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Measuring and modelling soil erosion and sediment yields in a large cultivated catchment under no-till of Southern Brazil

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ABSTRACT

Erosion processes can be exacerbated when inappropriate soil conservation practices are implemented. In Brazil, very few measurements are available to quantify the impact of conservation practices on erosion processes in agricultural catchments. The objective of this study is to quantify the impact of different conservation measures on soil erosion and sediment dynamics in an agricultural catchment under no-till of southern Brazil, and to simulate conservation scenarios using a model calibrated with sediment data measured at the catchment outlet. Monitoring was carried out in a large agricultural catchment (800 km^2) of southern Brazil affected by extensive soil erosion and runoff despite the widespread use of no-till. Rainfall, river water discharges and suspended sediment concentrations were monitored during a five-year period (2011–2015). The WaTEM/SEDEM model was then calibrated. Then, four scenarios including a Business-As-Usual (BAU) scenario and the implementation of alternative conservation strategies were simulated, and their impact on erosion, sediment deposition and sediment yield was quantified. All four scenarios were simulated twice, using either rainfall measured during a dry year or during a humid year. All the scenarios including alternative conservation measures drastically reduced erosion and sediment yields, with reductions reaching up to 400% when compared to the BAU scenario. The implementation of mechanical conservation measures such as crop levelling and terracing had the highest impact on soil erosion, and the most effective scenario included the implementation of crop rotation, crop levelling, terracing and the creation of forest protected areas. Model simulations indicated that no-till alone has a low impact on erosion processes and that additional measures increasing the vegetation cover/density of the soil are necessary to significantly reduce sediment transfers in these agricultural areas. The simulations also demonstrate that during wet years, erosion processes increase on average by 33.9% for all scenarios. This study demonstrates that soil losses due to erosion processes remain significant and unsustainable in agricultural catchments of southern Brazil. Soil erosion is exacerbated by the lack of information provided to the farmers and the use of isolated conservation measures without coordination at the catchment scale. Farmers' and local communities' awareness should be raised to reduce soil degradation and sediment transfer to river systems.

1. Introduction

According to Montgomery (2007), soil erosion remains the main mechanism of soil degradation, which threatens the global sustainability of the food production systems (Lal et al., 2012). In tropical and subtropical regions, soil erosion has often been accelerated by improper agricultural practices, and particularly by the failure to implement appropriate soil conservation measures, such as crop rotation, runoff control and contour farming. Several studies showed that soil degradation generates the loss of basic soil properties relevant to the farming system and/or an increase of the production costs (Derpsch et al., 2014; Lal, 2007; Reicosky, 2015).

In southern Brazil, farmers have often reduced conservation agriculture to the use of no-till alone (Reicosky, 2015). However, minimum tillage is not sufficient to control runoff production (Gómez et al., 2003) To be efficient, it should be associated with other measures such as contour farming and terracing to avoid an increase in surface runoff and the occurrence of erosive processes when runoff concentrates (Bertol et al., 2007; Bolliger et al., 2006; Denardin et al., 2008). In addition, the low residue cover of the soil, due to the absence of crop rotation, is insufficient to protect the soil surface against the direct impact of rainfall (Souza et al., 2012).

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Few studies have documented the impacts of no-till farming on runoff and erosion at the catchment scale. However, there is a need to better understand the impact of conservation agriculture on the spatial and temporal dynamics of soil degradation and to identify the combination of control measures that would be the most efficient for controlling losses and transfers of water, soil, nutrients and agrochemicals.

Accordingly, catchment monitoring and modelling should be combined to design effective strategies to reduce the deleterious impacts of intensive farming. In large catchments (Boix-Fayos et al., 2008), the flow response and sediment concentrations can be monitored and related to rainfall and physiographic characteristics (relief, soil, use and management) in order to identify the main factors controlling runoff and sediment generation and their transfer across the landscape. Models can also be used to simulate the spatial and temporal dynamics of hydrological and erosive processes. They can be either deterministic (Knapen et al., 2007; Nearing et al., 1999; Okoro and Ibearugbulem, 2013) or empirical (Foster et al., 2003; Kinnell, 2010) and their performance will depend on the quality of the monitoring data and the availability of the input parameters (Horowitz et al., 2014; Merten et al., 2006). Once they have been calibrated, these models can also be used to simulate the impact of climate change (Nearing et al., 2004), or the effectiveness of various scenarios of conservation practices (Fu et al., 2005; Terranova et al., 2009; Wang et al., 2009) on sediment yields.

Empirical mathematical models based on the Universal Soil Loss Equation (Alatorre et al., 2012; Bezak et al., 2015; Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2002) and incorporating a transport capacity equation, such as WaTEM/SEDEM (Van Rompaey et al., 2001) provide powerful tools to simulate erosion and sediment transport at the catchment scale (De Vente et al., 2008; Poesen, 2011). Studies with WaTEM/SEDEM model have generated satisfactory estimations of soil redistribution on hillslopes (de Moor and Verstraeten, 2008; Notebaert et al., 2011; Verstraeten et al., 2009) and sediment yields from catchments (Haregeweyn et al., 2013; Rompaey et al., 2005). The model has been widely used in different topographic, climatic and soil use conditions (Keesstra et al., 2009; Quiñonero-Rubio et al., 2014; Rompaey et al., 2005). However, to the best of our knowledge, this model has never been applied in large catchments of Brazil despite the very high erosion rates occurring in this region of the world.

The objective of the current research is to quantify the impact of conservation measures on spatial variations of runoff and soil erosion in an agricultural catchment under no-till of southern Brazil. Accordingly, the impact of different conservation scenarios will be assessed through the use of a model calibrated based on 5-yrs monitoring data. The need to combine monitoring and modelling will then be discussed to propose the optimal set of conservation measures for a sustainable soil and water management in this region of the world.

2. Material and methods

2.1. Study area

The Conceição catchment is located in the northwest of the southernmost State of Brazil (Rio Grande do Sul). It drains a surface area of 800 km^2, and the monitoring station is located at the outlet (coordinates: 28°27′22″S and 53°58′24″ W). According to Köppen's classification, the climate is of Cfa type, i.e. subtropical humid without dry season, with an average annual rainfall comprised between 1750 and 2000 mm and an average temperature of 18.6 °C. The geological bedrock is basaltic, and it is overlaid with deep and highly weathered soils (Oxisols, Ultisols, and Alfisols), with the Oxisols being the dominant soil class in the catchment. These soils are enriched in iron oxides and kaolinite. The landscape is characterized by gentle slopes (6–9%) on the top and on the hillsides, whereas steeper slopes (10–14%) are found near the drainage channels. The main crops are soybean (*Glycine max*) during summer and wheat (*Triticum spp.*), oats (*Avena strigosa*), and ryegrass (*Lolium multiflorum*) during winter. The two latter crops provide straw for mulching during summer and these fields may also be used as pasture for dairy cattle. No-tillage is applied on > 80% of the cropland, without the implementation of additional erosion control measures such as terraces, strip cropping, vegetated ridges, or contour-farming. Other land uses including forests, wetlands, and urban areas cover less than 15% of the total catchment surface area.

The riparian areas found along the permanent river network are narrow (< 10 m wide) and affected by cattle trampling, which prevents them from providing effective traps to stop sediment originating from upper parts of the catchment. The current land cover distribution in the catchment was used to define a business-as-usual (BAU) scenario representative of the conditions found in areas dedicated to intensive grain farming in southern Brazil.

2.2. Hydro-sedimentary monitoring

River monitoring was conducted during a 5-year period, from January 2011 to December 2015. Rainfall (R), river discharge (Q) and suspended sediment concentrations (SSC) were measured automatically at the catchment outlet every 10-min. In addition, manual measurements were made every 30–60 min during flood events.

River discharge (Q) was estimated from water level measurements using a limnigraph at the outlet station, through the conversion of pressure values into flow using the appropriate discharge rating curve calculated for the monitoring section. Consistence of this continuous monitoring data was compared to the daily measurements made by a local observer. SSC dta were acquired in 10-min intervals indirectly using a turbidimeter. Signals (mV) were converted into NTU by using Polymer bead calibration solutions and the NTU was converted into SSC by using the SSC equation obtained from daily manual samples using a DH-48 sampler (USGS).

Samples collected during flood events were brought back to the Sedimentology Laboratory at the Federal University of Santa Maria, Brazil, to determine SSC after evaporation and filtration of the samples (Shreve and Downs, 2005). In addition to the traditional sampling methods, a turbidity meter was used to increase the frequency of measurements. It was calibrated using SSC data acquired simultaneously, following the method described by (Merten et al., 2006; Minella et al., 2008).

Suspended solid discharge SSD (kg s^{-1}) was estimated by multiplying instantaneous Q (Ls^{-1}) and SSC (gL^{-1}) data. SSD was then used to calculate sediment yield (SY; t $year^{-1}$), (Porterfield, 1977).

2.3. Modelling erosion processes

Erosion processes were simulated using the spatially-distributed WaTEM-2000 model (Van Rompaey et al., 2001) developed to estimate water and tillage erosion, sediment deposition and to quantify sediment supply to the river channels. The model is divided into three modules: (I) assessment of annual soil loss using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997); (II) evaluation of the annual sediment transport capacity (Van Rompaey et al., 2001; Verstraeten et al., 2002), and (III) simulation of the sediment transfer pathway. The annual average of the gross soil erosion (E; kg m^{-2} $year^{-1}$) is calculated for each pixel using Eq. (1):

$$E = R*K*LS_{2D}*C*P \quad (1)$$

Where R is the rainfall erosivity factor (MJ mm m^{-2} h^{-1} yr^{-1}), K is the soil erodibility factor (kg h MJ^{-1} mm^{-1}), LS_{2D} is a parameter reflecting the slope steepness and length based on the algorithms of Desmet and Govers (1996), and the slope factor LS_{2D} is adjusted using a two-dimensional routing algorithm (Van Oost et al., 2000) to account for rill, inter-rill and gully erosion (Desmet et al., 1999), C is soil coverage factor (including biomass and mulch depending on soil use and