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Direct and indirect controls of the interannual variability in atmospheric CO_2 exchange of three contrasting ecosystems in Denmark

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ABSTRACT

The understanding of the controlling factors determining interannual variability (IAV) of carbon dioxide (CO_2) exchange between different ecosystems is crucial when assessing present and future responses to climate variability and climate change. Six years of eddy covariance (EC) data from three neighboring sites (agriculture, forest, and meadow) subjected to management in variable degree were evaluated to determine typical CO_2 budgets and controlling factors of IAV. In terms of average annual net ecosystem exchange (NEE) the agricultural and wet meadow site showed identical rates of −156 (±110 and ±116, respectively) g C m^{-2} y^{-1}, with large IAV and individual years even showing near zero net uptake. In contrast, the forest was a substantial and persistent sink of CO_2 (avg. ± s.d. −691 ± 143 g C m^{-2} y^{-1}), but had a higher absolute IAV. A homogeneity-of-slopes (HOS) model was utilized to partition sources of IAV of CO_2 fluxes between direct climatic effects and indirect effects (functional changes). This analysis showed that NEE at the forest (through both GPP and RE) was most prone to interannual functional changes. The wet meadow showed moderate functional changes with respect to RE and thus NEE, whereas the cropland did not show any statistically significant functional changes. We argue that the delicate interplay between climate forcing, land use specific traits, management practices and intensities, and functional changes has to be taken into account when predicting the atmospheric CO_2 sink/source strengths of land ecosystems for longer timescales.

1. Introduction

The terrestrial biosphere acts as an important sink of atmospheric carbon dioxide (CO_2), and thus partially counteracts the radiative forcing caused by anthropogenic greenhouse gas (GHG) emissions (Houghton, 2007). However, this balance may be subject to changes as a result of land use management and feedbacks to climatic changes. The net biosphere sink is the composite flux of two oppositely directed fluxes; the photosynthetic assimilation of CO_2 by the vegetation (gross primary production, GPP), and the sum of ecosystem heterotrophic and autotrophic respiratory release of CO_2 from soil and vegetation (ecosystem respiration, RE). The annual global GPP is tenfold higher (~125 Gt C y^{-1}) than the total annual anthropogenic emissions (Beer et al., 2010), but concurrently global RE is in the same order of magnitude as GPP, resulting in relatively small net C uptake. Hence, interannual climatic variations and environmental disturbances can have relatively large effects in causing an imbalance in the budget. A major part of the uptake and release of CO_2 takes place in natural ecosystems (e.g. forests, grasslands, and wetlands). However, a substantial part of the terrestrial biosphere is managed ecosystems, and thus it plays a significant role in the global terrestrial carbon cycle.

In this context, measurements of CO_2 and other relevant GHG fluxes are essential to assess the C sequestration strength and sensitivity to interannual climatic variations (Goulden et al., 1996; Yuan et al., 2009). On short timescales (hourly to multi-daily), a near-static CO_2 flux response to meteorological conditions can be assumed. However, at multi-weekly, seasonal, annual, and interannual timescales the flux response to meteorological conditions might be altered (i.e. non-static), due to biotic or functional changes (Chu et al., 2016; Hui et al., 2003; Richardson et al., 2007; Wu et al., 2012). Here we define functional changes or indirect causes of IAV

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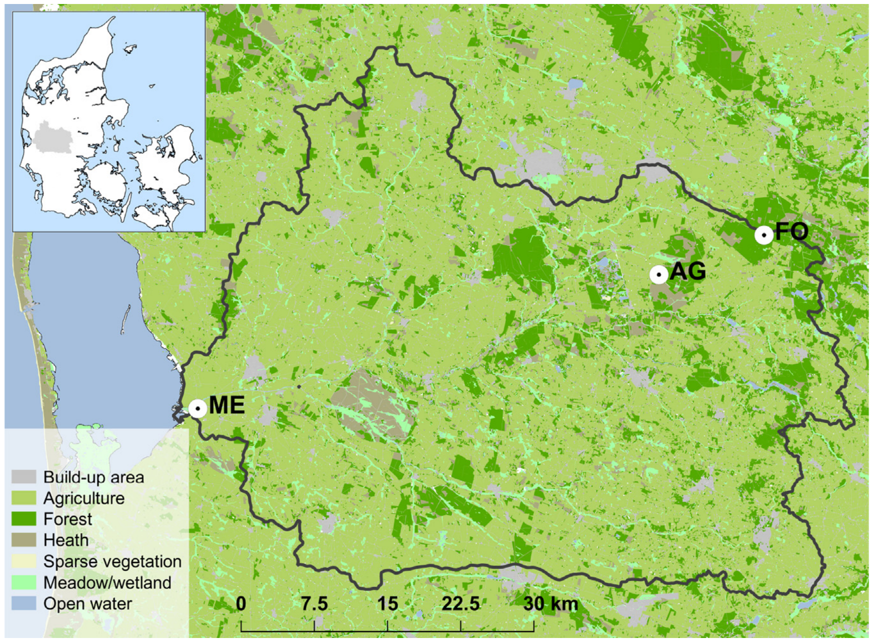

Fig. 1. Location of the three study sites (white dots and site label) within the Skjern River Catchment (black line is catchment divide) in the Western part of Denmark. ME is Skjern meadow site, AG is Voulund agricultural site, and FO is Gludsted forest site.

as; changes in the plant functional traits that govern the assimilation and respiration processes (e.g. changes in plant physiology, nutrient status, structure, phenology, etc.).

Several works have analyzed CO_2 fluxes among various ecosystems at different timescales, to elucidate these issues. Global and regional networks of eddy covariance flux stations (e.g. FLUXNET, CarboEurope, Ameriflux, ICOS), covering all main plant functional types and many different climatic regions, have been highly beneficial in answering many of the critical research questions of this field of science (Baldocchi, 2014). However, generally the stations are not in close proximity and thus face different environmental conditions. Such studies have been valuable to assess typical carbon budgets, the relative importance of RE and GPP, response to environmental variability, etc. (e.g. Beer et al., 2010; Chen et al., 2015; Luyssaert et al., 2007). On the other hand, short-term studies covering one to three years at most have been conducted, where CO_2 fluxes were measured at several neighboring sites, in order to assess the differences in seasonal and annual budgets of CO_2, effects of land use management, and ecosystem restoration, etc. (e.g. Anthoni et al., 2004b; Han et al., 2014; Herbst et al., 2011a; Hommeltenberg et al., 2014; Knox et al., 2014; Schmidt et al., 2012). Though such studies can elucidate important differences in seasonal and annual CO_2 budgets and functional differences, they do not necessarily show the typical picture of the average state of the ecosystems under consideration and the effect of anomalous climatic events on CO_2 budgets. Chu et al. (2016) addressed this effect based on a three-year record of CO_2 fluxes from three neighboring sites during years with anomalous climatic conditions, however their data set was not yet long enough to analyze the typical impact of the interannual variability of ecosystem CO_2 fluxes.

The present study is among few, where long-term flux data from different, and neighboring, land use types have been coherently analyzed. Six years (2009–2014) of eddy covariance CO_2 flux data were collected at three disparate sites representing typical managed land use types (cropland, forest, meadow) in Denmark. Due to the close proximity of the sites, they were experiencing similar day-to-day meteorological variations and annual climatic conditions. To ensure inter-site comparability, the instrumental setups and data processing routines were identical.

Denmark is an intensive agricultural country (62% cropland) and the major part of all land use types are managed. This means that not only environmental factors (e.g. temperature, solar radiation, and precipitation) have considerable effects on CO_2 fluxes in such ecosystems. Anthropogenic factors, such as agricultural management (fertilization, irrigation, harvest, etc), clear-cutting and timber harvest in forests, hay-cutting, and grazing of cattle can alter carbon dynamics.

The aim of this study is to examine how CO_2 fluxes of three typical Danish managed ecosystems respond to the interannual variability of climatic forcing. We will elucidate how the contrasting ecosystems respond to the same climatic conditions and to what extent this is related to changes in ecosystem functioning. Therefore, our main research questions are; (1) How much does the sensitivity to interannual variations in climatic conditions vary between ecosystems? (2) How much of the inter-annual variability in ecosystem carbon fluxes is caused by functional changes?

2. Material and methods

2.1. Site description

Fluxes of CO_2, water vapor, sensible heat, and momentum along with standard meteorological variables were measured at three sites, Voulund (agricultural, AG), Gludsted (forest, FO), Skjern (meadow, ME). The sites are part of the hydrological observatory, HOBE (Jensen and Illangasekare, 2011), and are all placed in the Skjern River catchment on the peninsula of Jutland, in Western Denmark. The catchment covers 2500 km^2 (Fig. 1). The region has a humid temperate climate with mean annual temperature (MAT) of 8.4 °C, and mean annual precipitation (MAP) of 1030 mm (catchment-wide average 2009–2014). The regional geological settings are dominated by sandy soils. In the western most part of the catchment, close to the river outlet to the Ringkøbing lagoon, there are marshes and occasionally flooded meadows.

Voulund agricultural site (hereafter AG) is located in an intensively managed agricultural area 10 km south of the town of Ikast (56.04°N 09.16°E). The flux tower is located in the northwestern corner of a fenced measuring plot (80 m x 20 m), which is