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Spatio-temporal drivers of soil and ecosystem carbon fluxes at field scale in an upland grassland in Germany

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ABSTRACT

Ecosystem carbon (C) fluxes in terrestrial ecosystems are affected by varying environmental conditions (e.g., soil heterogeneity and weather) and land management. However, the interactions between soil respiration (R_s) and net ecosystem exchange (NEE) and their spatio-temporal dependence on environmental conditions and land management at field scale is not well understood. We performed repeated C flux measurement at 21 sites during the 2013 growing season in a temperate upland grassland in Germany, which was fertilized and cut three times according to the agricultural practice typical of the region. Repeated measurements included determination of NEE, R_s, leaf area index (LAI), meteorological conditions as well as physical and chemical soil properties. Temporal variability of R_s was controlled by air temperature, while LAI influenced the temporal variability of NEE. The three grass cuts reduced LAI and affected NEE markedly. More than 50% of NEE variability was explained by defoliation at field scale. Additionally, soil heterogeneity affected NEE, but to a lower extent (>30%), while R_s remained unaffected. We conclude that grassland management (i.e., repeated defoliation) and soil heterogeneity affects the spatio-temporal variability of NEE at field scale.

1. Introduction

The interactions between environmental factors, including hydrological, meteorological and chemical conditions, and ecosystem carbon (C) fluxes have a profound influence on wider biogeochemical processes, yet they are not well understood (Chapin III et al., 2009; Lohse et al., 2009). While permanent grassland systems do not store as much carbon as forests, they are still potentially important in carbon cycles (Novick et al., 2004; Scharlemann et al., 2014). In Europe, more than 180 million ha (∼34% of agricultural area) is occupied by permanent grassland (Smit et al., 2008). In Central Europe (i.e., Atlantic Central Environmental Zone; Metzger et al., 2005) upland temperate grassland ecosystems are characterized by mild temperatures and uniform precipitation over the growing season (i.e., 296 days with >10 °C) that facilitates an annual grassland productivity of up to 7 t dry mass ha^{-1} (Dierschke and Briemle, 2002; Smit et al., 2008). Thus, during the growing season, grass can be intensively managed and cut at least twice a year, promoting species such as *Lolium perenne* (Dierschke and Briemle, 2002; Pontes et al., 2007). Beside biomass productivity and associated photosynthetic fixation of C in biomass, grassland ecosystems store large amounts of C in soils (Kuzyakov and Domanski, 2000; Guo and Gifford, 2002; Rees et al., 2005).

Defoliation in terms of cutting and grazing may affect C fluxes and sequestration capabilities (Wan and Luo, 2003; Wohlfahrt et al., 2008). Defoliation reduces leaf area, which affects photosynthesis and hydrocarbon allocation in plants as well as soil temperature and moisture (Wan et al., 2002; Reichstein et al., 2003; Wan and Luo, 2003; Carbone and Trumbore, 2007). This in turn reduces the capacity of grassland to capture C from atmosphere via photosynthesis while soil respiration (R_s) may be reduced or unaffected after defoliation (Bahn et al., 2006, 2008), making the grassland a potential source of C. Several days after

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defoliation grassland may turn back into a net sink (Novick et al., 2004; Zwicke et al., 2013), as leaf area recovers, facilitating photosynthetic C assimilation that over-compensates the C release from the soil. Seasonal variability of precipitation, air temperature, and radiation also affects leaf area development and associated NEE (Suyker and Verma, 2001; Li et al., 2005). Typically, high air temperatures are accompanied by high atmospheric vapor pressure deficits (VPD; i.e., low humidity), which affects stomata conductance (Buckley et al., 2003; Klumpp et al., 2007). The latter potentially limits photosynthesis if stomata are closed (Farquhar and Sharkey, 1982). Furthermore, radiation also affects NEE, due to the strong relation between photosynthetically active radiation (PAR) and photosynthesis (Gilmanov et al., 2007; Chapin III et al., 2011). In fact, numerous flux measurements revealed complex interactions between seasonally changing environmental factors (e.g., temperature, moisture, etc.) and R_s as well as NEE (Reichstein et al., 2003; Lasslop et al., 2010). Yet, the relationships between NEE, site-specific variability of soil properties and vegetation have hardly been considered at field scale.

Since soil properties frequently vary considerably within distances shorter than 100 m in fields (Stutter et al., 2009; Schirrmann and Domsch, 2011), the spatial pattern of plant performance and productivity (i.e., leaf area and photosynthetic activity) is equally complex (Ehrenfeld et al., 2005; Krüger et al., 2013). Additionally, R_s in grassland may correspond to daytime NEE (Gomez-Casanovas et al., 2012), probably due to the rapid release of root exudates (e.g., easily decomposable carbohydrates) into the soil that fuel R_s (Kuzyakov and Domanski, 2000; Carbone and Trumbore, 2007). Carbon assimilation and transformation as well as C fluxes also respond to biogeochemical nutrient dynamics, soil physical properties, soil moisture and soil temperature (Raich and Tufekciogul, 2000; Fornara et al., 2013), but their interactions and spatio-temporal dynamics that influence NEE at field scale remain unclear.

Therefore, the aim of this study was to determine R_s and NEE variability at field scale in order to derive their spatio-temporal drivers. To this end, we established a net of 21 measurement sites and repeated C flux and LAI measurements weekly during the growing season in a permanent grassland in Rollesbroich (Germany). Additionally, chemical soil analyses and geophysical measurements were performed for all measurement sites. This approach allowed the assessment of (i) the temporal effect of seasonally changing environmental drivers (i.e., temperature, soil moisture, PAR) and leaf area on R_s and NEE as well as (ii) the spatio-temporal impact of spatially fragmented grassland management (i.e., different cutting regimes) and soil heterogeneity on spatial variability of R_s and NEE at field scale.

2. Material and methods

2.1. Site description and experimental design

The Rollesbroich test site is located in Germany (50°37′N, 6°19′E; Fig. 1) and includes an area of ~20 ha at altitudes ranging

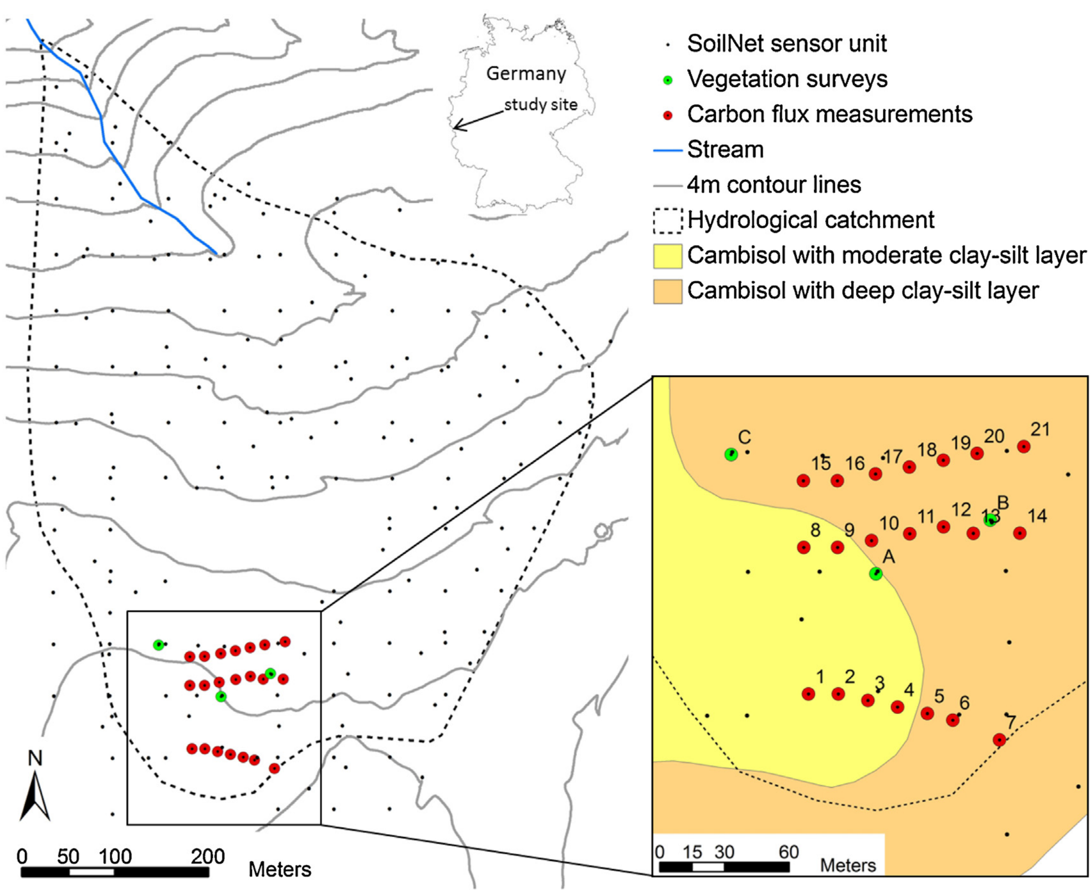

Fig. 1. The Rollesbroich test site where repeated carbon flux and leaf area measurements were performed at 21 measurement sites in a permanent grassland. This site is part of the TERENO project and provides framework for the installed 188 SoilNet sensor units that measure soil temperature and soil moisture at soil depths of 5 cm, 20 cm and 50 cm (Baatz et al., 2014). Near measurement site number 20, meteorological conditions (i.e., air temperature, precipitation, photosynthetically active radiation and vapor pressure) are continuously measured with a temporal resolution of 15 min. At sites A, B and C vegetation was surveyed. Soils differed in thickness of periglacial solifluction clay–silt layer with moderate to (max. 60 cm) deep layers (max. 100 cm; Steffens, 2007).