driven by changes in the emission rates, but also by the movement of the footprint area from one patch type to another. Understanding how fluxes vary between and among patch types is critical to understanding the total CH_4 budget of the wetland ecosystem.

The CH_4 emission rates from specific components of heterogeneous terrain can be directly measured using the non-steady state chamber method. Multiple chambers can be used to measure various patch types in an area, and thus, chamber data can be used to illustrate differences in flux magnitude between patches. Chambers are broadly grouped as either manual chambers (requiring a technician to draw samples) or automated chambers (automatically sample at regular time intervals). Both classes of chambers have potential drawbacks. Manual chamber measurements are labor intensive, which greatly limits the total number of chambers that can be sampled. Automated chamber measurements rely on closed-path gas analyzers that need to be placed in close proximity to the chambers, and are relatively expensive. Automated chambers are therefore limited in the spatial distance between chambers and the number of patches they can sample. Because of these limitations, manual chamber studies are more common. In most cases, manual chamber data are gathered during the day on an intermittent sampling schedule, typically on a monthly or biweekly basis. As a result, sudden, high magnitude flux events and diurnal dynamics are rarely observed via chamber techniques (Morin et al., 2014b; Podgrajsek et al., 2014). Additionally, chamber measurements are often filtered to remove ebullition (Altor and Mitsch, 2006; Bellisario et al., 1999; Christensen et al., 2003; Leppala et al., 2011) and are ineffective when turbulent diffusion is the dominant transport mechanism due to the disruption of wind over shallow water (Godwin et al., 2013). In many studies, chamber data for methane fluxes have been up-scaled to the site level (Clement et al., 1995; Desai et al., 2015; Godwin et al., 2013; Podgrajsek et al., 2014; Schrier-Uijl et al., 2010). However, point measurements cannot effectively sample the full spatial variation of patch-specific fluxes from the wetland landscape. Similarly, they cannot observe the full short-term (intra-daily) and intermediate (inter-daily) temporal variations that occur within a site. As a result, several studies have shown that up-scaling temporally and spatially sparse point measurements can bias site-level flux estimates (Desai et al., 2015; Forbrich et al., 2011; Sachs et al., 2008; Zhang et al., 2012).

The limitations of flux monitoring techniques have restricted the quality of wetland CH_4 flux estimates. Combining chamber point observations with eddy covariance site-level observations has the potential to mitigate the weaknesses associated with using either method on its own. Forbrich et al. (2011) and Sachs et al. (2010) successfully combined the two methods to down-scale eddy covariance data in sites with regularly patterned terrain (northern polygonal peatlands). However, little work has focused on unpatterned and varied terrain, as is typical of mid-latitude wetland ecosystems (Matthes et al., 2014).

In this study, we used eddy covariance and chamber measurements of CH_4 in tandem to correct for their respective limitations and achieve a better estimate of the patch-level and overall site-level net CH_4 budget. A continuous time series of CH_4 emissions from a 'fixed-frame' area comprised of the different patch types was established at the urban wetland park. The fixed-frame approach normalized the flux levels to a non-shifting site level footprint with the particular mixture of patch types of interest to the study. Chamber measurements were used to correct for the effects of patch-type emission variability within the footprint of the eddy covariance tower. We then conducted an uncertainty analysis of the final scaled CH_4 data product to determine the contributions of different sources of uncertainty to the overall fixed-frame flux estimate.

2. Methods

2.1. Site description

The study was conducted at the Wilma H. Schiermeier Olentangy River Wetland Research Park (ORWRP), a 20 ha research facility located on the Ohio State University campus in Columbus, Ohio. The site was designed in 1991-92 with the initial experimental wetlands constructed in 1993–94. The ORWRP consists of two 1 ha created experimental flow-through wetlands, a 3 ha created