# Quantifying the impact of no-tillage on soil redistribution in a cultivated catchment of Southern Brazil (1964–2016) with $^{137}Cs$ inventory measurements

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Elizeu Jonas Didoné[1] (*), Jean Paolo Gomes Minella[1], Fabio José Andres Schneider[1], Ana Lúcia Londero[1], Irène Lefèvre[2], Olivier Evrard[2]

[1]Universidade Federal de Santa Maria (UFSM), Department of Soil Science, 1000 Avenue Roraima, Camobi, CEP 97105-900, Santa Maria, RS, Brazil

[2]Laboratoire des Sciences du Climat et de l'Environnement (LSCE/IPSL), UMR 8212 (CEA/CNRS/UVSQ), Université Paris-Saclay, Centre CEA Paris-Saclay, l'Orme des Merisiers, bât. 714, 91191 Gif-sur-Yvette Cedex, France.

**(*) Corresponding author:**

Elizeu Jonas Didoné

Avenida Roraima n° 1000, Prédio 42, sala 3311ª, Santa Maria-RS-Brazil, CEP: 97105-900

Phone +55(55)999718525.

**E-mail**: didoneagroufsm@gmail.com

## Abstract

No-tillage is a soil management practice that results in reduced soil losses when compared to conventional tillage systems. However, when this practice is overly simplified, it may lead, over the years, to higher levels of soil loss than expected. In this context, this study sought to compare the rates of long-term soil redistribution on three hillslopes used for grain production under different soil management on deep weathered soils (Ferralsols) in southern Brazil. Soil samples were collected along three transects in different hillslopes characterized by either no-tillage or conventional tillage. Cs-137 inventories were used to estimate the soil redistribution rates based on Mass Balance Model - 2. The results indicate that along the three slopes and during the last five decades, changes in soil management impacted the patterns of soil erosion in the landscape, showing the occurrence of significant soil loss in the upper and

backslope segments, and deposition in the lower parts of the three hillslopes studied. Even with no-tillage, erosion has continued to occur, although at lower rates when compared to conventional tillage. The use of the $^{137}Cs$ marker associated with the Mass Balance Model - 2 (MBM - 2) conversion model provided an effective tool for estimating soil redistribution rates under different management systems. Although the introduction of no-tillage in the last 28 years has reduced erosion rates, these processes remain significant and the implementation of additional runoff and/or erosion control practices is recommended in order to keep erosion rates at sustainable levels.

**Keywords**: Soil erosion; direct sowing; soil loss; agriculture; fallout radionuclides.

## 1 Introduction

No-tillage, which occurs in an area of more than 32 million hectares of agricultural land, is the main strategy for soil and water conservation in Brazil (Kassam et al., 2018). The gradual shift from conventional to no-tillage has improved soil management (Reicosky, 2015), through the reduction of soil and water losses due to erosion (Deuschle, et al., 2019) and positive modifications of chemical, physical and biological properties of the soil (Derpsch et al., 2014).

In Southern Brazil, no-tillage has been a good example of soil conservation practice (Cassol et al., 2003, Bertol et al., 2007 and Merten et al., 2015) given its efficiency in controlling soil erosion when compared to conventional tillage which causes greater soil disturbance. While under conventional tillage soil losses can exceed dozens of tons per hectare and per year, no-tillage is associated with much lower erosion rates comprised between 1-2 Mg $ha^{-1}$ $year^{-1}$ (Cassol et al., 2003, Cogo et al., 2007). Intensive agriculture started in the 1960s in Southern Brazil, a period during which conventional tillage was systematically implemented generating high soil losses, reaching values up to 40 Mg $ha^{-1}$ $yr^{-1}$. These high erosion rates called attention to the need to implement conservation measures to reduce the degradation of soils and water bodies. In the 1990s, in the framework of the so-called ‘conservationist’ approach, the no-tillage system became widespread along with other conservation measures such as contour farming all of which aimed  to reduce soil losses (Bertol, et al., 2004; Cogo, et al., 2007; Denardin et al., 2008).

However, the efficiency of no-tillage to control soil losses does not guarantee the control of runoff (Merten et al., 2015; Londero et al., 2018; Deuschle, et al., 2019) which can cause concentrated erosion in thalwegs. In addition,  excess runoff may deliver high amounts of sediment, nutrients and pesticides to water bodies, leading to the degradation of riverine habitats and water quality as demonstrated by Tiecher et al. (2018). Studies conducted on cultivated hillslopes in Southern Brazil suggest that implementing of no-tillage as a single conservation measure is insufficient to control runoff. Londero et al. (2018) showed that runoff coefficients might be as high as  21%  on fields where this practice is implemented. The simplification of the agricultural production system has also likely contributed to the increase of sediment supply to water bodies in this region (Didoné et al., 2017; Tiecher et al, 2018).

Traditional soil erosion assessment methods (i.e. plot monitoring) are associated with several drawbacks, and there is a need for alternative and retrospective techniques. To this end, several investigations have used radionuclides as tracers, in order to document soil redistribution rates and spatial patterns across landscapes (Ritchie and McHenry, 1990, Walling and Quine, 1995). The use of tracers avoids time-consuming and expensive operations required for long-term monitoring (Ritchie and Ritchie, 2008; Li et al., 2011; Mabit et al., 2013).

Among these potential tracers, caesium-137 ($^{137}$Cs), which is an artificial radionuclide produced during nuclear tests and accidents (Zapata, 2002), is characterized by a strong affinity for fine soil particles and has therefore been widely used to quantify soil erosion and deposition rates based on the measurement of its inventories in soil profiles (Davis, 1963; Ritchie and McHenry, 1990; Oztas, 1993, Ritchie and Ritchie 2007). Although its use has been recently debated in the literature (Mabit et al., 2013; Parsons and Foster, 2011), $^{137}$Cs has been increasingly used worldwide (Mabit et al., 2008, 2009; Chartin et al. 2013) to estimate the erosion and deposition rates since its emission into the environment (i.e., 1954-1963; Ritchie and McHenry, 1990; Walling and He, 1997; Zapata, 2002; Mabit *et al*., 2008).

Most of the sedimentological and erosion studies using radionuclides have been conducted in the northern hemisphere (Walling and Quine, 1992; Zapata, 2002; Ritchie and Ritchie, 2008; Chartin et al, 2013). However, although less often, this technique has also been applied in the southern hemisphere, including in South America (e.g., Schuller et al. (2004, 2007). In Brazil, the feasibility of the $^{137}$Cs tracer technique was verified for different soil types and land uses (e.g Schuch et al. (1994b), Bacchi et al. (2000), Andrello et al. (2002), Antunes et al. (2010) and Minella et al. (2014)). However, these studies did not specifically consider the impact of soil management (no- and conventional tillage) on the long-term soil redistribution by erosion and deposition.

In this context, the Cs-137 inventory technique could be useful to demonstrate the potential mitigation of soil erosion after no-tillage was introduced in the 1990s, after 30 years of conventional tillage. Currently, there are few quantitative information on how the improvement of soil management may have led to a decrease in the long-term magnitude of erosion and deposition on cultivated hillslopes under these farming systems. In this context, this study seeks to compare the long-term soil redistribution by erosion in Ferralsols on three hillslopes under different soil conservation management methods in Southern Brazil in order to quantify the impact of no-till over the last several decades.

## 2. Materials and methods

### 2.1 Study site and hillslope characteristics

The study was carried out on three agricultural hillslopes of Southern Brazil (Fig. 1), located in the Conceição River experimental catchment (Didoné et al., 2017). The geological bed-rock is basaltic overlaid with deep and highly weathered soils with Ferralsols being the dominant soil type (FAO, 2014). These soils contain high amounts of clay (45-60%) composed by kaolinite and oxides. Despite the excellent physical structure of this soil type, it is highly sensitive to compaction (Reichert et al., 2016). 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 catchment is predominantly cultivated with soybean using no-tillage as the main soil management practice, although runoff control and crop rotation are not implemented. Only low densities of biomass (i.e. the residues of previous crops) protect the soils against the erosive power of rainfall.

**Figure 1 - Location of Conceição river catchment with the three hillslopes investigated in details.**

In order to choose hillslopes representative of the agricultural systems present within the Conceição river catchment, a preliminary field investigation was carried out to determine hillslope features. Three hillslopes – with 12% gradient, minimum 90 m length, Ferralsols and contrasted soil management – were selected (Hillslope I, Hillslope II and Hillslope III). They are described in Table 1. All three slopes present similar geomorphological features (Fig. 2).

**Figure 2 - Characteristics of the selected hillslopes and individual soil core sampling sites in the Conceição river catchment, Brazil: Hillslope I, Hillslope II and Hillslope III.**

Land use information was obtained through interviews with farmers who have owned and workedthese fields for over 40 years (Tab.1). This information was compiled for three main cultivation periods in the investigated region, i.e. (1) from 1960 to 1979, (2) from 1980 to 1999 and (3) from 2000 to 2016.

Each hillslope is representative of one of the three main farming systems used in Southern Brazil (conventional tillage (Hillslope I) and two different no-tillage conditions (Hillslopes II and III)) since cultivation was intensified in the 1960s. However, it is important to emphasize that both Hillslopes II and III had been under conventional tillage in the past (1960- 1990s).

**Table 1 - Main characteristics of the three hillslopes investigated**

Despite these differences, Hillslope I is one of the few slopes still under conventional tillage in the region. It is noteworthy that Hillslope I is 2/3s shorter in length than Hillslopes II and III (Tab.1). Crop fields with either soybean or corn production under conventional tillage are not commonly found in areas with a similar relief and soil type as Hillslopes II and III. Despite the shorter length, the slope/length (LS factor) in the Hillslope I is lower than that of the other hillslopes, the deposition rates are high (toeslope) reflecting the system of cultivation in addition to being the highest slope (Fig. 1).

In the 1960s, with the onset of farming activities in the region, native forests were removed from Hillslopes I, II and II. Since then, Hillslope I has been kept under conventional tillage until present day. The main crops, cultivated over the last decades, are corn, millet, soybeans and winter pastures. In Hillslope II, the conventional tillage system with broad-based terraces was implemented between the 1960s and 1990s, and the main crops were grains (corn, wheat and soybean) and winter pastures. Subsequently, no-tillage was introduced and the terraces were gradually removed. The crops in the region remained the same, although soybean has been increasingly cultivated. In contrast, in Hillslope III, the native forest was replaced by pasture areas and, later, by cropland under conventional tillage which was implemented until the 1990s with terraces. Later, with the onset of no-tillage terraces were removed; however, from 2000 onwards, crop rotation was introduced and, consequently, a higher amount of biomass added though crop rotation which led to better soil cover and protection against erosion.

## 2.2 Soil sampling and Cs-137 analyses

Three samples from each of the three profiles (summit, backslope and toeslope) were collected and evaluated in order to characterize each hillslope(Schoeneberger and Wysocki, 2012). In this study, in order to limit the analytical costs and the logistical requirements, the technique was only tested on three slopes and on a limited number of soil profiles, although in future studies a larger number of slopes and points will potentially be analyzed. A local reference site under natural pasture without evidence of soil erosion and/or deposition was also selected.

Soil depth collected for the different profiles varied depending on their position in the landscape, and on the occurrence or the absence of soil redistribution at these locations. These samples were collected using a 1-meter long core tube (surface area of 33.2 $cm^2$) inserted at a sufficient depth to include the full depth of soil containing $^{137}Cs$. The soil profile was sampled up to 40 cm in the summit and backslope positions and 140 cm in toeslopes. The soil cores were sectioned into 3-cm increments, oven-dried at 102°C and sieved to 2 mm. Bulk density was systematically measured for each level. The soil profiles from the reference area were subdivided into 2-cm increments to provide in details $^{137}Cs$ activity variations within soildepth.

For each sample (n=150), approximately 70 g of material was sealed airtight in 60 mL polypropylene containers, and $^{137}Cs$ was measured at 662 keV for 85,000 to 200,000 seconds by gamma spectrometry using the low background GeHP detectors available at the *Laboratoire des Sciences du Climat et de l'Environnement* (Gif-sur-Yvette, France). Measured activities were decay-corrected to the sampling date. Counting efficiencies and reliability were checked using certified International Atomic Energy Agency (IAEA) standards (e.g., IAEA-444, 135, 375, RGU-1 and RGTh-1). Uncertainties on $^{137}Cs$ activities did not exceed 10%. As the peak of $^{137}Cs$ fallout was recorded in the southern hemisphere in 1963, which was used as the initial year for evaluating soil redistribution across the landscape (Correchel et al., 2005; Bacchi et al., 2011 and Minella et al., 2014).

## 2.3 Conversion model

Models are applied to the sequence of $^{137}Cs$ measurements carried out along individual transects, so that estimates of deposition at individual points can be based on the $^{137}Cs$ content of sediment eroded from upslope areas, with the $^{137}Cs$ activity of eroded soil being inversely related to the erosion rate (Walling and He, 1997; Walling et al., 2002, 2011; Walling et al., 2014). The use of $^{137}Cs$ fallout measurements to estimate soil erosion and deposition rates is based on a comparison between $^{137}Cs$ inventories for individual sampling points and the local reference inventory. When $^{137}Cs$ inventories are lower than the local reference value, they correspond to erosion, whereas greater inventories indicate deposition. The model calculates the potential changes in the erosion/deposition rates between 1963 and 2016.

In this study, the $^{137}Cs$ measurements obtained for the sampling sites were used in the Mass-Balance Model 2 - MBM-2 (Walling et al., 2002, 2011) developed for cultivated soils. The model (Eq. 1) takes account of changes in the $^{137}Cs$ content of the soil profile over time in response to fallout input, such as, losses due to erosion, additions due to deposition and progressive incorporation of fresh soil from beneath the original plough horizon by tillage, as the soil depth is reduced by erosion, and radioactive decay.

$$\frac{d\,A(t)}{dt} = (1-\Gamma)I\,(t) - \left(\lambda + P\,\frac{R}{d}\right)A\,(t) \qquad (Eq. 1)$$

where: A(t) = cumulative $^{137}Cs$ activity per unit area (Bq $m^{-2}$); R = erosion rate (kg $m^{-2}$ $yr^{-1}$); d = cumulative mass depth representing the average plough depth (kg $m^{-2}$); $\lambda$ = decay constant for $^{137}Cs$ ($yr^{-1}$); I(t) = annual $^{137}Cs$ deposition flux (Bq $m^{-2}$ $yr^{-1}$); $\Gamma$ = percentage of the freshly deposited $^{137}Cs$ fallout removed by erosion before being integrated into the plough layer; P = particle size correction factor.

The plough depth varied over time depending on the changes in farming practices observed in the study area. Under conventional tillage, which was implemented in all hillslopes prior to the 1990's, the tillage depth was estimated at 20 cm. Under no-tillage, this depth was estimated at 5 cm because of the soil disturbance caused by the sower. As highlighted by Walling et al. (2007), the model includes the time-variant fallout input and the fate of the recently deposited fallout before its incorporation into the plough layer by cultivation.

## 3. Results and discussion

### 3.1 $^{137}$Cs inventories

The $^{137}$Cs inventory at reference sites was 393±75 Bq m$^{-2}$, and 70% of this amount was found in the uppermost soil layer, i.e. down to 12 cm depth (Fig. 3). This confirms the limited disturbance of the soil profile at this location since the main fallout period and the relatively low migration of $^{137}$Cs into soil depth, which is likely driven mainly by biological activities (Jagercikova et al., 2014, 2015).

The reference value obtained in our study remained very close to that of 398 Bq m$^{-2}$ found by Minella et al. (2014) while investigating three reference sites in a nearby region (200 km) located at a similar latitude in Southern Brazil.

**Figure 3 - Distribution of $^{137}$Cs with depth at the reference site**

The global pattern of bomb-derived $^{137}$Cs fallout indicates that inputs ranged from about 160 to about 3,200 Bq m$^{-2}$ depending on the latitude (Davis, 1963; Ritchie and McHenry, 1990; Garcia Agudo, 1998). In the southern hemisphere, $^{137}$Cs concentrations in reference areas may vary significantly. Schuller et al. (2004, 2007) found 525 ± 12 Bq m$^{2}$ in southern Chile, in a reference area with an average precipitation of 1,100 mm yr$^{-1}$. Andrello et al. (2007) found values between 296 and 369 Bq m$^{-2}$ in the Paraná State, Southern Brazil, with average annual rainfall of 1,615 mm yr$^{-1}$. Schuch et al. (1994b) found reference values around 329 Bq m$^{-2}$ in the state of Rio Grande do Sul, which is characterized by a mean rainfall of 1800 mm yr$^{-1}$.

The range of $^{137}$Cs inventories in Hillslope I varied from 138 to 1400 Bq m$^{2}$ along the slope, indicating that sediment redistribution by erosion has been significant under this farming system. The pattern on Hillslope I is characteristic of a slope that has undergone severe erosion, with lower $^{137}$Cs inventories on the backslope and a high accumulation of $^{137}$Cs in the toeslope position (1,400 Bq $m^2$), which reflects that the farming system implemented on this hillslope led to significant deposition of material at the base of this slope. The increase in erosion (reflected by a reduction in $^{137}$Cs inventories) along Hillslope I is due to the soil being exposed to erosive agents, which has favored the amplitude of these processes over the years. Moreover, the absence of crop residue on the surface has increased the ability of rainfall to disaggregate the soil, especially when it concentrated in the furrows oriented in the same direction as the main slope gradient (Cassol et al., 2003; Morgan, 2005).

Figure 4 shows the redistribution of the $^{137}$Cs inventory along Hillslope I under conventional tillage.

**Figure 4 - Distribution of $^{137}$Cs inventories with depth in soil profiles collected on (A) the summit, at (B) the backslope and on the (C) toeslope of the Hillslope I.**

Considering that Hillslope I underwent more soil degradation due to a much longer period under conventional tillage (60 years compared to 30 years for Hillslopes II and III), higher $^{137}$Cs inventories at backslope position were expected on Hillslopes II and III when compared to Hillslope I. However, values found at the summit and backslope locations of Hillslope I were similar to those found in Hillslopes II and III.

The Hillslope II and III slope patterns also reflect the occurrence of erosion in the main slope and deposition on the toeslope, which was expected. However, despite the significant change in soil management that occurred over the last 30 years with the onset of no-tillage, there were no significant differences in the magnitude of $^{137}$Cs inventories found in the summit or the backslope positions.

The major difference between these systems was found at the depositional sites. On the two slopes under no-tillage (Hillslope II and III), $^{137}$Cs inventories were significantly lower than in Hillslope I under conventional tillage while remaining higher than those found in the reference area, indicating the occurrence of deposition.

Although in Hillslope II, no-tillage was introduced in the 1990s, $^{137}$Cs inventory was higher in the backslope position when compared to the other hillslopes indicating the occurrence of significant erosion. In addition, particularly high $^{137}$Cs inventories were found in the toeslope. Figure 5 shows the distribution of $^{137}$Cs inventories in Hillslope II.

**Figure 5 - Distribution of $^{137}$Cs inventories with depth in soil profiles collected on (A) the summit, at (B) the backslope and on the (C) toeslope of the Hillslope II.**

The inventory of $^{137}$C was only 76 Bq m² in the backslope of Hillslope III, indicating the occurrence of severe erosion (Figure 6).

**Figure 6 - Distribution of $^{137}$Cs inventories with depth in soil profiles collected on (A) the summit, at (B) the backslope and on the (C) toeslope of the Hillslope III.**

The lowest inventory value of $^{137}$Cs found in the backslope of Hillslope III can likely be explained by the occurrence of erosion before the implementation of no-tillage in the early 1990s, or by the lack of additional soil conservation measure implemented with no-tillage since this period.

Regarding the different slopes, the inventories of $^{137}$Cs for the summit position of the slopes are of 234, 246 and 202 Bq m$^{-2}$ for Hillslopes I, II and III respectively. The difference between these values is small although significant, which may be explained by the low slope gradient (< 2%) and the large impact of tillage when this practice was generalized in the region (1960-90s). The mean $^{137}$Cs inventory for the three Hillslopes (I, II and III) in eroding areas was 186, 249 and 139 Bq m$^{-2}$ respectively, while the mean values recorded in depositional Hillslopes (I, II and III) areas were 1400, 1124 and 447 Bq m$^{-2}$ respectively. These distinct $^{137}$Cs inventory values indicate the occurrence of significant spatial redistribution of $^{137}$Cs across those hillslopes under different management systems.

## 3.2 Model of conversion of $^{137}Cs$ inventories into redistribution rates

The results provided by the conversion model for the three slopes demonstrate the magnitude of the erosive processes under contrasting management practices during the last 55 years (1960-2016). The corresponding soil redistribution rates calculated with the MBM - 2 are provided in Table 2.

**Table 2 - Results of the conversion of the cesium 137 inventories into soil redistribution rates for each transect.**

The MBM-2 determined that mean erosion rates occurred with different intensities. It may be expected that the currently observed patterns of $^{137}Cs$ inventories mainly reflect the redistribution of soil across the landscape in the 1960s, when agriculture expanded in the region (Moreno, 1972; Bernardes, 1997). When evaluating the mean erosion rates in Hillslope I, an erosion value of 28 Mg $ha^{-1}yr^{-1}$ was observed at the summit position while a mean value of 57 Mg $ha^{-1}yr^{-1}$ was found at the backslope position. When analyzing the traditional studies of soil erosion losses using the Wischmeier & Smith plot methodology (1978) under the conditions prevailing in the study area (i.e., climate, topography, soil type and management), Cogo et al. (2003) found mean values of 13 Mg $ha^{-1}$ $yr^{-1}$ for sites with 8-12% slope, after two years of monitoring. Furthermore, Beutler et al. (2003) found soil losses of 6.1 Mg $ha^{-1}$ $yr^{-1}$ under the same experimental conditions. Soil erosion was particularly severe for the hillslope under conventional tillage. According to Bertoni & Lombardi Neto (1993) and Bertol & Almeida (2000), the soil loss for similar clay soils are comprised between 13 and 15 Mg $ha^{-1}$ $yr^{-1}$ under conventional tillage. Nowadays, this cultivation system has become very unusual in the study area, and its use is currently restricted to prepare the soil for annual pasture areas and the cultivation of subsistence crops (cassava, potato, vegetables, etc.)

The erosion rates at the summit positions on Hillslopes II and III were 25 and 38 Mg $ha^{-1}yr^{-1}$, respectively, while at the backslope they reached 18 and 87 Mg $ha^{-1}yr^{-1}$. Cogo et al. (2003)

and Beutler et al. (2003) determined soil losses varying between 0.8-1.2 Mg $ha^{-1}yr^{-1}$ in a period of five years under similar farming conditions. Bertol et al. (2007) quantified that no-tillage may lead to a reduction of 57% in water losses and 88% in soil losses, when compared to conventional tillage, because it provides a denser soil cover. The tolerable soil loss for Ferralsols in Southern Brazil is estimated between 12-15 Mg $ha^{-1}$ $yr^{-1}$ (Eltz et al., 1984; Bertol and Almeida, 2000; Cogo et al., 2003).

Estimates of soil redistribution rates obtained by sampling individual points on the transects of the three Hillslopes (I, II, III) indicated that annual erosion rates for summit and backslope erosion sites were 30 and 54 Mg $ha^{-1}$ $yr^{-1}$ respectively, with a mean deposition value of 111 Mg $ha^{-1}$ $y^{-1}$ in the toeslope. In contrast, when we compare only Hillslopes II and III, the erosion average values are practically the same for the summit and backslope positions (31 and 52 Mg $ha^{-1}$ $yr^{-1}$), although the mean rate found in the toeslope is reduced to 66 Mg $ha^{-1}$ $yr^{-1}$.

When comparing erosion values determined based on the $^{137}Cs$ inventory method with those reported in erosion studies based on the monitoring of standard erosion plots under natural rainfall (77 $m^2$), the values presented in Table 2 can be considered to be high. Values of 1 to 15 Mg $ha^{-1}$ $yr^{-1}$ were commonly observed for fields planted with annual crops under no-tillage and conventional tillage, respectively, on slopes with gradients comprised between 8-12% (Cogo et al., 2003; Beutler et al., 2003). However, the average value determined in the current research based on $^{137}Cs$ inventories was 54 Mg $ha^{-1}$ $yr^{-1}$ (Tab. 2), which is up to one order of magnitude higher than the values commonly observed in similar conditions during classical field monitoring. This may be due to the longer slope lengths evaluated in this study when compared to traditional plot studies and the longer period over which the rates derived from $^{137}Cs$ inventories were calculated, including a period of conventional tillage.

While the standard plots are generally a few meters long and show a rectilinear curvature, our study considered the entire hillslopes with complex curvature, which could, as shown by our findings, enhance soil erosion. These variable conditions explain why a wider range of erosion rates may be found, mainly in the backslope position with much higher erosion levels than those reported in the traditional plot monitoring studies. In addition, Morais & Cogo (2001) and Barbosa et al. (2012) concluded that the positive impact of denser covers of crop residues to slow down runoff under no-tillage may be less significant over long hillslopes, when the flow accumulates.

In contrast, the erosion rates found on the summit of the three investigated slopes remained in the same order of magnitude as those obtained in plot studies conducted in Southern Brazil under conventional tillage. Of note, there is no significant difference in the mean erosion rates for Hillslopes II and III which have been under no-tillage since 1990s, when compared to those found for Hillslope I which has remained under conventional tillage during this period.

These observed patterns reflect mainly the soil redistribution that started in the 1960s, when intensive agriculture expanded in the region. Furthermore, in addition to water erosion, tillage erosion removed progressively the upper layers of the soil in convexities (i.e. summit and backslope positions), with redistribution of material along the concave positions of the landscape (i.e. toeslope).

According to Moore et al. (1993) and Wilson & Gallant (1996), the shape of the slope affects soil erosion and influences the amount and the intensityof runoff. While convex slopes increase the intensity of flow, detachment and transport capacity, flow speed decreases in concave slopes where deposition may occur (Morgan, 2005). This can be observed for the three studied slopes, especially in Hillslopes II and III, where the longer length increased erosion, and prevented deposition. Moore and Burch (1986) showed that the shape of the slope can be even more important than its length, while Govers et al. (1994) concluded that erosion on convex slopes may be greater than in more uniform slopes. This is illustrated on Hillslope I which, despite its shorter slope length, shows higher erosion / deposition rates than the other slopes investigated in the current research.

This demonstrates that conservation measures such as no-tillage, without additional measures are not sufficient to control soil erosion and redistribution of sediment along the slopes. Thehe absence of additional conservation measures (mechanical / vegetative) may have accelerated the soil redistribution along the slopes. Hillslopes II and III were cultivated under conventional tillage for 30 years before the no-till introduction in 1990s (Tab. 1). Soil compaction has accelerated runoff in particularly sensitive sections of the hillslopes, increasing the connectivity of runoff and sediment across the landscape and their increased supply to the rivers (Le Gall et al., 2017, Tiecher et al., 2018). Although Ferralsols are more resistant to erosion than other soil types, they are sensitive to soil compaction. Accordingly, under no-tillage and with a low biomass cover of the soil, they may be exposed to accelerated erosion.

The soil redistribution rates determined from the $^{137}Cs$ inventories calculated in this study correspond to the mean annual erosion rates for the last 55 years, although they may necessarily reflect variations in these erosion rates associated with the main changes in land use and soil management throughout time.

An average loss of 3 mm $yr^{-1}$ between 1963-1990 was found for the three slopes. Studies from a wide range of environments and geological settings showed that soil erosion rates under conventional agricultural practices almost systematically exceeded 0.1 mm $yr^{-1}$, with mean values >1 mm $yr^{-1}$ (Montgomery 2007). From 1990 onwards, losses were considered to be constant for Hillslope I,while soil losses on Hillslopes II and III were reduced to 2.6 and 0.5 mm $yr^{-1}$, respectively, as a result of a more sustainable management. Van Oost et al. (2007) estimated based on a compilation of $^{137}Cs$ inventory measurements that the global erosion rates ranged from 0.4 to 2.3 mm $yr^{-1}$, and the values found in our study,therefore, remain in the same order of magnitude.

Cumulative soil erosion until 1990 was estimated for the three slopes investigated in this study to an average of 84 mm. After the 1990s, cumulative soil losses under no-tillage for Hillslope II were estimated to 71 mm, compared to 19 mm for Hillslope III under simplified tillage and 74 mm for Hillslope I under the conventional system. Current agricultural techniques (Hillslope I) generate higher rates of erosion when compared to mechanized systems under no-tillage (Govers et al., 1996; Van Oost et al., 2006).

The interaction of sediment sources, their transfer and deposition in the landscape is highly complex. However, the use of no-tillage in association with additional mechanical measures (terracing and contour farming) has fallen in disuse, and only no-tillage has remained the main conservation system. According to Tiecher et al., (2014), cropland was the main source of sediment delivered to the rivers in the investigated region, and Didoné et al., (2015) modelled that approximately 18% of the sediments produced in the cultivated areas were delivered to the rivers, with the remaining 82% being redistributed on the hillslopes mainly at the base of the slopes.

## 4 Future challenges

### 4.1 Recommendations for soil conservation in Southern Brazil

Although no-till is currently the main cultivation system in the region, the current research demonstrates that soil continues to be eroded and massively transported to lower landscape locations. Accordingly, additional soil conservation measures should be implemented in association with no-tillage to improve infiltration and, consequently, reduce soil losses and the deleterious impacts that they generate in river systems. Additional soil conservation measures such as contour farming, strip cropping and terracing should be associated with no-tillage.

A strategy combining the installation of measures at the source and that of physical barriers along the main flow pathways in the catchment with the use of terracing and/or strip-cropping for example may lead to an effective increase of productivity and a reduction of water losses and sediment/nutrients/pesticides delivery to rivers in this region. Furthermore, it is necessary to investigate the connectivity achieved by landscape features between the agricultural areas (slopes) and the water bodies considering the different systems that compose the landscape (roads, tracks, pastures, sunken lanes, field drains, ditches, banks, culverts and permeable field boundaries). The impact of connectivity between the areas seems to be even more important than the local erosion rates (Boardman et al., 2019).

4.2 Recommendations for future research

Although the $^{137}Cs$ inventory method was shown to have a high potential in determining sediment redistribution rates along hillslopes in southern Brazil, this technique should be applied on a larger scale and in contrasted environments to quantify soil redistribution rates across wider regions. So far, this technique has been applied to individual hillslopes, transects or local catchments (Porto et al., 2014; Minella et al., 2014). Proposing upscaling methods to implement similar techniques at the large catchment scale while minimizing logistical and analytical constrains would be very useful.

## 5. Conclusions

Despite the logistical and analytical constrains that limit the number of samples that may be analyzed, the $^{137}Cs$ inventory method provides one of the few methods available to reconstruct soil redistribution during the last several decades. This is particularly useful in Southern Brazil, where different management systems have been implemented since the intensification of agriculture in the 1960s, which coincides with the main radiocesium fallout period.

Although conventional tillage was the management of choice for a 55 year period, the introduction of no-tillage in the last 28 years has reduced erosion rates, although erosion processes remain significant nowadays. Accordingly, the adoption of additional practices is urgently required to reduce these losses and keep them at sustainable levels. Future studies are needed to quantify soil loss in agricultural slopes, under different management systems in South America.

**Acknowledgements**

Financial support for this study was provided by the CAPES-COFECUB Franco-Brazilian collaboration programme (project Te870-15) and the National Council for Scientific and Technological Development (CNPq), Brazil.

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Table 1
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**Table 1** - Main characteristics of the three hillslopes investigated

| | | Hillslope (I) | Hillslope (II) | Hillslope (III) |
|---|---|---|---|---|
| | | *B/B/B | *B/M/M | *B/B/G |
| | Soil type | Ferralsols | Ferralsols | Ferralsols |
| | Slope length (m) | 100 | 260 | 260 |
| | LS Factor (Desmet & Govers, 1996) | 1.6 | 2.0 | 2.1 |
| | Average declivity | 13.8% | 11.4% | 11.8% |
| **1st period (1960-1979)** | 1960s | Native forest with progressive deforestation and intensification of agriculture under conventional tillage since late 1960s. | Native forest with progressive deforestation for agriculture under conventional tillage since early 1960s. | Native pasture for extensive cattle raising with the presence of low vegetation, gully erosion and low natural soil fertility. Increased use for grain production since 1960s. |
| | 1970s | Conventional Tillage | Conventional Tillage | grassland with high soil degradation (diffusive and concentrated erosion) |
| **2nd period (1980-1999)** | 1980s | Conventional Tillage | Conventional Tillage | Conventional Tillage |
| | 1990s | Conventional Tillage | No-tillage with terraces until | No-tillage with terraces |

| | | | 1990 | |
|---|---|---|---|---|
| **3rd period (2000-2016)** | 2000s-2016 | Conventional Tillage | No-tillage system | No-tillage with crop rotation without terraces |

*Quality of soil management during the 1st period, 2nd period and 3rd period (B: Bad with high erosion; M: Average with medium erosion and G: Good with low erosion).

**Table 2** - Results of the conversion of the cesium 137 inventories into soil redistribution rates for each hillslope transect.

| | Depth (cm) | $^{137}Cs$ ($Bq.m^{-2}$) | Slope (%) | Density ($g.cm^3$) | Redistribution rate ($Mg\ ha^{-1}\ yr^{-1}$) MBM - 2 |
|---|---|---|---|---|---|
| **Reference site** | | | | | |
| Ref | 42 | 393±75 | ~ 0 | 1.33 | - |
| **Hillslope I** | | | | | |
| *Summit | 18 | 234 ±28 | | 1.48 | -28 ±7 |
| *Backslope | 24 | 138 ±35 | 13.8 | 1.41 | -57 ±15 |
| *Toeslope | 54 | 1400 ±84 | | 1.15 | 201 ±2 |
| **Hillslope II** | | | | | |
| Summit | 21 | 246 ±31 | | 1.40 | -25 ±8 |
| Backslope | 21 | 253 ±80 | 11.4 | 1.33 | -18 ±16 |
| Toeslope | 109 | 1124 ±136 | | 1.48 | 120 ±12 |
| **Hillslope III** | | | | | |
| Summit | 21 | 202 ±36 | | 1.47 | -38 ±10 |
| Backslope | 21 | 76 ± 31 | 11.8 | 1.43 | -87 ±34 |
| Toescope | 80 | 447 ±79 | | 1.46 | 13 ±12 |

MBM - 2 =Mass Balance Model - 2. *(References) - Schoeneberger and Wysocki (2012).

## Figure Captions

**Figure 1** - Location of Conceição river catchment where three hillslopes studied.

**Figure 2** - Characteristics of the selected hillslopessects and individual soil core sampling sites in Conceição river catchment, Brazil: Hillslope I, Hillslope II and Hillslope III.

**Figure 3 -** Distribution of $^{137}Cs$ with depth at the reference site

**Figure 4** - Distribution of $^{137}Cs$ inventories in slope I with depth in soil profiles collected on (A) the summit, at (B) backslope and on the (C) toeslope of the hillslope (Hillslope I).

**Figure 5** - Distribution of $^{137}Cs$ inventories with depth in soil profiles collected on (A) the summit, at (B) backslope and on the (C) toeslope of the hillslope (Hillslope II).

**Figure 6** - Distribution of $^{137}Cs$ inventories with depth in soil profiles collected on (A) the summit, at (B) backslope and on the (C) toeslope of the hillslope (Hillslope III).

Figure 1
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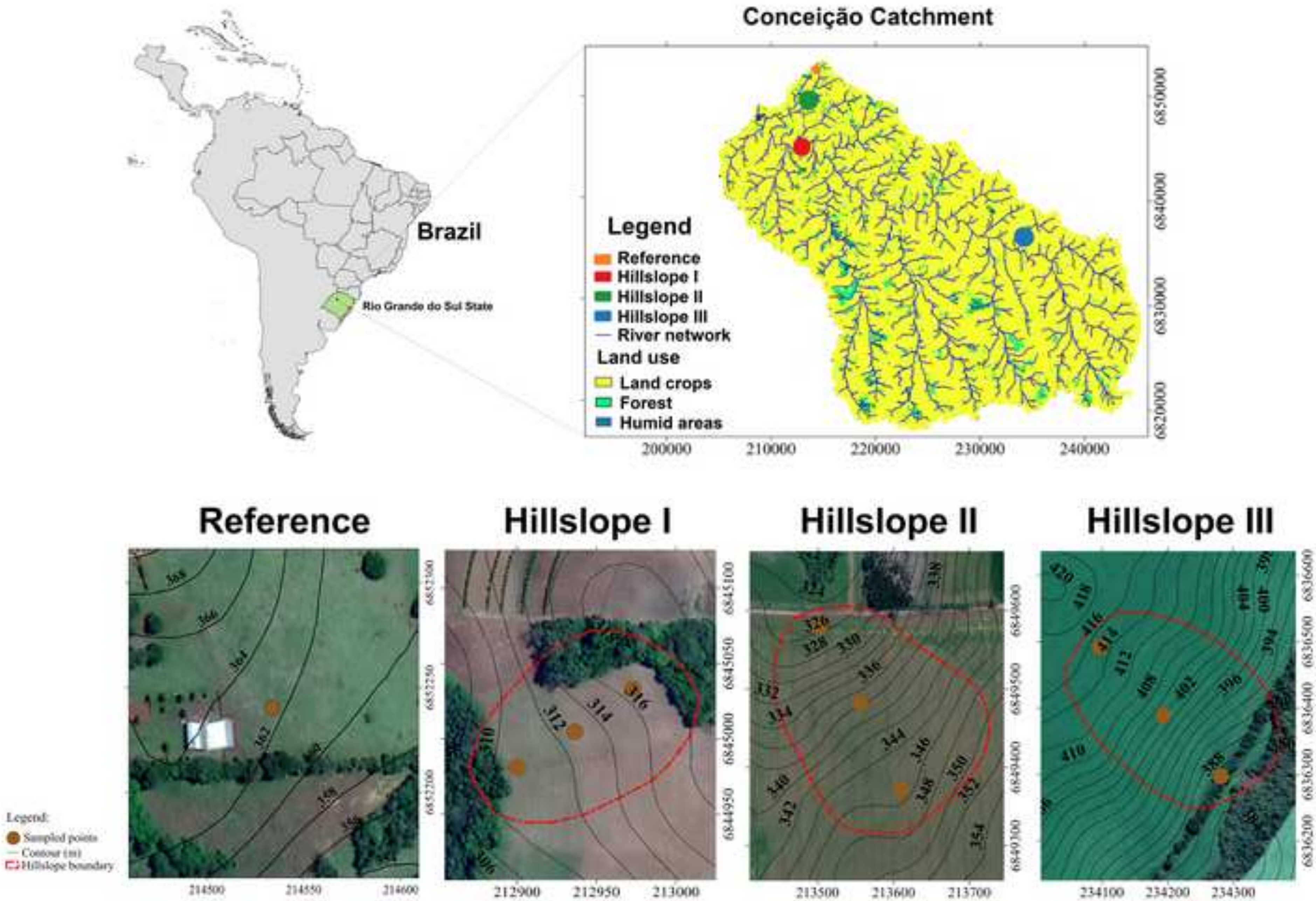

Figure 2
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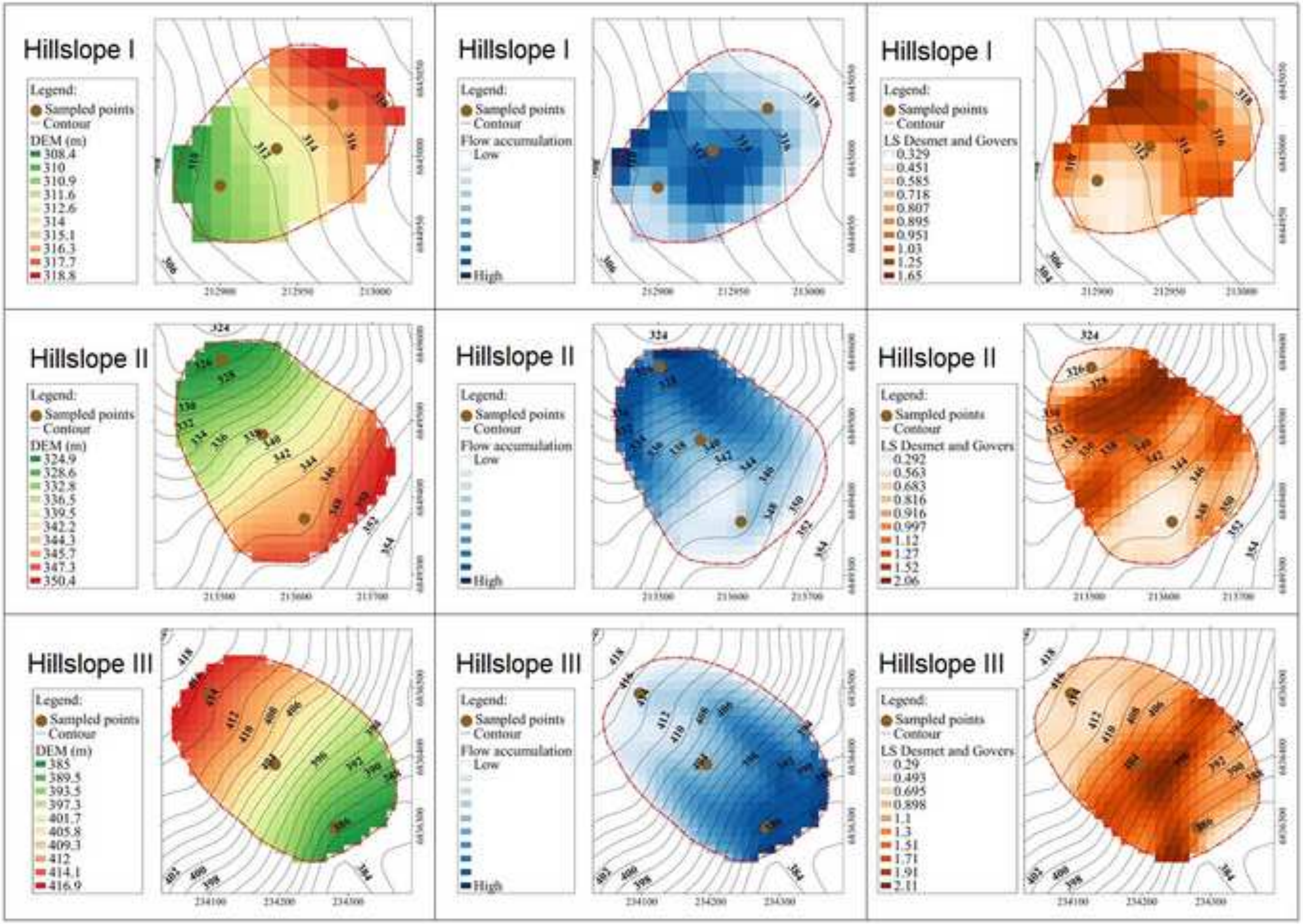

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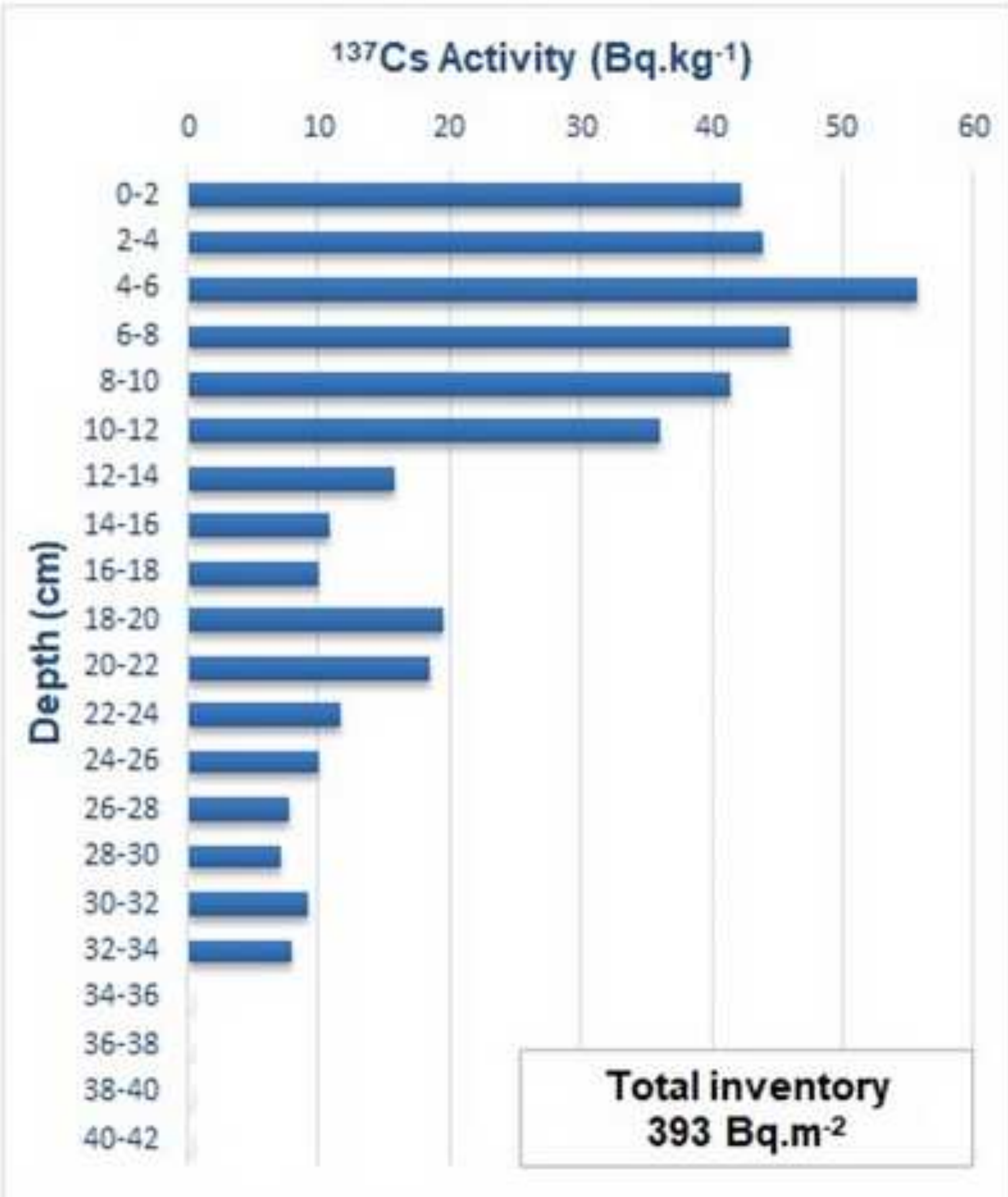

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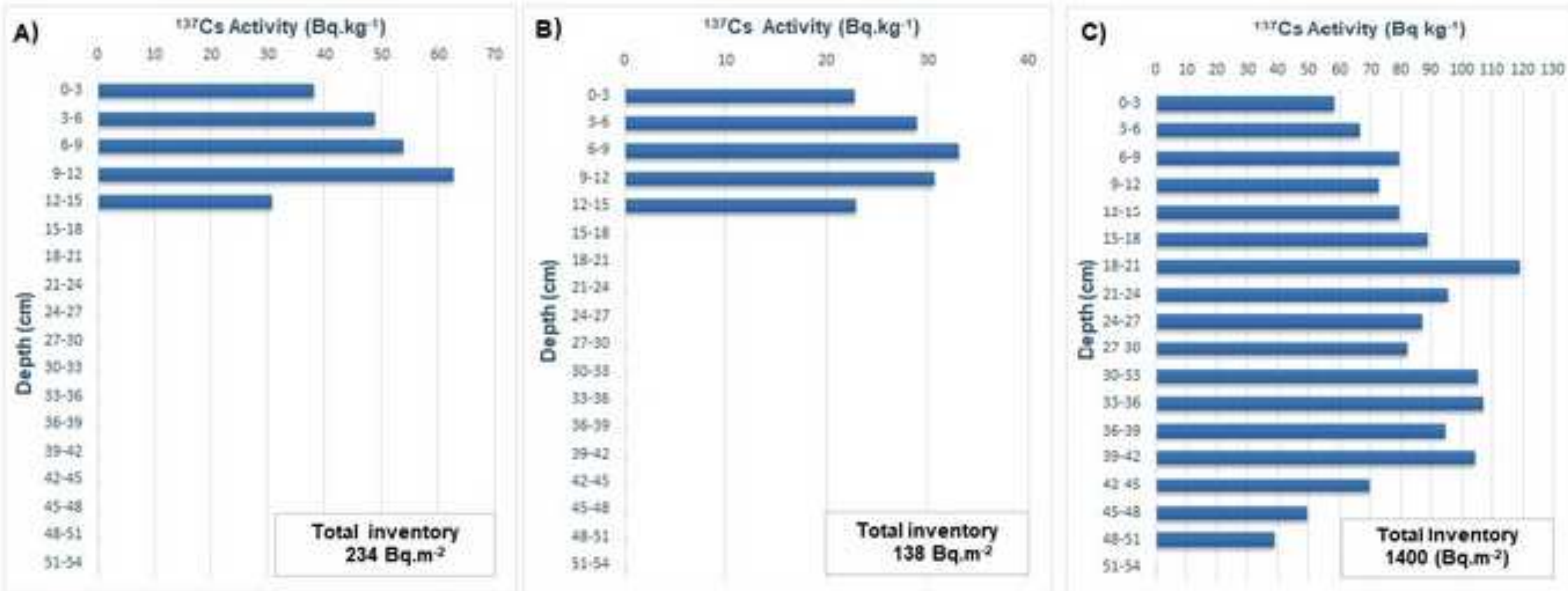

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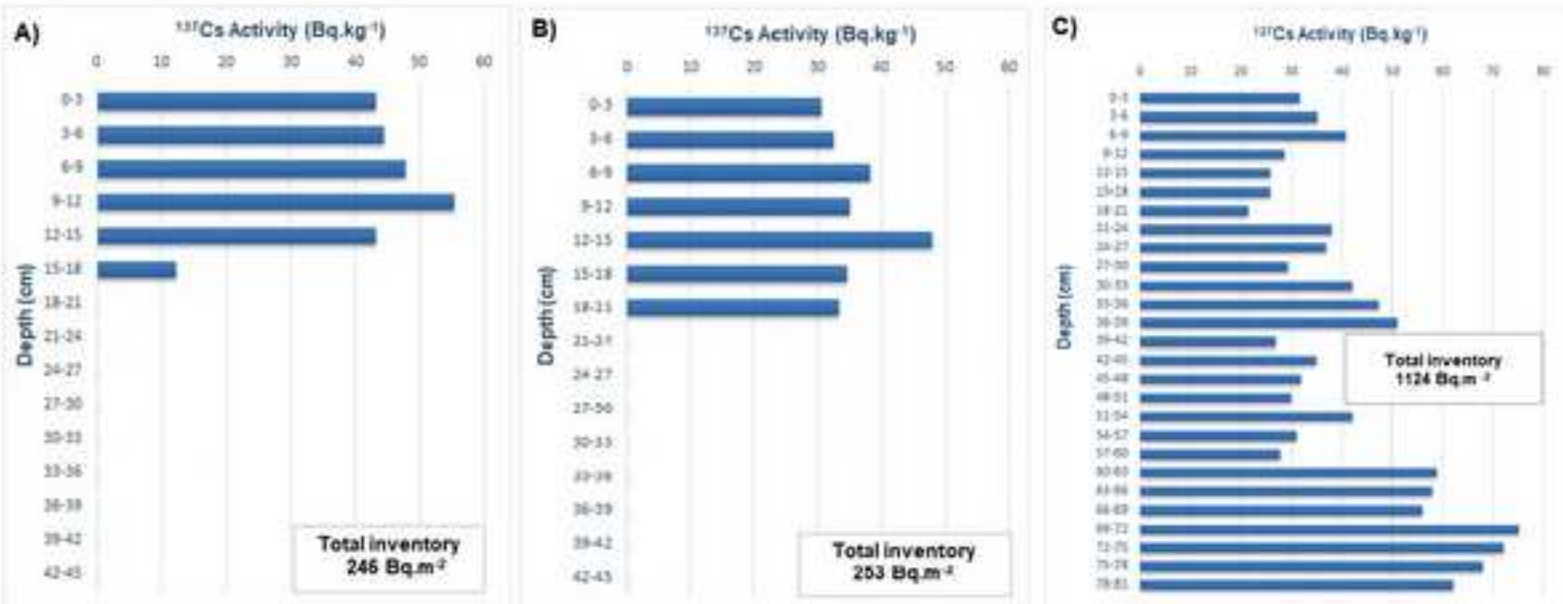

Figure 6
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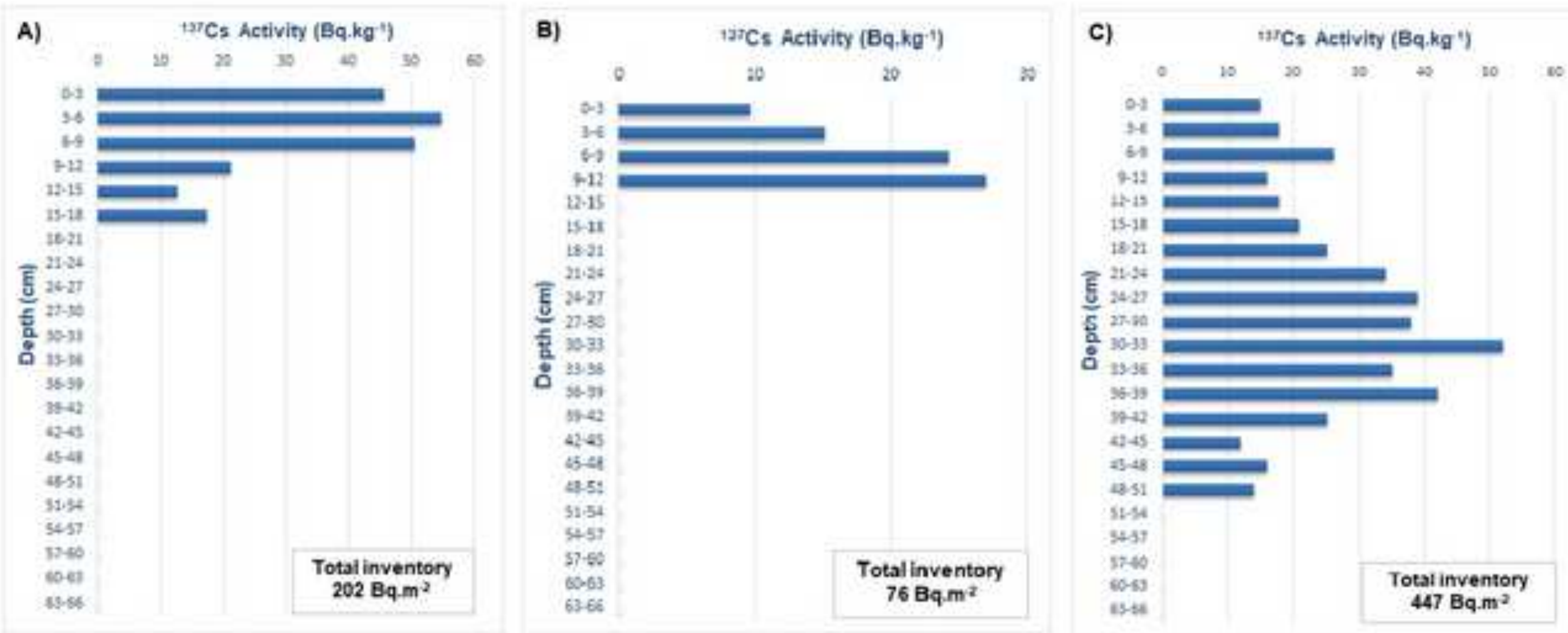

**Graphical Abstract**