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Reproducing CO_2 exchange rates of a crop rotation at contrasting terrain positions using two different modelling approaches

X. Specka[a], C. Nendel[b,*], U. Hagemann[a], M. Pohl[a], M. Hoffmann[c], D. Barkusky[d], J. Augustin[a], M. Sommer[c], K. van Oost[e]

[a] Institute of Landscape Biogeochemistry, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany
[b] Institute of Landscape Systems Analysis, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany
[c] Institute of Soil Landscape Research, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany
[d] Research Station, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany
[e] George Lemaitre Centre for Earth and Climate Research, Earth and Life Institute, Catholic University of Louvain, Place Louis Pasteur 3, 1348 Louvain-la-Neuve, Belgium

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ABSTRACT

In undulating landscapes erosion is largely responsible for the spatial distribution of C stocks in agricultural soils. Whether these stocks contribute to global atmospheric CO_2 concentrations as source or sink of CO_2 is under constant debate. Periodic CO_2 measurements were carried out at a hummocky ground moraine site grown with maize, fodder rye and sorghum using dynamic non-steady-state transparent and opaque chambers. Flux calculation for CO_2 was conducted using the empirical gap-filling model of Hoffmann et al. (2015b), which uses temperature and radiation to simulate ecosystem respiration (R_{eco}) and gross primary production (GPP) and to calculate net ecosystem CO_2 exchange (NEE). This model was compared with a process-based agro-ecosystem simulation model, MONICA, which was tested for its ability to simulate R_{eco}, GPP and NEE, using the empirical model as benchmark. Both models simulated GPP and R_{eco} in the same order of magnitude, with MONICA simulating a considerably higher amount of CO_2 produced by photosynthesis for maize and less deviating CO_2 produced by photosynthesis for the other crops and CO_2 consumed by respiration for all crops as compared to the empirical model. Both models largely agree in CO_2 flux patterns, but show considerable differences directly after harvest and during bare soil periods. Strengths and weaknesses of both approaches were discussed and synergies of applying both approaches in conjunction were identified in a way that (i) MONICA may act as an independent method to identify significant deviations from the optimum crop growth pattern and thus point at times during which assumptions of the empirical model for simulating NEE may be violated and that (ii) the empirical model may act as a calibration benchmark for MONICA flux simulations.

1. Introduction

In undulating landscapes erosion is the most important soil-forming process. These landscapes mostly most exhibit very heterogeneous soil properties, especially with regard to soil carbon (C) stocks (Doetterl et al., 2012; van Oost et al., 2007, 2012; Vandenbygaart et al., 2012). The consequences of the spatial distribution of C stocks for C fluxes between ecosystem compartments and CO_2 exchange with the atmosphere are mainly unknown. For this reason, the contribution of agricultural land to global atmospheric CO_2 concentrations (later referred to as [CO_2]), being either source or sink of CO_2, is under constant debate (Houghton et al., 2012; Schimel et al., 2015; Smith et al., 2012). Changes in C stocks of agricultural soils occur as a result of alterations to the balance between C input and loss. In a soil–plant system, C input is considered when CO_2 is captured from the atmosphere by plants via photosynthesis and stored in their living tissue. C is lost from the system through autotrophic respiration (R_a) of the plants and through microbial decomposition of plant tissue, when soil organic carbon (SOC) is respired again to CO_2 (heterotrophic respiration R_h). This happens in a slow, continuous process, but land use change may also trigger large peaks (Wei et al., 2014). Within the system, C is transferred from the plant to the soil by deposition of plant residues on the soil's surface or in

* Corresponding author. Tel.: +49 33432 82355; fax: +49 33432 82334.
E-mail address: nendel@zalf.de (C. Nendel).

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the soil column as dead roots (Jones et al., 2009). Root exudates add additional C to the soil during active plant growth. In sloped landscapes, erosion and deposition may significantly alter this balance (Sanderman and Chappell, 2013; van Oost et al., 2007). However, it remains unclear at which point of the erosion–deposition process chain C sequestration or C liberation processes dominate (Berhe et al., 2007; Berhe and Kleber, 2013; Kirkels et al., 2014; Lal and Pimentel, 2008; Vandenbygaart et al., 2015).

C fluxes in and out of a soil–plant system are observed by means of concentration differences in the surrounding air (Smith et al., 2010). CO_2 concentration measurements require a skilled set-up which does not significantly alter the environmental conditions or else interferes with the processes that are subject of subsequent interpretation. Closed chambers are widely used to introduce an artificial system boundary for CO_2 exchange with the wider atmosphere (Livingston and Hutchinson, 1995). However, closed chambers also inhibit heat and moisture exchange which causes the environmental conditions in the trapped air volume to change quickly, with significant consequences for the plant's physiological behaviour (Lai et al., 2012; Langensiepen et al., 2012; Pumpanen et al., 2004). For this reason, continuous CO_2 concentration monitoring is extremely difficult and campaign-based, discontinuous data acquired by means of short-term chamber measurements prevail for flux analysis. Gap filling methods are then required to derive continuous flux series from single event data. Such methods are often based on simple empirical models, which simulate CO_2 fluxes based on temperature and radiation dynamics (Elsgaard et al., 2012; Falge et al., 2001; Hoffmann et al., 2015b; Richardson et al., 2006). These empirical models deliver not much more than a gap-free time series of what was measured and may fail in reproducing intensity and dynamics of ecosystem CO_2 fluxes, consequently misinterpreting the system's contribution to the atmospheric C budget, if plant physiological development is not well captured by adequately spaced measurement campaigns.

As an alternative, computer simulation models are available, which were constructed on the basis of biophysical processes and have been used already for decades to assess the impact of environmental conditions on plant growth as well as on water and nutrient dynamics in soil–plant–atmosphere systems (Ewert et al., 2015; Martre et al., 2015). Some of these models even allow for a deconstruction of the ecosystem C balance into its components (Abdalla et al., 2014; Abrahamsen and Hansen, 2000; Huang et al., 2009). However, these models have rarely been designed or tested at the level of the above-mentioned CO_2 fluxes, being rather used to predict environmental or management impact on more integrating variables, such as plant biomass production, yield formation or net C stocks of soils (Jandl et al., 2014; Neill, 2011; Schmid et al., 2006; Smith et al., 2012).

We compared the empirical gap-filling algorithm of Hoffmann et al. (2015b, later referred to as the empirical model) with MONICA, an established process-based agro-ecosystem simulation model (Nendel et al., 2011), using field-measured CO_2 exchange data from a field experiment investigating the C budget of maize, fodder rye and sorghum grown on different erosion-induced transient soils in the undulating landscape of North-eastern Germany. Prior to this performance test we calibrated (i) MONICA's soil part against long-term soil C dynamics in various crop rotation experiments and (ii) MONICA's crop part against the aboveground biomass data obtained from the field experiment. From the conceptual point of view, MONICA should be able to reflect the influence of site properties and weather on actual CO_2 fluxes and crop growth and successfully predict cumulative CO_2 fluxes, CO_2

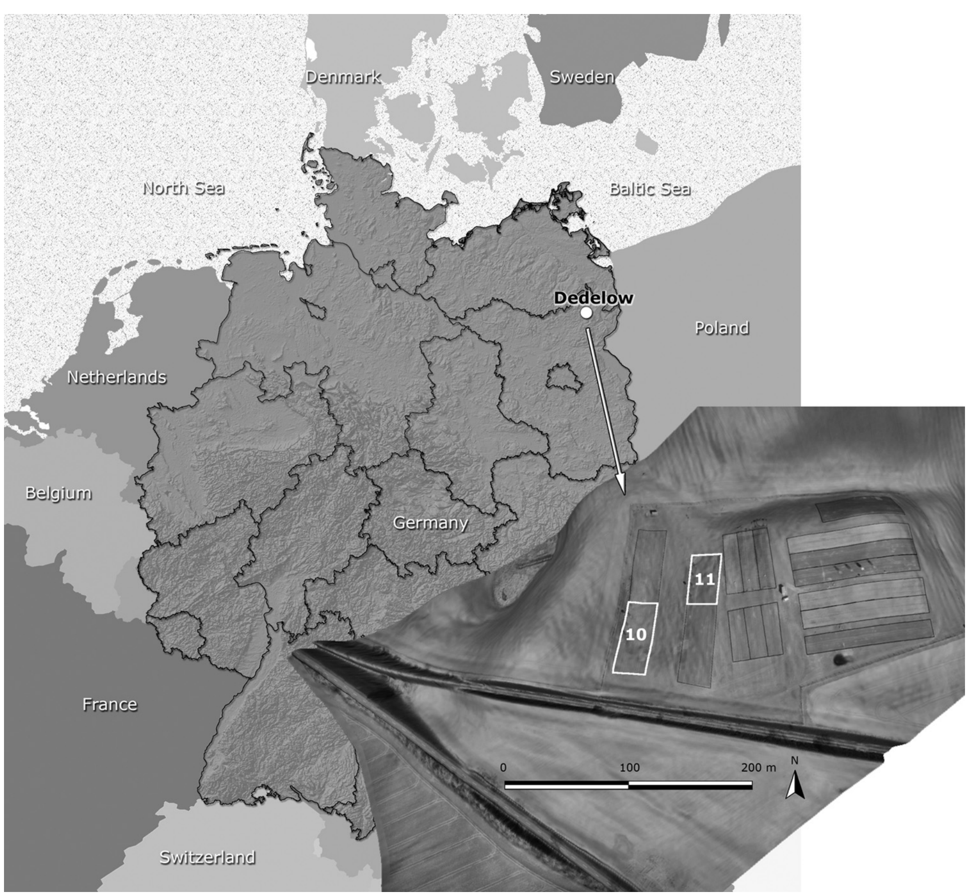

Fig. 1. The CarboZALF experimental site in north-eastern Germany.