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Research paper

Maize carbon dynamics are driven by soil erosion state and plant phenology rather than nitrogen fertilization form

M. Hoffmann[a,b,*], M. Pohl[c,*], N. Jurisch[c], A.-K. Prescher[d], E. Mendez Campa[b], U. Hagemann[c], R. Remus[c], G. Verch[e], M. Sommer[b,f], J. Augustin[c]

[a] Department for Research Information Systems, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany
[b] Institute of Soil Landscape Research, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany
[c] Institute for Landscape Biogeochemistry, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany
[d] Institute of Forest Ecosystems, Johann Heinrich von Thünen Institute, Alfred-Möller-Straße 1, 16225 Eberswalde, Germany
[e] Agricultural Landscape Data Centre, Research Station Dedelow, Leibniz Centre for Agricultural Landscape Research (ZALF), Steinfurther Straße 14, 17291 Prenzlau, Germany
[f] University of Potsdam, Institute of Earth and Environmental Sciences, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany

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ABSTRACT

Carbon (C) stored in soils represents the largest C pool of terrestrial ecosystems and consequently plays a crucial role in the global C cycle. So far, it is widely unclear to what extent different land uses and land use change influence soil C storage. The hummocky ground moraine landscape of northeastern Germany is characterized by distinct small-scale soil heterogeneity on the one hand, and intensive energy crop cultivation on the other. Both factors are assumed to significantly influence gaseous C exchange; as such, they likely drive soil organic carbon (SOC) stock dynamics in terrestrial agricultural ecosystems. To date, it is not clear to what extent N fertilization forms, which are associated with energy crop cultivation (e.g., application of biogas fermentation residues) and soil type relative to soil erosion state, influence soil C dynamics, nor is it clear whether one of these factors is more important than the other. To investigate the influence of soil erosion state and N fertilization form on soil C dynamics, we present dynamic and seasonal net ecosystem carbon balances (NECB) as a proxy for changes in soil organic carbon stocks. Measurements were conducted for maize (*Zea mays* L.) at five sites in the "CarboZALF-D" experimental field during the 2011 growing season. Measurement sites represent different soil erosion states (non-eroded Albic Luvisols, extremely eroded Calcaric Regosols and depositional Endogleyic Colluvic Regosols) and N fertilization forms (100% mineral fertilizer, 50% mineral and 50% organic fertilizer, and 100% organic fertilizer). Fertilization treatments were established on the Albic Luvisol. Net ecosystem CO_2 exchange (NEE) and ecosystem respiration (R_{eco}) were measured every four weeks using a dynamic flow-through non-steady-state closed manual chamber system. Gap filling was performed based on empirical temperature and PAR dependency functions and was used to derive daily NEE values. In parallel, daily above-ground biomass production (NPP_{shoot}) was estimated using a logistic growth equation, fitted on periodic biomass samples. Finally, C dynamics were calculated as the balance of daily NEE and NPP_{shoot} based on the initial C input due to organic fertilization. Resulting NECB varied from pronounced soil C losses at the Endogleyic Colluvic Regosol (592 g C m^{-2}) to soil C gains at the Calcaric Regosol (-124 g C m^{-2}). Minor to modest C losses were observed for the Albic Luvisol. Compared to N fertilization forms, soil erosion states generally had a stronger impact on derived NECB. However, interannual variations in plant phenology and interactions between soil erosion states and fertilization forms might result in different NECB values over multiple years. Hence, long-term measurements of different fertilization treatments on characteristic soil landscape elements are needed.

1. Introduction

Soils store ~1500 Gt of carbon (C; to 1 m depth), which constitutes the largest C pool of any terrestrial ecosystem (Paustian et al., 2016). Consequently soils play a crucial role in the global C cycle (Van Oost et al., 2007). So far, it is largely unclear to what extent different land uses and land use change influence soil C storage (Eglin et al., 2010). This is particulary the case for the hilly ground moraine landscape of

* Corresponding authors at: Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany.
E-mail addresses: mathias.hoffmann@zalf.de (M. Hoffmann), madlen.pohl@zalf.de (M. Pohl).

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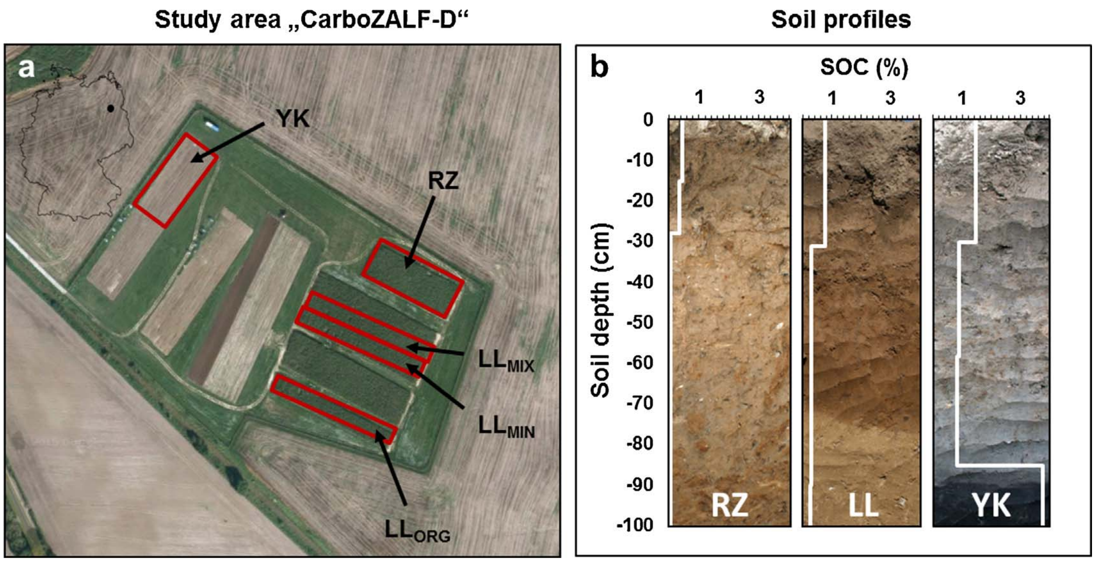

Fig. 1. Location of (a) the five measurement sites, representing three different soil erosion states and fertilization treatments at the experimental field "CarboZalf-D". (b) Soil profiles of the Calcaric Regosol (RZ), Albic Luvisol (Cutanic; LL) and Endogleyic Colluvic Regosol (YK) with soil depth-specific SOC amounts (%).

northeastern Germany, which is strongly affected by both soil erosion and increased energy crop cultivation – two factors assumed to significantly alter soil C storage (Eglin et al., 2010).

Physico-chemical soil properties, such as soil texture and porosity, define the aerational status of the soil and influence mineralization processes, preferential water flow, and soil air diffusion. As a result, the different soil types of an erosion shaped heterogeneous agricultural landscape affect gaseous C exchange and soil C dynamics. However, the specific soil C sink or source function of different soils in an erosionally influenced landscape is still the subject of a controversial scientific debate. Van Oost et al. (2007) and Kirkels et al. (2014) propose that tillage erosion contributes to the "missing terrestrial C sink" by sequestering additional C, while Lal (2004) argues that water erosion in particular may result in a strong soil C release.

A similar uncertainty exists with respect to the influence of energy crop cultivation. Cannell (2002), Lal (2010) and Lemus and Lal (2005) assume a crop- and management-dependent potential for additional C sequestration related to energy crop cultivation; however, negative impacts of energy maize on soil C storage are mentioned by Ceschia et al. (2010) and Zeri et al. (2011). In Germany, energy crop cultivation is politically encouraged and currently covers 2.2 million hectares (FNR, 2017). Maize accounts for as much as 66% of this area, forming the largest share of energy crop cultivation (FNR, 2017). To enhance or sustain soil fertility while cultivating energy crops such as maize, organic amendments, manure and biogas fermentation residues (ORG) are increasingly used to replace mineral N fertilizer (Möller and Müller, 2012). Compared to mineral N fertilizer, ORG contains N, but also other nutrients such as P, K and a considerable amount of organic C. Hence, it is assumed that ORG application offsets losses in nutrients and soil organic matter stocks (Brock et al., 2013; Coban et al., 2015; Garg et al., 2005; Odlare et al., 2008), caused by intensive energy crop cultivation (Möller and Müller, 2012). However, little is known of the direct effects of N fertilization form (organic vs. mineral) on soil C dynamics. Mineral as well as organic N fertilizer application can decrease as well as increase soil C. On the one hand, soil C might be decreased due to increasing mineralization. On the other hand, soil C can accumulate through increased N fertilizer (indirect) or the return of crop residues related to increased crop growth (direct; Blair et al., 2006a, 2006b; Kaur et al., 2007; Russell et al., 2009; Smith et al., 2012). Using isotope labelling, Coban et al. (2015) concluded that ORG contributes to soil organic matter formation over a few years. In contrast, Alburquerque et al. (2012) performed an incubation experiment which revealed that highly biodegradable ORG can lead to high soil CO_2 emissions and indicated the importance of organic matter stability in ORG in order to avoid harmful effects on the plant-soil system. In another incubation experiment, slower mineralization and lower soil CO_2 emissions were observed for soil treated with ORG compared to soil treated with maize straw (Chen et al., 2012). However, no attempt has been made yet to directly assess the influence of ORG on soil organic carbon (SOC) stocks. Hence, it is important to consider the impact of soil type and N fertilization form when assessing the soil C dynamics of erosion-influenced agricultural landscapes under energy crop cultivation.

To date, the assessment of changes in SOC is mainly based on two methods, namely: (1) repeated soil inventories, and (2) determination of net ecosystem carbon balances (NECB; Smith et al., 2010). Compared to repeated soil inventories, estimates of the NECB as a proxy for change in SOC not only allows to access multiple fluxes of the C budget but also recording them in a higher temporal resolution. This might help reveal the environmental variables and processes that drive soil C dynamics. Common approaches to measure gaseous C exchange include the eddy covariance technique, which integrates C fluxes over a large variable footprint area (several hectares), and closed chamber measurements, which are often used to measure gaseous C exchange at different plots within a crop field experiment (e.g., Eickenscheidt et al., 2015; Pohl et al., 2015). Compared to eddy covariance measurements, the manual chamber technique combines spatially distinct measurements, which allow small-scale treatment comparisons, with the advantage of sensitive, NECB-based estimates of soil C dynamics (Hoffmann et al., 2017a).

In our study, we combine manual closed-chamber measurements of the net ecosystem CO_2 exchange (NEE) and empirically modeled aboveground biomass production (NPP_{shoot}) to (1) determine the short-term effect of ORG on soil C stocks, (2) determine the short-term effect of soil erosion on C stocks, and (3) identify the relative importance of N fertilization form in the context of energy crop cultivation and soil erosion state on soil C dynamics. Measurements were performed for maize during the 2011 growing season, at five sites representing three different erosion states and three fertilization treatments.

2. Material and methods

2.1. Study sites and experimental setup

Measurements were carried out at the experimental field