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Towards pairing plot and field scale measurements in managed ecosystems: Using eddy covariance to cross-validate CO_2 fluxes modeled from manual chamber campaigns

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ABSTRACT

Manual chamber campaigns are a versatile method to study management effects at plot scale in factorial experiments. The eddy covariance technique has the advantage of continuous measurements but it requires large homogeneous areas. By pairing the two techniques, the uncertainties of the CO_2 fluxes modeled from the chamber campaigns can be quantified through cross-validation with the continuous eddy covariance data. This is particularly important in managed ecosystems with high temporal dynamics. At our agricultural site in Northern Germany, we installed both techniques in parallel for two crop cultivation periods, winter oilseed rape in 2012/13 and winter wheat in 2013/14. First, we compared *measured* net CO_2 exchange (NEE) obtained from the closed chambers with the corresponding half-hourly fluxes from the eddy covariance technique. Despite largely different footprints and measurement windows, the measured fluxes were highly correlated ($R^2 = 0.83$ in 2012/13 und $R^2 = 0.93$ in 2013/14).

Interpolating from chamber campaigns to the entire measurement period is commonly performed by modeling half-hourly fluxes based on non-linear regressions for photosynthesis and respiration. These modeled fluxes were compared to the fluxes measured with the eddy covariance technique. To understand the observed differences, we performed five modeling setups: 1) Non-linear regressions based algorithm with default settings, 2) non-linear regressions with expert settings, 3) purely empirical modeling with artificial neural networks, 4) cross-validation using eddy covariance measurements as campaign fluxes on original campaign days, and 5) cross-validation on weekly campaign days.

The modeled seasonal course of daily NEE agreed well with the eddy covariance measurements for all five setups (R^2 from 0.77 to 0.92) but with periods of systematic offsets in the range of $\pm$ 5 $g\,C\,m^{-2}\,day^{-1}$. Though the pattern of the offsets was different, all setups had comparable root mean square errors around 1.5 $g\,C\,m^{-2}\,day^{-1}$ despite having opposite limitations. Cross-validation by simulating campaigns with artificial gaps from the continuous eddy dataset in setup 4) and 5) resulted in bias errors of around 0.4 $g\,C\,m^{-2}\,day^{-1}$. This translates to a total uncertainty on annual NEE of around $\pm$ 175 $g\,C\,m^{-2}\,a^{-1}$ purely from the modeling, i.e. the interpolation in-between campaigns. By leave-one-campaign-out scenarios, the sensitivity to single campaigns was examined. The mean effect on the annual total was higher for setup 4 (30 $g\,C\,m^{-2}$) with the original number of campaigns than for setup 5 (9 $g\,C\,m^{-2}$) with four times more campaigns. Furthermore, the interpolation in-between the campaigns can be improved by deriving vegetation proxies from the continuous eddy covariance measurements, such as an effective green area index (GAI) presented herein.

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1. Introduction

Quantifying ecosystem-atmosphere exchange of greenhouse gases – particularly of CO_2 – has been in the focus of environmental research for several decades. Ideally, the observations should also give information on the natural and anthropogenic driving factors. This attribution is non-trivial (IPCC, 2002) and the terrestrial CO_2 sources and sinks have the highest uncertainties in the global carbon cycle (Le Quéré et al., 2016). Factoring-out direct human-induced changes in carbon stocks and greenhouse gas emissions from indirect human-induced and natural effects will require a portfolio of approaches including long-term monitoring as well as multi-factorial experiments (IPCC, 2003).

Ecosystem fluxes of CO_2 at agricultural sites are commonly measured with three different methods: Continuously at plot scale with automated chambers, on scheduled campaigns at plot scale with manual chambers, and continuously at field scale with the eddy covariance technique. Automated chambers allow high temporal sampling frequency but only from limited areas (Burrows et al., 2005) since the technical equipment requires high initial investment and is maintenance-intensive. Manual chamber measurements on scheduled campaigns are best suited for factorial experiments at plot scale (e.g. used in Eickenscheidt et al., 2015; Pohl et al., 2015) since they can be easily and cheaply replicated, but usually lack high temporal resolution due to their labor intensity. At landscape scale, the eddy covariance technique has evolved to be the most common method to directly measure the net exchange of CO_2 between ecosystems and the atmosphere (Aubinet et al., 2000; Baldocchi, 2008). Eddy covariance measurements allow continuous sampling but costs and feasibility often prohibit spatial replication. Eddy covariance measurements are often complemented with manual or automated chambers for measuring ecosystem respiration (e.g. Aurela et al., 2007; Jassal et al., 2007; Krauss et al., 2016; Schrier-Uijl et al., 2010; Wohlfahrt et al., 2005). Complementing chamber measurements at multiple-plot experiments with eddy covariance measurements are promising for robust, scalable observations, and a step forward in understanding the attribution of underlying factors to CO_2 fluxes.

Manual chamber measurements have been widely used since decades for monitoring the net CO_2 exchange typically in natural ecosystems with short permanent vegetation such as mires or tundra ecosystems (e.g. Alm et al., 1997; Bubier et al., 1998; Carroll and Crill, 1997; Whiting et al., 1992; Wilson et al., 2016) but also managed ecosystems like grasslands (e.g. Beetz et al., 2013; Görres et al., 2014; Poyda et al., 2017). Managed ecosystems are more challenging since the CO_2 fluxes may vary faster and more abruptly than they do in unmanaged systems. For highly cultured annual crops, the time span from a very strong CO_2 exchange during the main plant growth followed by weak net efflux of the ripened crop to pure respiration of the bare soil after the harvest maybe be less than six weeks. Here the need of the manual-chamber method to interpolate time periods in-between the campaign days might limit its applicability (Huth et al. 2017). Due to the high dynamics of managed ecosystems, the amount and timing of the campaigns will have an effect on the reliability of the seasonal flux estimates. Quantifying the uncertainty of CO_2 fluxes modeled from chamber campaigns is challenging (Beetz et al., 2013) and no consensus exists about how to propagate modeling errors for the derived annual sums (Kandel et al., 2013).

To investigate the reliability and to get an estimate of the uncertainties in CO_2 fluxes from a managed crop, we set up manual chamber and eddy covariance measurements in the same field for a two-year period cropped with winter oilseed rape in 2012/13 and winter wheat in 2013/14. Based on the manual chamber measurements, CO_2 fluxes were interpolated between campaigns with five different modeling setups: 1) Standard setting of the non-linear regressions based algorithm (after Hoffmann et al., 2015) to test the default algorithm settings; 2) Including expert knowledge to optimize the algorithm settings; 3) Purely empirical modeling with artificial neural networks (after Moffat et al., 2010) to examine differences in algorithm behavior; 4) Cross-validation by using eddy covariance measurements themselves as campaign fluxes to exclude input data effects; and 5) Using one day per week of eddy covariance measurements as campaign fluxes to analyze the influence of the interpolation length. The half-hourly CO_2 flux estimates of all five modeling setups were then compared to the continuous eddy covariance measurements. For each setup, we derived error estimates and investigated the effects of leaving out single campaigns on the cumulative sum of CO_2.

The aim of this study is to gain a better understanding of the method-specific uncertainty induced by interpolating between campaigns in an agricultural ecosystem with high temporal dynamics. For this, we investigate the seasonal course of the modeled CO_2 fluxes, their cumulative sums, and their sensitivity to single campaigns. Furthermore, we combine the plot and field scale by deriving a vegetation proxy from the continuous eddy covariance flux measurements to support the interpolation between the chamber campaigns.

2. Materials and methods

2.1. Study site

The study site (53°22′ N, 13°49′ E, 35 m a.s.l.) is located in the Uckermark region in the north-east lowlands of Germany, close to a long-term research site with various agricultural plot scale field trials of the Leibniz Centre for Agricultural Landscape Research (ZALF). The regional climate is sub humid with a strong continental influence. The long-term (1992–2010) mean annual temperature and mean annual precipitation are 8.6 °C and 489 mm. July is the warmest month with on average 18.2 °C and January the coldest with 0.2 °C. The driest and wettest months are usually February (22 mm) and June/July (61 mm, ZALF weather station network), respectively.

The landscape is a glacial drift area which is characterized by a hummocky terrain and closed depressions. However, the area around the research field is flat (± 5 m within a one kilometer radius). The soil type is luvisol and the top-soil texture is loamy sand with approximately 10% clay, 0.8% organic carbon, and a bulk density of 1.6 g cm^{-3} (Müller et al., 2009).

During the study period, the research field was cultivated with a crop rotation of rapeseed (*Brassica napus* L.) in 2012/13 and winter wheat (*Triticum aestivum* L.) in 2013/14. Soil cultivation, sowing, fertilization and crop protection measures were applied by the local farmer (Table 1).

2.2. Chamber campaigns

Approximately six weeks prior to the first measurements, a reference plot with three chamber collars was set up close to the eddy flux tower (inside the footprint at ~50 m distance). Manual chamber measurements of CO_2 were conducted at intervals of three to six weeks from 13th November 2012 until 19th July 2013 on rapeseed and from 8th October 2013 until 16th July 2014 on winter wheat with in total 22 campaigns. Throughout this manuscript, the term "1st cultivation period" will refer to the time between the first campaign until the campaign on the day of the rapeseed harvest and "2nd cultivation period" to the time between the restart of campaigns four weeks after the sowing of winter wheat and the last campaign one week before harvest (Table 1). Since there were no campaigns between the two cultivation periods on the bare field until four weeks after sowing, this period will be considered separately.

The measured CO_2 fluxes are the net of two opposing fluxes, the uptake by photosynthesis (gross primary production, GPP) and the release by respiration (ecosystem respiration, ER). This net flux is called either net ecosystem exchange (NEE) with atmospheric sign conversion or net ecosystem productivity (NEP) for its additive inverse