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Drivers of dissolved organic carbon export in a subarctic catchment: Importance of microbial decomposition, sorption-desorption, peatland and lateral flow

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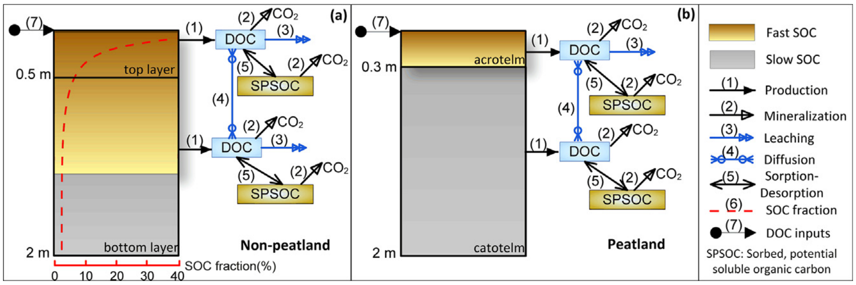
HIGHLIGHTS

- A set of DOC related processes has been integrated into LPJ-GUESS.
- Wet fen (*Eriophorum*) peatland is hotspot of DOC export in subarctic region.
- DOC production, sorption-desorption and mineralization control soil DOC exports
- Lateral flow through landscape is important for capturing catchment DOC.
- Peatlands act as an important source for DOC export in this subarctic catchment.

GRAPHICAL ABSTRACT



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ABSTRACT

Tundra soils account for 50% of global stocks of soil organic carbon (SOC), and it is expected that the amplified climate warming in high latitude could cause loss of this SOC through decomposition. Decomposed SOC could become hydrologically accessible, which increase downstream dissolved organic carbon (DOC) export and subsequent carbon release to the atmosphere, constituting a positive feedback to climate warming. However, DOC export is often neglected in ecosystem models. In this paper, we incorporate processes related to DOC production, mineralization, diffusion, sorption-desorption, and leaching into a customized arctic version of the dynamic ecosystem model LPJ-GUESS in order to mechanistically model catchment DOC export, and to link this flux to other ecosystem processes. The extended LPJ-GUESS is compared to observed DOC export at Stordalen catchment in northern Sweden. Vegetation communities include flood-tolerant graminoids (*Eriophorum*) and *Sphagnum* moss, birch forest and dwarf shrub communities. The processes, sorption-desorption and microbial decomposition (DOC production and mineralization) are found to contribute most to the variance in DOC export based on a

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Sorption-desorption
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detailed variance-based Sobol sensitivity analysis (SA) at grid cell-level. Catchment-level SA shows that the highest mean DOC exports come from the *Eriophorum* peatland (fen). A comparison with observations shows that the model captures the seasonality of DOC fluxes. Two catchment simulations, one without water lateral routing and one without peatland processes, were compared with the catchment simulations with all processes. The comparison showed that the current implementation of catchment lateral flow and peatland processes in LPJ-GUESS are essential to capture catchment-level DOC dynamics and indicate the model is at an appropriate level of complexity to represent the main mechanism of DOC dynamics in soils. The extended model provides a new tool to investigate potential interactions among climate change, vegetation dynamics, soil hydrology and DOC dynamics at both stand-alone to catchment scales.

1. Introduction

Tundra soils in high latitudes account for approximately 50% of global stocks of organic carbon (OC) in soils (Tarnocai et al., 2009; Hugelius et al., 2014; Köchy et al., 2015). Currently high latitude ecosystems constitute a sink for atmospheric CO_2 (Forkel et al., 2016) but with the amplified climate warming in northern high latitudes, relative to the globe as a whole (AMAP, 2012; Callaghan et al., 2013; IPCC, 2013), it is hypothesised that increased decomposition of the vast OC stocks in high latitudes could increase greenhouse gas concentrations in the atmosphere, with repercussions for the global climate (Zimov et al., 2006). Furthermore, warmer climate and changed precipitation could contribute to large impacts on carbon (C) cycling in this region and are expect to increase dissolved organic carbon (DOC) transport from soil to aquatic systems (Frey and Smith, 2005; Jantze et al., 2013). Northern aquatic ecosystems are generally considered to be net sources of C to the atmosphere with emissions of carbon dioxide (CO_2) and methane (CH_4), largely resulting from mineralization of dissolved and particulate C of terrestrial origin (Walter et al., 2008; Tranvik et al., 2009). The importance of inland waters in transporting, mineralizing and emitting C originating from terrestrial ecosystems has been recently addressed (Battin et al., 2009; Tranvik et al., 2009; Tranvik, 2014) and emissions of greenhouse gases (CO_2 and CH_4) from inland water have been suggested to contribute significantly to the global C cycle (Cole et al., 2007; Tranvik et al., 2009). As the main C source, the lateral transfer of terrestrial C to the aquatic realm needs to be taken into account not only for complete land-atmosphere C budget estimations (Finlay et al., 2006; Olefeldt et al., 2012), but also for quantifying the contributions and linkages to downstream aquatic C cycling (Lundin et al., 2013).

DOC, often defined as consisting of organic molecules that can pass through a filter of 0.45 μm pore size (Kalbitz et al., 2000), is produced through microbial decomposition of organic materials. Major factors influencing soil DOC concentration and export from terrestrial ecosystems can be grouped into the following categories: climatic conditions, land cover (vegetation) composition, hydrological characteristics, soil properties and biogeochemical conditions (summarized in Supplementary Table S1). Terrestrial DOC fluxes arise through the imbalance between production and consumption of DOC. Vegetation, fresh and decomposing litter, and soil OC (SOC) provide substrate for producing DOC (Kalbitz et al., 2000; Neff and Asner, 2001). Climatic factors (e.g., atmospheric CO_2 concentration, temperature and precipitation) constitute important drivers, as they impact vegetation composition and primary production, in turn affecting both the quantity and quality of litter inputs for producing DOC (Jennings et al., 2010). Apart from the biological production of DOC, desorption of soluble OC immobilised by accretion to soil particles could also release DOC into soil water (Neff and Asner, 2001; Yurova et al., 2008; Moore, 2013). DOC sinks, on the other hand, include microbial mineralization and adsorption by soil surfaces. Microbial mineralization (degradation and release as respiratory CO_2) as a biological sink of DOC, is linked to microbial activities (Parton et al., 1987), and is negatively related to the recalcitrant fraction of the DOC pool (Kalbitz et al., 2003). The microbial mineralization of both SOC and DOC is sensitive to soil temperature (Freeman et al., 2001) and soil moisture conditions (Kalbitz et al., 2000). Adsorption by soil surfaces, as a physical sink of DOC, has been linked to soil texture (mainly clay fraction) (Parton et al., 1987), organic compounds (Neff and Asner, 2001), and soil anion exchange and ligand exchange (Kaiser and Zech, 1998). Hydrological flow conditions and flow paths determine export of produced and desorbed DOC from terrestrial ecosystems (Ågren et al., 2007; Olefeldt and Roulet, 2014).

In subarctic and boreal regions, peatland DOC export can be a significant component of net ecosystem carbon balance (NECB) (Limpens et al., 2008; Öquist et al., 2014). Multi-year observations have revealed that DOC export has the same order of magnitude as the long-term accumulation of organic matter in peatlands for several boreal peatlands (Roulet et al., 2007; Nilsson et al., 2008). The contribution of boreal peatland DOC exports to the whole-catchment carbon balance can also be significant (Öquist et al., 2014). Comparing to boreal peatlands, much less is known about the role of DOC for subarctic peatlands. Olefeldt et al. (2012) found the loss of DOC from nutrient-poor permafrost peatlands is relatively low, mainly due to restricted runoff generation.

A wide range of models depicting DOC fluxes and concentrations in soil and aquatic systems exist, including both statistical (Boyer et al., 1996; Frolking et al., 2002) and process-based models (Currie and Aber, 1997; Neff and Asner, 2001; Yurova et al., 2008; Wu et al., 2013). The process-based models, differing both in complexity and in the spatial scales considered (Manzoni and Porporato, 2009), can be generally divided into three categories. The first category of models focuses on describing physical and geochemical interactions (e.g., sorption to Fe and Al oxides and hydroxides) of organic compounds with soil surfaces, e.g., DocMod (Currie and Aber, 1997), DyDOC (Michalzik et al., 2003) and ORCHESTRA (Lumsdon et al., 2005), but in general are difficult to apply for larger regions and moreover lack consideration of the controlling influence of vegetation. The second category of models, which consider both soil properties and plant litter quality and quantity, includes a synthetic DOC model in TerraFlux (Neff and Asner, 2001) and the CENTURY model (Parton et al., 1994). However, this category typically has less focus on the potential contribution of DOC fluxes from different land cover types that may significantly contribute to variability in DOC export (Laudon et al., 2011). The third category of models accounts for DOC routing and lateral transport across landscapes to aquatic systems, e.g. INCA-C (Futter et al., 2007) and the TOPMODEL-based DOC model (Hornberger et al., 1994), and normally assumes constant litter inputs and/or constant DOC concentrations. An advantage of the latter class of models is that depth of flow is traced, allowing the contributions of organic and mineral soils to the total DOC export to be reconstructed. No current model fully combines the advantages of all three categories of DOC models. Taking our starting point from both the process complexity and limitations of these different model approaches, we propose an implementation of DOC-related processes within a dynamic ecosystem model, LPJ-GUESS (Smith et al., 2001), that links ecosystem soil C cycling, vegetation dynamics and hydrological processes with soil DOC dynamics. Additionally, we also propose an approach to consider lateral DOC routing within the catchment boundary.