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# Computational assessment of sediment balance and suspended sediment transport pathways in subsurface drained clayey soils

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ABSTRACT

Efficient mitigation of environmental loads from agricultural fields to surface waters requires sufficient knowledge of dominating erosion processes and sediment transport pathways. Computational models are often applied in sediment load assessments but their structure inherently includes assumptions and uncertainties, which can hinder their predictive and explanatory capabilities. In this study, a 3D dual-permeability model was applied with field-scale data from a high-latitude site to investigate sediment balances and structural uncertainties in sediment transport components. The two-year data encompassed hourly records of water flow and sediment concentration composite samples from tillage layer runoff and drain discharge in two adjacent clayey fields with different slopes (1% and 5%). Three model structures with different assumptions of sediment transport pathways were built to test their performance against the data. The simulations demonstrated how different model structures can reproduce the data with varying results on sediment balance. The varying results revealed the importance of flow, erosion, and sediment transport observations from the fields to improve the simulations. Structural uncertainty analysis revealed uncertainties which parameter sensitivity analysis could not describe. Concentration data was shown to include more information about erosion and sediment transport processes than solely the load data. The results suggest that a major part (48–69%) of the detached particles remained in the field and that lateral subsurface transport contributed to load generation (10–21% of total loads) especially in the steeper field. The results demonstrated that the majority (84–87%) of sediment loads occurred via subsurface drain discharge and groundwater outflow with the slope gradient of 1–5%, which suggests that load mitigation measures should also be directed to decrease loads via subsurface transport pathways. The simulations demonstrated how transport processes were controlled not only by water flow but also by soil structure.

## 1. Introduction

Detachment and mobilization of particulate soil material from land areas lead to harmful consequences including loss of fertile topsoil in arable areas and eutrophication in surface waters (e.g. Quinton et al., 2010). Soil erosion rates are typically high in agricultural land areas due to tillage operations and periodic lack of vegetative cover (García-Ruiz et al., 2015) and therefore, the arable land areas are of particular interest from the point of view of sediment load mitigation. Factors such as local climatic conditions, terrain topography and land-use are known to impact erosion rates (e.g. Vanmaercke et al., 2011), but the processes and factors leading to erosion and sediment transport are wide-ranging and complex (Vereecken et al., 2016). Understanding of these processes and particle transport pathways is, however, a prerequisite for controlling particle detachment and sediment loads.

Characteristic features of the northern land areas in the Baltic Sea catchment area include wet spring and autumn periods, short growing seasons, and cold winters with seasonal snow cover (e.g. Vagstad et al., 2004). Clayey soils are abundant in the cultivated areas, where subsurface drainage methods are commonly applied to convey excess water from agricultural fields to surface waters (Panagos et al., 2012; Eriksson et al., 1999; Puustinen et al., 1994). In these regions, the main environmental consequence of soil erosion is considered to be the transport of sorbed nutrients on sediment particles to surface water bodies (Ulén et al., 2012). Due to the changing climatic conditions, winter snow depths are going to decrease (Räisänen, 2008) and the amount of erosion is expected to increase (Puustinen et al., 2007). Sediment loads are regularly monitored in field-, plot- and catchment scales in the region (Bechmann 2012; Rankinen et al., 2010; Puustinen et al., 2007; Øygarden et al., 1997). It is widely known that part of the sediment

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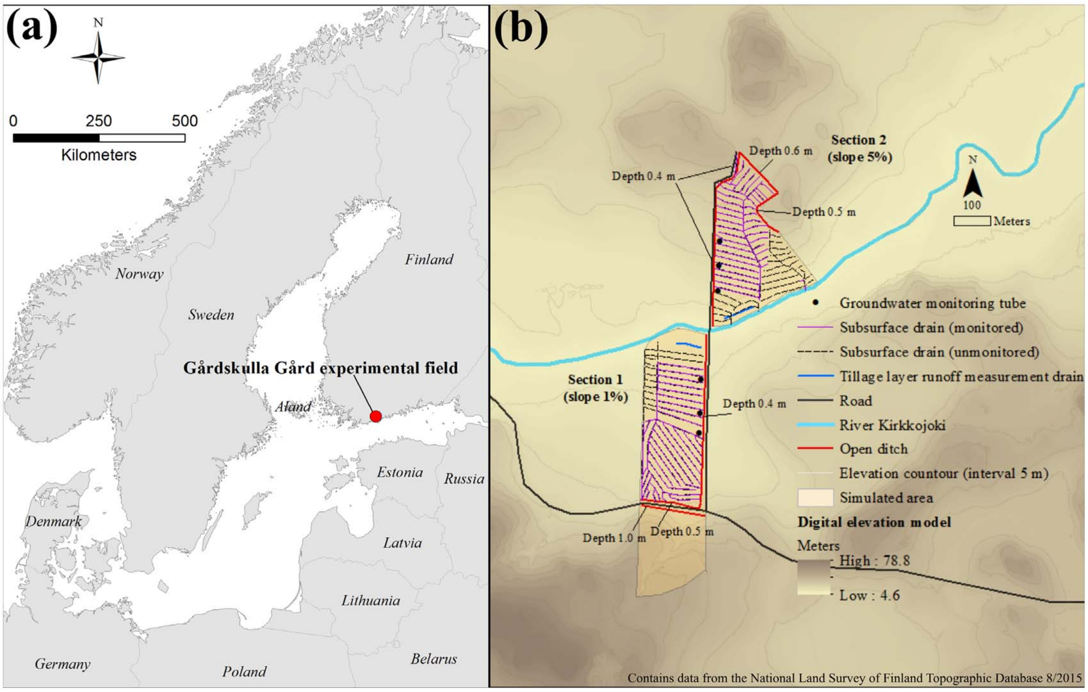


**Fig. 1.** (a) Location of the Gårdskulla Gård experimental field and (b) layout of the two monitored field sections.

load can occur via surface runoff, but a distinct feature of sediment transport in high-latitude clayey soils is the large share of total sediment loss via subsurface drains (Warsta et al., 2013a; Bechmann 2012; Turtola et al., 2007; Uusitalo et al., 2001; Øygarden et al., 1997; Culley et al., 1983). Empirical studies have suggested that suspended sediment can be transported to subsurface drains in both vertical and lateral macropores in soil (Ulén et al., 2014; Nielsen et al., 2010; Øygarden et al., 1997). However, as pointed out by Allaire et al. (2009), lateral transport is far less studied compared to vertical transport, and contribution of these different flow routes to the distribution of eroded particles in different load pathways remains unknown. Furthermore, as the amount of particle detachment is rarely monitored on site, it remains unclear how sediment balances are formed and how much sediment is detached from the soil, deposited back on the field surface or retained in the soil profile.

Computational erosion and sediment transport models are commonly applied to assess sediment processes and their controlling factors (Rankinen et al., 2010; Tattari et al., 2001; Jarvis et al., 1999; Wicks and Bathurst, 1996), and to produce predictions of sediment losses and loads (Nearing et al., 2005; Bhuyan et al., 2002; Zhang et al., 1996). Empirical models such as the Universal Soil Loss Equation can be useful tools for assessing long-term patterns and trends, but spatially and temporally distributed models are required when erosion and sediment transport processes within a field or catchment are of interest (Bryan, 2000). Conceptual models have been reported to yield satisfactory results in terms of spatially lumped sediment load reproduction in clayey areas across different scales (Rankinen et al., 2010; Lundekvam, 2007), but process-based models have a potential to describe erosion processes in more detail. Field-scale process understanding can be beneficial when designing and evaluating erosion mitigation methods, because for example catchment outlet data contains only aggregated information of the processes occurring within the catchment (Wellen et al., 2014) and plot-scale is often considered to provide biased information of the erosion rates (García-Ruiz et al., 2015). However, only few model codes (Warsta 2011; Jarvis et al., 1999) are suitable for describing spatially variable sediment transport on field surface and in the soil profile, and performance of such models has been rarely comprehensively evaluated against long-term concentration and load data representing different pathways.

Since the processes and factors which influence detachment and transport of sediment in clayey soils are not well known, the distinctive features of computational models are their assumptions related to erosion and sediment transport processes. Furthermore, it is well established that different models and parameterizations can lead to a similar fit of calibrated variables against observations but to different results of variables outside the calibration setting (Refsgaard et al., 2006; Højberg and Refsgaard, 2005). Assumptions due to the incomplete knowledge of the studied processes (e.g. choice of hydrogeological model structure and processes included in the model) are often called model structural uncertainties (e.g. Højberg and Refsgaard, 2005). The structural uncertainties have been rarely evaluated in erosion modelling studies, although such an evaluation would be potentially beneficial to reduce uncertainty of erosion and sediment transport models.

The objectives of this study were to (1) produce computational sediment balances of clayey subsurface drained agricultural fields using different model structures and (2) to evaluate impacts of the structures and parameterizations on sediment transport pathways and model performance against sediment load data. Three different model structures were generated with the 3D process-based FLUSH model. The main difference between the structures was the description of subsurface sediment transport pathways in vertical and lateral directions. The reference data included discharge and suspended sediment concentration observations, and data-based estimates of sediment loads from tillage layer runoff and subsurface drain discharge (Äijö et al., 2014). The two-year data period represented winters with intermittent or low snow cover and generation of runoff and sediment loads through all seasons.

## 2. Materials and methods

### 2.1. The experimental site and data

The Gårdskulla Gård experimental site is located in southern Finland (60° 10′ 32″ N, 24° 10′ 17″ E) and consists of two monitored and subsurface drained field sections (1 and 2 in Fig. 1). The study