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Modelling long-term soil organic carbon dynamics under the impact of land cover change and soil redistribution

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ABSTRACT

During the last millennia, anthropogenic land cover change has caused a significant release of carbon from soils while also accelerating rates of soil erosion by one to two orders of magnitude. However, mechanistic frameworks that explicitly link land cover change, erosion and soil organic carbon (SOC) cycling and, in addition, can be applied to longer timescales are currently lacking. This study presents a 4D soil-landscape model coupling sediment fluxes and carbon dynamics in response to continuous land cover change over a period of 1000 years. We applied the model to a well-studied catchment of 591 km^2 in Central Belgium. The model evaluation showed that the simulated magnitude and spatial patterns of soil redistribution and SOC stocks are in good agreement with field observations. At the catchment scale, land cover change over the last 1000 years decreased the SOC stock of the top 1 m of soil by 33.1 tC·ha^{-1} (32% loss compared to the initial SOC stock) while in contrast, erosion resulted in an uptake of 31.9 tC·ha^{-1} from the atmosphere (29% gain compared to the initial SOC stock). As a result, the combined effect is a small source of c. 1.2 tC·ha^{-1} over the last 1000 years. While the SOC released from the soil to the atmosphere quickly responded to land conversion, the erosion induced sink operated at a much lower intensity but with a longer duration. These transient simulations show that the soil carbon budget is highly variable in both space and time.

1. Introduction

The terrestrial carbon cycle is to a large extent regulated by soil-atmosphere interactions whereby organic carbon from vegetation debris and roots can be stored in soils while biologic activity and re-mineralization release carbon (C) back to the atmosphere (Houghton, 2007). This process is important in regulating the atmospheric CO$_2$ given the large size of the soil organic carbon (SOC) pool which is estimated to store approximately 1417 Pg in the first meter, three times the size of the atmospheric CO$_2$ pool (Hiederer and Köchy, 2011; Houghton, 2007). Human activities on the Earth's surface have become one of the major drivers by drastically altering the soil system through changes in land cover (Vanacker et al., 2013). Land conversion from natural forest or grassland to cropland have direct impact on the C cycle: generally, carbon input to soil is reduced and SOC mineralization increased due to the disturbance introduced by farming practices. It is estimated that anthropogenic land cover change (ALCC) has released approximately 50–357 Pg C for the pre-industrial Holocene and 156 Pg C to the atmosphere over the industrial era (post-1850) globally (Houghton, 2003; Kaplan et al., 2010; Stocker et al., 2011).

Conversion from native vegetation to cropland also has a profound impact on soils and can result in an increase of soil erosion rates by up to two orders of magnitude on cropland compared to the natural land cover condition (Montgomery, 2007). Accelerated (anthropogenic) soil erosion has, therefore, increased lateral fluxes of carbon by as much as 0.6 to 1.5 Gt per year (Quinton et al., 2010). These enhanced lateral SOC fluxes result in a higher spatial variability of SOC in agricultural fields (Doetterl et al., 2013; Li et al., 2007; Van Oost et al., 2005; Wang et al., 2015b) and increasing C exchange between soil and atmosphere (Berhe, 2012; Stallard, 1998; Van Oost et al., 2007) driven by various interlinked processes: (i) the dynamic replacement of eroded C, i.e. the replacement of eroded SOC by new photosynthate at eroding sites due to the exposure of subsoil layers at the surface (Billings et al., 2010; Harden et al., 1999; Stallard, 1998), (ii) enhanced SOC mineralization during or after transport through the destruction of the physical structure of soil aggregates (Lal, 2003) and (iii) the effective protection and preservation of transported C buried in depositional areas over longer time scales (Berhe et al., 2008; Hoffmann et al., 2009; Hoffmann et al., 2013; Van Oost et al., 2012; Wang et al., 2014). However, different assumptions on the relative strength of those mechanisms result in a

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considerable uncertainty about the magnitude of the impact of erosion on the C cycle (Doetterl et al., 2016; Kirkels et al., 2014). At present, only a limited number of modelling frameworks have been developed to study the interactions between erosion and C cycling processes. Parsimonious models can be used to estimate the magnitude of lateral C fluxes at the global scale (e.g. Doetterl et al., 2012b). Insights into erosion-C cycling processes have been gained using mechanistic models that operate at the landscape scale (Dialynas et al., 2016; Vanwalleghem et al., 2013).

Until now, soil landscapes are typically described using geostatistical approaches, which rely on the *catena* concept and represent the relationship between soils and landforms using empirical approaches (Gerrard, 1992; Hall, 1983; Milne, 1936). At present, a variety of geostatistical models exist to predict the SOC in topsoil (i.e. Herbst et al. (2006), Takata et al. (2007) or Minasny and McBratney (2007)). Lateral and vertical distribution in the soil landscape have been investigated by i.e. Mueller and Pierce (2003), Dlugoss et al. (2010), Stevens et al. (2014) or Aldana Jague et al. (2016). Geostatistical models mainly rely on topographical indices such as slope (Mueller and Pierce, 2003), curvature or elevation (Herbst et al., 2006; Sumfleth and Duttmann, 2008; Takata et al., 2007). Although the modeled spatial patterns of SOC storage can be used to infer processes, geostatistical models remain empirical and are limited to short timescales (years to decades) and to the region they were developed for, thereby restricting their application to other landscapes. The shortcomings of geostatistical models highlight the necessity of developing coupled process-based soil landscape models to study the interplay of geomorphic and pedogenic processes, in particular the effect of erosion on SOC dynamics (Kirkels et al., 2014).

On one hand, models have been developed to assess the impact of land cover change from native vegetation to the cropland on the SOC stock without considering the indirect impact of the erosion acceleration (Kaplan et al., 2010; Kaplan et al., 2012). On the other hand, SOC cycling models have been coupled with soil erosion models to investigate the effect of lateral SOC fluxes by agricultural erosion (e.g. Van Oost et al., 2005; Yoo et al., 2006). However, few efforts have been directed towards the investigation of the impact of land conversion from native vegetation to arable land cover at longer timescales (i.e. centennial to decadal timescales, e.g. Kuhn (2007)) whereby both direct C emission in relation to land cover change as well as the indirect changes related to erosion-induced alteration of soil-atmosphere C fluxes are considered.

In this study, we link a long-term soil landscape evolution model to a model of C turnover. We present a modified version of the SPEROS-C model and apply it to a 591 km^2 catchment in central Belgium for the last millennium (1000–2015 CE) where substantial changes in land cover have occurred (Notebaert et al., 2011a). We confront the long-term model simulations with high-resolution observations on soil C profiles. The use of long-term data provides a stringent test of the coupled model as it allows isolating erosion-induced C fluxes from processes related to primary production or microbial activity which occur at shorter timescales. In a second step, we quantify and discuss the impact of anthropogenic land cover change on the long-term SOC dynamics at the regional scale.

2. Materials and methods

To assess the impact of human-induced land cover change on the C budget, we applied a spatially and depth-explicit model which couples erosion and SOC processes: SPEROS-CLT (Long Term) (Nadeu et al., 2015; Van Oost et al., 2005). We ran the model for the last 1000 years with and without erosion processes to evaluate the impact of land cover conversion. This allows us to isolate and compare the effects of (i) changes in C input and mineralization and (ii) erosion-induced changes in C turnover. Our study encompasses 3 steps: (i) downscaling and spatial allocation of land cover for the simulation period, (ii) calibration of the sediment and carbon modules of the SPEROS-CLT model and (iii) analysis of the model behavior and evaluation of the simulation results.

2.1. Study area

The study was performed in the catchment of the Dijle river (Belgium) (591 km^2), which consists of a gently incised plateau. Elevation ranges from 65 m to 165 m asl with slope gradients up to 36%. The region has a temperate climate with an average annual temperature of approximately 9.5 °C and an average annual precipitation of 750–800 mm. Soils in the area are mainly loess-derived loamy Luvisols and Cambisols. Texture and clay content do not vary significantly across the catchment, with clay ranging between 9 and 18% in the topsoil, with typical values from 11 to 15% (Doetterl et al., 2012a; Rommens et al., 2005). Urban areas (32%) and croplands (37%) are predominantly situated on plateaus and slopes (Notebaert et al., 2011a). Grasslands (18%) and forests (13%) are mainly found in the floodplains and plateaus. The catchment has a long history of human settlement with observations showing human presence as early as the Atlantic Period (ca. 5800–3000 BCE) (de Smedt, 1973). The vegetation cover has been severely disturbed from the Roman Period onward: several cycles of deforestation and land abandonment are reported for this period (Notebaert et al., 2009; Notebaert et al., 2011b). A steady and large increase in forest clearance and urbanization rates is documented for the last 400 to 500 years (Notebaert et al., 2011b).

2.2. SPEROS-CLT model

SPEROS-CLT is a modified version of SPEROS-C (Van Oost et al., 2005), a model that couples a depth-explicit version of the Introductory Carbon Balance Model (ICBM, Andren and Katterer, 1997) with the spatially explicit WATEM-SEDEM erosion model (Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2002). SPEROS-C was originally developed for agricultural fields or micro-catchments and annual to decadal timescales (Fiener et al., 2015; Nadeu et al., 2015). Modifications involved adding the ability to dynamically simulate different land cover and their changes over time. The model provides direct estimates of the sediment and carbon budget as well as export from the catchment (Fig. 1). Note that SPEROS-CLT only simulates hillslope processes and models particulate carbon fluxes. Implementation of the model at longer temporal and larger spatial scales requires a correct representation of the spatial and temporal patterns of land cover and C turnover processes. In the following section we provide an overview of the model and describe in detail how it was modified to allow for transient simulations over several millennia in response to changing land cover.

2.2.1. SOC dynamics

The ICBM model is a two-pool (young and old pool) SOC model which simulates SOC fluxes of (i) C input into the young pool from roots, residues and manure, (ii) transfer from the young pool to the old pool and (iii) the mineralized C leaving each pool (Andren and Katterer, 1997). SOC losses from these pools are described using the following equations:

$$\frac{dY}{dt} = i - k_y r Y \tag{1}$$

$$\frac{dO}{dt} = h k_y r Y - k_o r O \tag{2}$$

where Y (Mg C ha^{-1}) and O (Mg C ha^{-1}) are young and old SOC pools respectively, k_y (yr^{-1}) and k_o (yr^{-1}) are the turnover rates of young and old SOC pools respectively. I represents the C input to soil, and is composed of C input from crops (ic) and C input from manure (im), h is the humification coefficient (Eq. (3)), i.e. the fraction of mineralized young SOC pool that is transformed to old SOC pool and r is the climate