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Erosion-induced carbon redistribution, burial and mineralisation — Is the episodic nature of erosion processes important?

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ABSTRACT

There is still an ongoing scientific discussion regarding the importance of erosion-induced lateral soil organic carbon (SOC) redistribution for the burial and/or mineralisation of carbon and the resulting long-term C balance at the catchment scale. Especially the effects of the event driven nature of water erosion and the potentially associated enrichment of SOC in sediment delivery are still unclear. In general, two processes lead to enrichment of SOC: (i) enrichment due to selective interrill erosion at erosion sites, and (ii) enrichment due to selective depletion at deposition sites. In this study, the conceptual soil erosion and SOC turnover model SPEROS-C was adapted to integrate these processes and applied in a small arable catchment (4.2 ha) in Germany for a 57-year period. A total number of 901 model runs were performed with different realisations of frequency and magnitude of water erosion as well as realisations of enrichment and depletion ratios taken from literature and compared to a reference model run representing mean annual erosion without enrichment processes. In general, our modelling study indicates that ignoring temporal variability and enrichment processes may lead to a substantial misinterpretation of erosion-induced C fluxes. Especially the vertical C flux (difference between C inputs from plant assimilates and organic fertilizer and SOC mineralisation) at deposition sites strongly depends on the model parameterisation ranging from a maximum C source of -336 g C m^{-2} to a maximum C sink of 44 g C m^{-2}. In combination with a substantially higher C export due to enrichment processes, the overall C balance of the catchment potentially turns into a maximum C source of -44 g C m^{-2} at the end of the simulation period compared to a C source of -1 g C m^{-2} for the reference run.

1. Introduction

There is a growing interest in the lateral redistribution of soil organic carbon (SOC) due to erosion processes and their effects on landscape scale carbon burial or mineralisation (Berhe et al., 2008; Doetterl et al., 2013; Dymond, 2010; Fiener et al., 2012; Quinton et al., 2010; Van Oost et al., 2007). A general challenge in this research field is the event-driven nature of water erosion processes (Fiener and Auerswald, 2007; Nearing et al., 1999) governing short-term effects of erosion, transport, and deposition of SOC on vertical C (carbon) fluxes (difference between C inputs from plant assimilates and organic fertilizer and SOC mineralisation) (scale: minutes to days), and long-term effects by building up three-dimensional patterns of total SOC and also specific SOC pools within our landscapes (scale: decades to centuries). Some research focuses on the event-based lateral fluxes of soil and SOC and more rarely its associated short-term C effluxes to the atmosphere (Bremenfeld et al., 2013; Van Hemelryck et al., 2010a, 2010b; Wang et al., 2014), while other studies use long-term patterns in SOC in conjunction with long-term erosion studies, mostly based on erosion tracers (e.g. ^{137}Cs) or soil truncation, to evaluate the long-term effect of erosion on the C balance (Afshar et al., 2010; Doetterl et al., 2013; Martinez et al., 2010; Quine and Van Oost, 2007). Catchment scale patterns in SOC distributions are also the basis for developing and testing coupled soil erosion and C turnover models (Dlugoß et al., 2012; Van Oost et al., 2005a). These modelling approaches need to deal with modelling periods of at least decades to use SOC patterns for model testing and validating. Therefore, these models typically assume steady state erosion conditions and are driven by long-term erosion estimates either using Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1960) technology (Dlugoß et al., 2012) or even more parsimonious approaches on global scales (Van Oost et al., 2007). However, the problem of these types of coupled models is that the event-based nature of erosion is statistically integrated into long-term mean annual erosion rates. This might be appropriate when focusing on bulk soil erosion alone, but the effects of the large temporal variability of erosion processes on C sequestration, mineralisation and lateral SOC export from a catchment remain unclear.

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At least three effects might bias the model-based analysis of SOC redistribution induced C fluxes using long-term mean erosion rates as the driver in coupled models: (i) Spatial patterns of erosional and depositional areas vary depending on erosion event characteristics. (ii) On the one hand, pronounced erosion and deposition in some years might accelerate dynamic replacement at erosional sites, while on the other hand, burial of SOC might be more effective when large quantities of SOC are buried at once and hence are more effectively protected from mineralisation due to the decrease of SOC turnover with depth (e.g. Berhe and Kleber, 2013; Berhe et al., 2008; Rosenbloom et al., 2001). (iii) The potentially most important effect is the enrichment of C in delivered sediments compared to the parent soil material within the catchment that is not integrated in long-term models but which has been proven in many experimental studies (e.g. Schiettecatte et al., 2008b). In general, two event-size specific processes affect the C enrichment in delivered sediments. Plot experiments indicate that SOC is preferentially eroded and hence delivered sediments are enriched in carbon. Here enrichment ratios decline with increasing erosion, which is either expressed as sediment concentration in runoff (Wang et al., 2010, 2013) or as sediment delivery rate (Schiettecatte et al., 2008b). The observed decline in selectivity is associated to a shift from selective interrill erosion to more or less unselective rill erosion (Schiettecatte et al., 2008b). Other studies more generally focus on the enrichment of substances associated to fine particles on different scales (plot to small catchment) without explicitly analysing enrichment processes during single events. These studies also indicate a general decline of C or P (phosphorus) enrichment with increasing event or long-term erosion rates (Auerswald and Weigand, 1999; Menzel, 1980; Polyakov and Lal, 2004; Sharpley, 1985). The second important process affecting carbon enrichment in the sediment delivery of a catchment is the preferential deposition of coarse and heavy particles, while carbon is mostly associated to fine and light sediments (Schiettecatte et al., 2008a; Van Hemelryck et al., 2010a; Wang et al., 2010). For example, Wang et al. (2010) found a depletion ratio of SOC in deposits ranging from 0.50 to 0.91, with lowest values in the winter (i.e. highest SOC enrichment in delivered sediments due to preferential deposition of coarse and heavy particles not included in aggregates) and highest values in the summer when sediments are mostly transported as aggregates. Similar but somewhat more extreme depletion during deposition in a flume experiment was found by Van Hemelryck et al. (2010a) with depletion ratios ranging from 0.35 to 0.75.

As described above, it is very difficult to address all these potential effects resulting from the temporal variability of erosion processes, as their analysis calls for measured data with a very high temporal resolution (minutes to hours) of rainfall, dynamic soil properties (e.g. moisture), soil cover, management, runoff, sediment delivery, etc., and for a continuous long-term monitoring (decades) of C sequestration and mineralisation following different erosion events. To address all aspects at once and take short-term processes of soil and SOC redistribution as well as long-term effects on C mineralisation and sequestration into account calls for a modelling study that couples a high resolution, process-based, sediment-size selective erosion model (e.g. Fiener et al., 2008; Laflen et al., 1997; Schmidt et al., 1999) with a state-of-the art C turnover model (e.g. Coleman and Jenkinson, 2008; Skjemstad et al., 2004). However, these model types are highly data demanding (e.g. they need exact timing of tillage operations) and therefore an application on a time scale of decades or centuries is associated with large uncertainties as most input data need to be estimated from generally available data sources, e.g. average harvesting time for a region.

The main aim of this modelling study is to assess the importance of variability of event-driven soil erosion when analysing the long-term effects of SOC redistribution on C mineralisation and burial within an arable landscape. Instead of tackling the issue with a process-based model with its specific difficulties that were identified above, we conceptually integrated the most important processes into the well-established long-term erosion and C turnover model SPEROS-C (Van Oost et al., 2005b), which operates at timescales of several years to decennia and that had already been successfully implemented at the study site (Dlugoß et al., 2012). This means that the event-driven variability of annual erosion, based on high resolution erosivity data (5-min, 50 years), an erosion magnitude specific SOC enrichment in delivered sediments, and depletion ratios based on different approaches and literature data were integrated into SPEROS-C.

2. Methods

2.1. Combined soil redistribution and SOC dynamics modelling

The model SPEROS-C (Dlugoß et al., 2012; Nadeu et al., 2015; Van Oost et al., 2005a) combines the water and tillage erosion model WaTEM (Van Oost et al., 2005a) with the Introductory Carbon Balance Model (ICBM; Andrén and Kätterer, 1997). The original model code was recently restructured and transferred from Delphi (Borland, USA) to Lazarus, which is a Delphi compatible cross-platform IDE for Free Pascal (http://www.lazarus.freepascal.org). The modifications made to the model for this study are described in detail here, while the original structure and process descriptions are only summarized. A detailed description of SPEROS-C can be found in Van Oost et al. (2005b) and Dlugoß et al. (2012).

In general, SPEROS-C is a raster-based, spatially explicit, multiple soil layer model that calculates soil and associated SOC redistribution by water, tillage and harvest erosion in an annual time step. The water erosion component is based on (i) the assessment of the potential erosion rate for each grid cell, (ii) the assessment of the local transport capacity, and (iii) a topography-based routing algorithm that redistributes the produced sediment over the land surface by accounting for flow-direction and the spatial pattern of the transport capacity. The potential water erosion for each grid cell is calculated according to the Revised Universal Soil Loss Equation (RUSLE), while the local transport capacity TC (kg m^{-1} a^{-1}; Eq. (1)) is assumed to be proportional to the erosion potential:

$$TC = ktc \cdot R \cdot C \cdot P \cdot K \cdot LS \quad (1)$$

where ktc is the transport capacity coefficient, R, C, P, K, L and S are the RUSLE (Renard et al., 1996) factors: R is the rainfall erosivity factor, C is the cover management factor, P is the conservation practice factor, K the soil erodibility factor, L the slope length factor, and S the slope gradient factor.

Erosion and deposition caused by tillage is calculated following the diffusion-type approach developed by Govers et al. (1994), while soil loss due to crop harvesting (Ruysschaert et al., 2004, 2005) can be included for root crops.

The ICBM (Andrén and Kätterer, 1997) describes SOC dynamics using two SOC pools ("young" and "old") and four C fluxes (C input from plants, mineralisation from the young and the old pool, and humification). In SPEROS-C, the C input into the soil by plant residues is estimated as a ratio of crop yield and added to the plough layer, while the C input by roots is assumed to decrease with soil depth following an exponential root density function. Additionally, the C input by cover crops and/or organic manure can be specified for the plough layer.

SOC erosion (C_{ero}) from the topsoil layer for the two SOC pools is modelled for each time step using the results from soil redistribution by water, by tillage, and the soil loss due to root crop harvesting. It is calculated as

$$C_{ero} = SOC_1 \cdot M_{ero}/M_1 \quad (2)$$

with SOC_1 being the amount of SOC in the first soil layer (g), M_{ero} being the mass of eroded soil (g) and M_1 being the total mass of the first soil layer (g).