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1 **Quantifying the impact of no-tillage on soil redistribution in a cultivated catchment of**
2 **Southern Brazil (1964–2016) with ¹³⁷Cs inventory measurements**

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15 **Abstract**

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

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

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

35 **1 Introduction**

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

41 In Southern Brazil, no-tillage has been a good example of soil conservation practice
42 (Cassol et al., 2003, Bertol et al., 2007 and Merten et al., 2015) given its efficiency in controlling
43 soil erosion when compared to conventional tillage which causes greater soil disturbance. While
44 under conventional tillage soil losses can exceed dozens of tons per hectare and per year, no-
45 tillage is associated with much lower erosion rates comprised between 1-2 $\text{Mg ha}^{-1} \text{ year}^{-1}$
46 (Cassol et al., 2003, Cogo et al., 2007). Intensive agriculture started in the 1960s in Southern
47 Brazil, a period during which conventional tillage was systematically implemented generating
48 high soil losses, reaching values up to 40 $\text{Mg ha}^{-1} \text{ yr}^{-1}$. These high erosion rates called attention
49 to the need to implement conservation measures to reduce the degradation of soils and water
50 bodies. In the 1990s, in the framework of the so-called ‘conservationist’ approach, the no-tillage

51 system became widespread along with other conservation measures such as contour farming all
52 of which aimed to reduce soil losses (Bertol, et al., 2004; Cogo, et al., 2007; Denardin et al.,
53 2008).

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

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

70 Among these potential tracers, caesium-137 (^{137}Cs), which is an artificial radionuclide
71 produced during nuclear tests and accidents (Zapata, 2002), is characterized by a strong affinity
72 for fine soil particles and has therefore been widely used to quantify soil erosion and deposition
73 rates based on the measurement of its inventories in soil profiles (Davis, 1963; Ritchie and
74 McHenry, 1990; Oztas, 1993, Ritchie and Ritchie 2007). Although its use has been recently
75 debated in the literature (Mabit et al., 2013; Parsons and Foster, 2011), ^{137}Cs has been

76 increasingly used worldwide (Mabit et al., 2008, 2009; Chartin et al. 2013) to estimate the
77 erosion and deposition rates since its emission into the environment (i.e., 1954-1963; Ritchie
78 and McHenry, 1990; Walling and He, 1997; Zapata, 2002; Mabit *et al.*, 2008).

79 Most of the sedimentological and erosion studies using radionuclides have been
80 conducted in the northern hemisphere (Walling and Quine, 1992; Zapata, 2002; Ritchie and
81 Ritchie, 2008; Chartin et al, 2013). However, although less often, this technique has also been
82 applied in the southern hemisphere, including in South America (e.g., Schuller et al. (2004,
83 2007). In Brazil, the feasibility of the ^{137}Cs tracer technique was verified for different soil types
84 and land uses (e.g Schuch et al. (1994b), Bacchi et al. (2000), Andrello et al. (2002), Antunes
85 et al. (2010) and Minella et al. (2014)). However, these studies did not specifically consider the
86 impact of soil management (no- and conventional tillage) on the long-term soil redistribution
87 by erosion and deposition.

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

96 **2. Materials and methods**

97 **2.1 Study site and hillslope characteristics**

98 The study was carried out on three agricultural hillslopes of Southern Brazil (Fig. 1),
99 located in the Conceição River experimental catchment (Didoné et al., 2017). The geological
100 bed-rock is basaltic overlaid with deep and highly weathered soils with Ferralsols being the

101 dominant soil type (FAO, 2014). These soils contain high amounts of clay (45-60%) composed
102 by kaolinite and oxides. Despite the excellent physical structure of this soil type, it is highly
103 sensitive to compaction (Reichert et al., 2016). According to Köppen's classification, the
104 climate is of Cfa type, i.e. subtropical humid without dry season, with an average annual rainfall
105 comprised between 1750 and 2000 mm and an average temperature of 18.6 °C. The catchment
106 is predominantly cultivated with soybean using no-tillage as the main soil management practice,
107 although runoff control and crop rotation are not implemented. Only low densities of biomass
108 (i.e. the residues of previous crops) protect the soils against the erosive power of rainfall.

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

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

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

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

123 Each hillslope is representative of one of the three main farming systems used in
124 Southern Brazil (conventional tillage (Hillslope I) and two different no-tillage conditions
125 (Hillslopes II and III)) since cultivation was intensified in the 1960s. However, it is important

126 to emphasize that both Hillslopes II and III had been under conventional tillage in the past
127 (1960- 1990s).

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

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

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

149 **2.2 Soil sampling and Cs-137 analyses**

150 Three samples from each of the three profiles (summit, backslope and toeslope) were
151 collected and evaluated in order to characterize each hillslope(Schoeneberger and Wysocki,
152 2012). In this study, in order to limit the analytical costs and the logistical requirements, the
153 technique was only tested on three slopes and on a limited number of soil profiles, although in
154 future studies a larger number of slopes and points will potentially be analyzed. A local
155 reference site under natural pasture without evidence of soil erosion and/or deposition was also
156 selected.

157 Soil depth collected for the different profiles varied depending on their position in the
158 landscape, and on the occurrence or the absence of soil redistribution at these locations. These
159 samples were collected using a 1-meter long core tube (surface area of 33.2 cm²) inserted at a
160 sufficient depth to include the full depth of soil containing ¹³⁷Cs. The soil profile was sampled
161 up to 40 cm in the summit and backslope positions and 140 cm in toeslopes. The soil cores were
162 sectioned into 3-cm increments, oven-dried at 102°C and sieved to 2 mm. Bulk density was
163 systematically measured for each level. The soil profiles from the reference area were
164 subdivided into 2-cm increments to provide in details ¹³⁷Cs activity variations within soildepth.

165 For each sample (n=150), approximately 70 g of material was sealed airtight in 60 mL
166 polypropylene containers, and ¹³⁷Cs was measured at 662 keV for 85,000 to 200,000 seconds
167 by gamma spectrometry using the low background GeHP detectors available at the *Laboratoire*
168 *des Sciences du Climat et de l'Environnement* (Gif-sur-Yvette, France). Measured activities
169 were decay-corrected to the sampling date. Counting efficiencies and reliability were checked
170 using certified International Atomic Energy Agency (IAEA) standards (e.g., IAEA-444, 135,
171 375, RGU-1 and RGTh-1). Uncertainties on ¹³⁷Cs activities did not exceed 10%. As the peak
172 of ¹³⁷Cs fallout was recorded in the southern hemisphere in 1963, which was used as the initial
173 year for evaluating soil redistribution across the landscape (Correchel et al., 2005; Bacchi et al.,
174 2011 and Minella et al., 2014).

175 2.3 Conversion model

176 Models are applied to the sequence of ^{137}Cs measurements carried out along individual
177 transects, so that estimates of deposition at individual points can be based on the ^{137}Cs content
178 of sediment eroded from upslope areas, with the ^{137}Cs activity of eroded soil being inversely
179 related to the erosion rate (Walling and He, 1997; Walling et al., 2002, 2011; Walling et al.,
180 2014). The use of ^{137}Cs fallout measurements to estimate soil erosion and deposition rates is
181 based on a comparison between ^{137}Cs inventories for individual sampling points and the local
182 reference inventory. When ^{137}Cs inventories are lower than the local reference value, they
183 correspond to erosion, whereas greater inventories indicate deposition. The model calculates
184 the potential changes in the erosion/deposition rates between 1963 and 2016.

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

$$191 \quad \frac{dA(t)}{dt} = (1 - \Gamma)I(t) - \left(\lambda + P \frac{R}{d} \right) A(t) \quad (\text{Eq. 1})$$

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

197 The plough depth varied over time depending on the changes in farming practices
198 observed in the study area. Under conventional tillage, which was implemented in all hillslopes
199 prior to the 1990's, the tillage depth was estimated at 20 cm. Under no-tillage, this depth was

200 estimated at 5 cm because of the soil disturbance caused by the sower. As highlighted by
201 Walling et al. (2007), the model includes the time-variant fallout input and the fate of the
202 recently deposited fallout before its incorporation into the plough layer by cultivation.

203 **3. Results and discussion**

204 **3.1 ^{137}Cs inventories**

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

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

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

214 The global pattern of bomb-derived ^{137}Cs fallout indicates that inputs ranged from about
215 160 to about $3,200 \text{ Bq m}^{-2}$ depending on the latitude (Davis, 1963; Ritchie and McHenry, 1990;
216 Garcia Agudo, 1998). In the southern hemisphere, ^{137}Cs concentrations in reference areas may
217 vary significantly. Schuller et al. (2004, 2007) found $525 \pm 12 \text{ Bq m}^{-2}$ in southern Chile, in a
218 reference area with an average precipitation of $1,100 \text{ mm yr}^{-1}$. Andrello et al. (2007) found
219 values between 296 and 369 Bq m^{-2} in the Paraná State, Southern Brazil, with average annual
220 rainfall of $1,615 \text{ mm yr}^{-1}$. Schuch et al. (1994b) found reference values around 329 Bq m^{-2} in
221 the state of Rio Grande do Sul, which is characterized by a mean rainfall of 1800 mm yr^{-1} .

222 The range of ^{137}Cs inventories in Hillslope I varied from 138 to 1400 Bq m^{-2} along the
223 slope, indicating that sediment redistribution by erosion has been significant under this farming
224 system. The pattern on Hillslope I is characteristic of a slope that has undergone severe erosion,

225 with lower ^{137}Cs inventories on the backslope and a high accumulation of ^{137}Cs in the toeslope
226 position (1,400 Bq m²), which reflects that the farming system implemented on this hillslope
227 led to significant deposition of material at the base of this slope. The increase in erosion
228 (reflected by a reduction in ^{137}Cs inventories) along Hillslope I is due to the soil being exposed
229 to erosive agents, which has favored the amplitude of these processes over the years. Moreover,
230 the absence of crop residue on the surface has increased the ability of rainfall to disaggregate
231 the soil, especially when it concentrated in the furrows oriented in the same direction as the
232 main slope gradient (Cassol et al., 2003; Morgan, 2005).

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

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

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

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

247 The major difference between these systems was found at the depositional sites. On the
248 two slopes under no-tillage (Hillslope II and III), ^{137}Cs inventories were significantly lower than

249 in Hillslope I under conventional tillage while remaining higher than those found in the
250 reference area, indicating the occurrence of deposition.

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

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

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

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

261 The lowest inventory value of ^{137}Cs found in the backslope of Hillslope III can likely be
262 explained by the occurrence of erosion before the implementation of no-tillage in the early
263 1990s, or by the lack of additional soil conservation measure implemented with no-tillage since
264 this period.

265 Regarding the different slopes, the inventories of ^{137}Cs for the summit position of the
266 slopes are of 234, 246 and 202 Bq m⁻² for Hillslopes I, II and III respectively. The difference
267 between these values is small although significant, which may be explained by the low slope
268 gradient (< 2%) and the large impact of tillage when this practice was generalized in the region
269 (1960-90s). The mean ^{137}Cs inventory for the three Hillslopes (I, II and III) in eroding areas
270 was 186, 249 and 139 Bq m⁻² respectively, while the mean values recorded in depositional
271 Hillslopes (I, II and III) areas were 1400, 1124 and 447 Bq m⁻² respectively. These distinct ^{137}Cs
272 inventory values indicate the occurrence of significant spatial redistribution of ^{137}Cs across
273 those hillslopes under different management systems.

274 **3.2 Model of conversion of ¹³⁷Cs inventories into redistribution rates**

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

279 **Table 2 - Results of the conversion of the cesium 137 inventories into soil** 280 **redistribution rates for each transect.**

281 The MBM-2 determined that mean erosion rates occurred with different intensities. It
282 may be expected that the currently observed patterns of ¹³⁷Cs inventories mainly reflect the
283 redistribution of soil across the landscape in the 1960s, when agriculture expanded in the region
284 (Moreno, 1972; Bernardes, 1997). When evaluating the mean erosion rates in Hillslope I, an
285 erosion value of 28 Mg ha⁻¹yr⁻¹ was observed at the summit position while a mean value of 57
286 Mg ha⁻¹yr⁻¹ was found at the backslope position. When analyzing the traditional studies of soil
287 erosion losses using the Wischmeier & Smith plot methodology (1978) under the conditions
288 prevailing in the study area (i.e., climate, topography, soil type and management), Cogo et al.
289 (2003) found mean values of 13 Mg ha⁻¹ yr⁻¹ for sites with 8-12% slope, after two years of
290 monitoring. Furthermore, Beutler et al. (2003) found soil losses of 6.1 Mg ha⁻¹ yr⁻¹ under the
291 same experimental conditions. Soil erosion was particularly severe for the hillslope under
292 conventional tillage. According to Bertoni & Lombardi Neto (1993) and Bertol & Almeida
293 (2000), the soil loss for similar clay soils are comprised between 13 and 15 Mg ha⁻¹ yr⁻¹ under
294 conventional tillage. Nowadays, this cultivation system has become very unusual in the study
295 area, and its use is currently restricted to prepare the soil for annual pasture areas and the
296 cultivation of subsistence crops (cassava, potato, vegetables, etc.)

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

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

305 Estimates of soil redistribution rates obtained by sampling individual points on the
306 transects of the three Hillslopes (I, II, III) indicated that annual erosion rates for summit and
307 backslope erosion sites were 30 and 54 Mg ha⁻¹ yr⁻¹ respectively, with a mean deposition value
308 of 111 Mg ha⁻¹ y⁻¹ in the toeslope. In contrast, when we compare only Hillslopes II and III, the
309 erosion average values are practically the same for the summit and backslope positions (31 and
310 52 Mg ha⁻¹ yr⁻¹), although the mean rate found in the toeslope is reduced to 66 Mg ha⁻¹ yr⁻¹.

311 When comparing erosion values determined based on the ¹³⁷Cs inventory method with
312 those reported in erosion studies based on the monitoring of standard erosion plots under natural
313 rainfall (77 m²), the values presented in Table 2 can be considered to be high. Values of 1 to 15
314 Mg ha⁻¹ yr⁻¹ were commonly observed for fields planted with annual crops under no-tillage and
315 conventional tillage, respectively, on slopes with gradients comprised between 8-12% (Cogo et
316 al., 2003; Beutler et al., 2003). However, the average value determined in the current research
317 based on ¹³⁷Cs inventories was 54 Mg ha⁻¹ yr⁻¹ (Tab. 2), which is up to one order of magnitude
318 higher than the values commonly observed in similar conditions during classical field
319 monitoring. This may be due to the longer slope lengths evaluated in this study when compared
320 to traditional plot studies and the longer period over which the rates derived from ¹³⁷Cs
321 inventories were calculated, including a period of conventional tillage.

322 While the standard plots are generally a few meters long and show a rectilinear
323 curvature, our study considered the entire hillslopes with complex curvature, which could, as

324 shown by our findings, enhance soil erosion. These variable conditions explain why a wider
325 range of erosion rates may be found, mainly in the backslope position with much higher erosion
326 levels than those reported in the traditional plot monitoring studies. In addition, Morais & Cogo
327 (2001) and Barbosa et al. (2012) concluded that the positive impact of denser covers of crop
328 residues to slow down runoff under no-tillage may be less significant over long hillslopes, when
329 the flow accumulates.

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

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

340 According to Moore et al. (1993) and Wilson & Gallant (1996), the shape of the slope
341 affects soil erosion and influences the amount and the intensity of runoff. While convex slopes
342 increase the intensity of flow, detachment and transport capacity, flow speed decreases in
343 concave slopes where deposition may occur (Morgan, 2005). This can be observed for the three
344 studied slopes, especially in Hillslopes II and III, where the longer length increased erosion,
345 and prevented deposition. Moore and Burch (1986) showed that the shape of the slope can be
346 even more important than its length, while Govers et al. (1994) concluded that erosion on
347 convex slopes may be greater than in more uniform slopes. This is illustrated on Hillslope I

348 which, despite its shorter slope length, shows higher erosion / deposition rates than the other
349 slopes investigated in the current research.

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

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

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

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

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

387 **4 Future challenges**

388 4.1 Recommendations for soil conservation in Southern Brazil

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

396 A strategy combining the installation of measures at the source and that of physical
397 barriers along the main flow pathways in the catchment with the use of terracing and/or strip-

398 cropping for example may lead to an effective increase of productivity and a reduction of water
399 losses and sediment/nutrients/pesticides delivery to rivers in this region. Furthermore, it is
400 necessary to investigate the connectivity achieved by landscape features between the
401 agricultural areas (slopes) and the water bodies considering the different systems that compose
402 the landscape (roads, tracks, pastures, sunken lanes, field drains, ditches, banks, culverts and
403 permeable field boundaries). The impact of connectivity between the areas seems to be even
404 more important than the local erosion rates (Boardman et al., 2019).

405 4.2 Recommendations for future research

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

413 **5. Conclusions**

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

420 Although conventional tillage was the management of choice for a 55 year period, the
421 introduction of no-tillage in the last 28 years has reduced erosion rates, although erosion
422 processes remain significant nowadays. Accordingly, the adoption of additional practices is

423 urgently required to reduce these losses and keep them at sustainable levels. Future studies are
424 needed to quantify soil loss in agricultural slopes, under different management systems in South
425 America.

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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
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*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
Toeslope	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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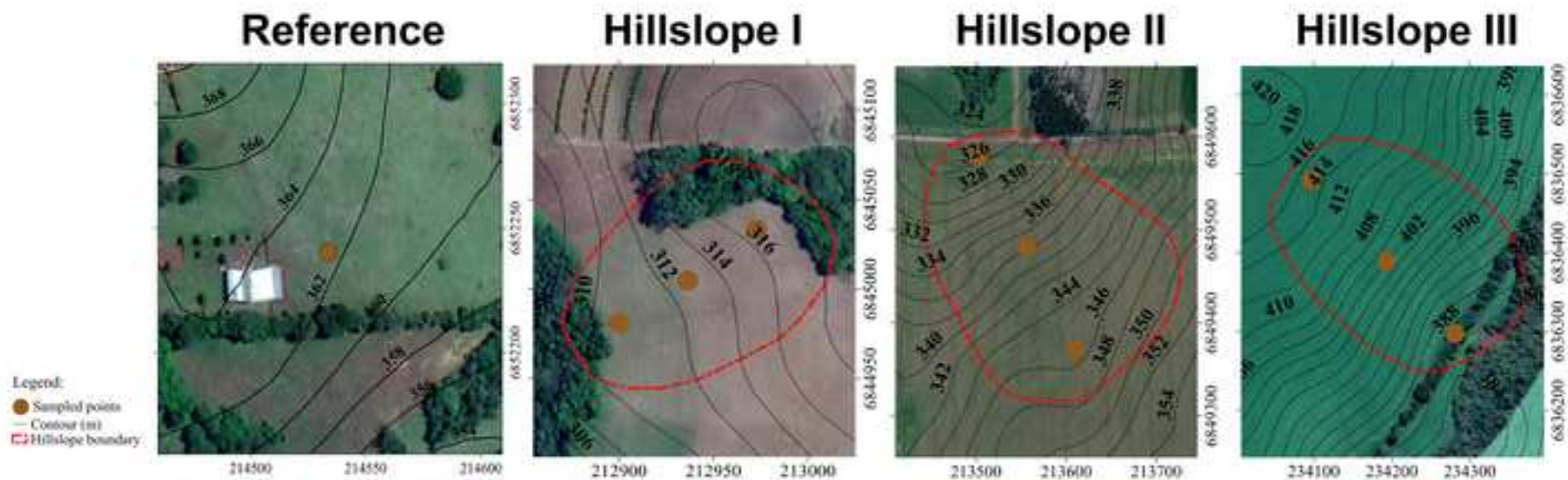
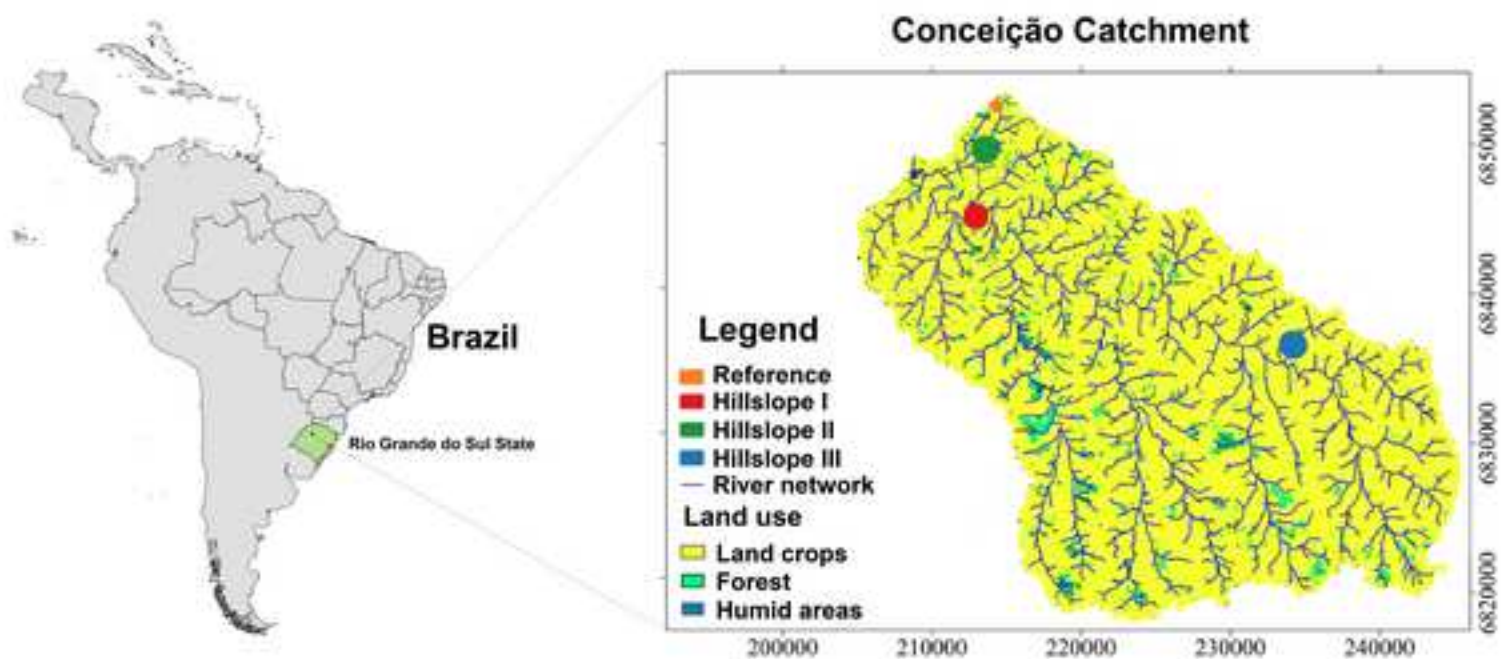


Figure 2
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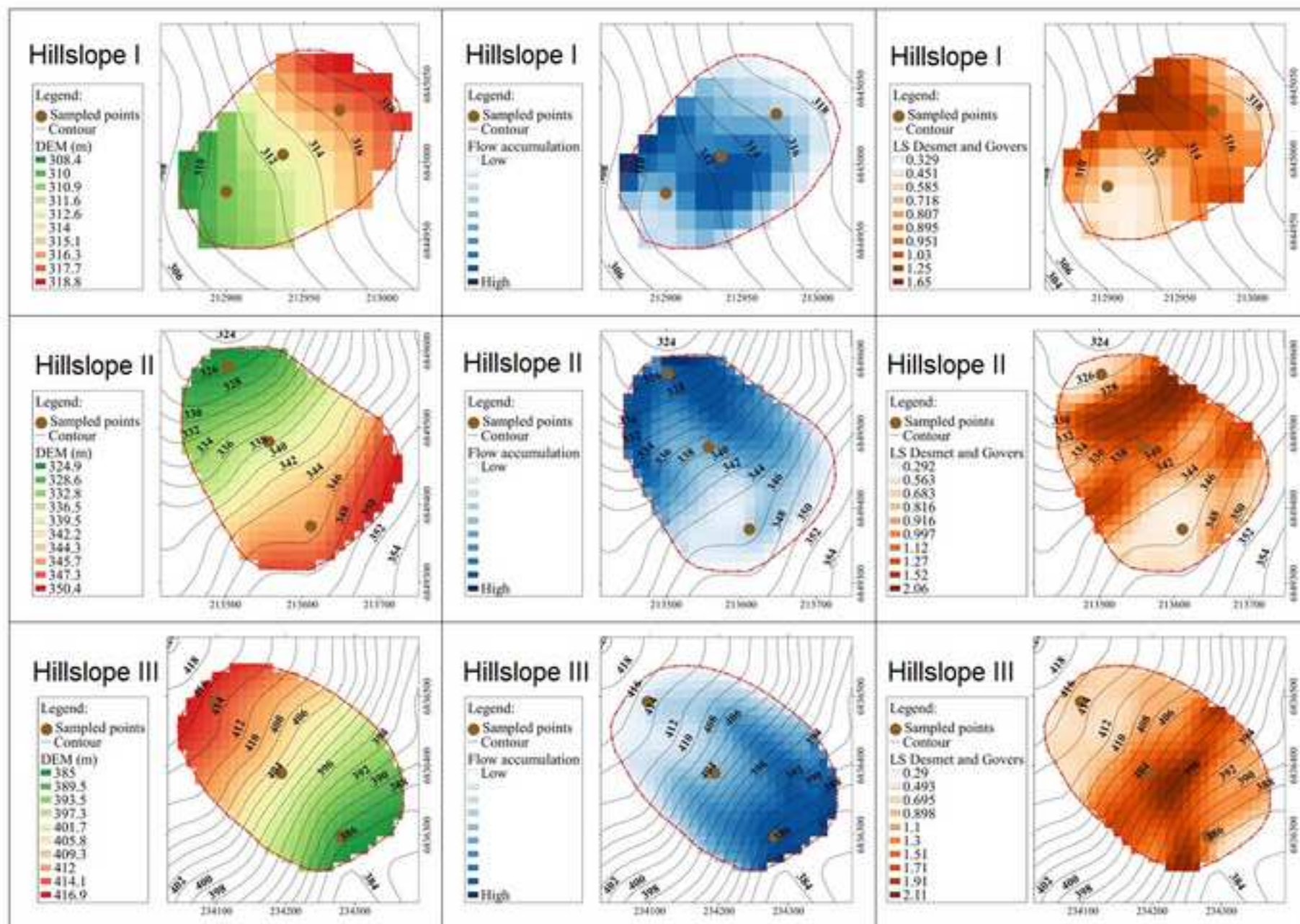


Figure 3

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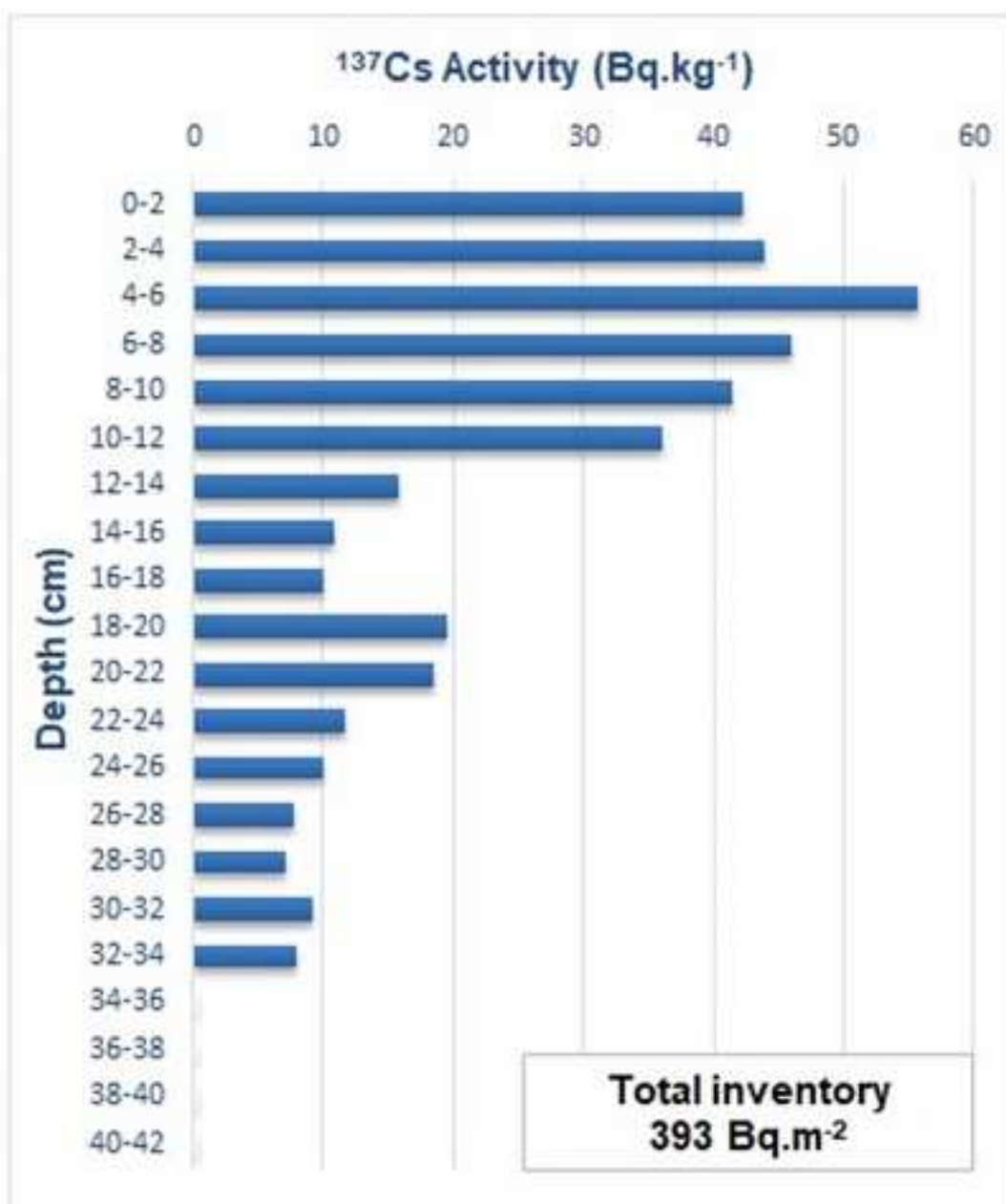


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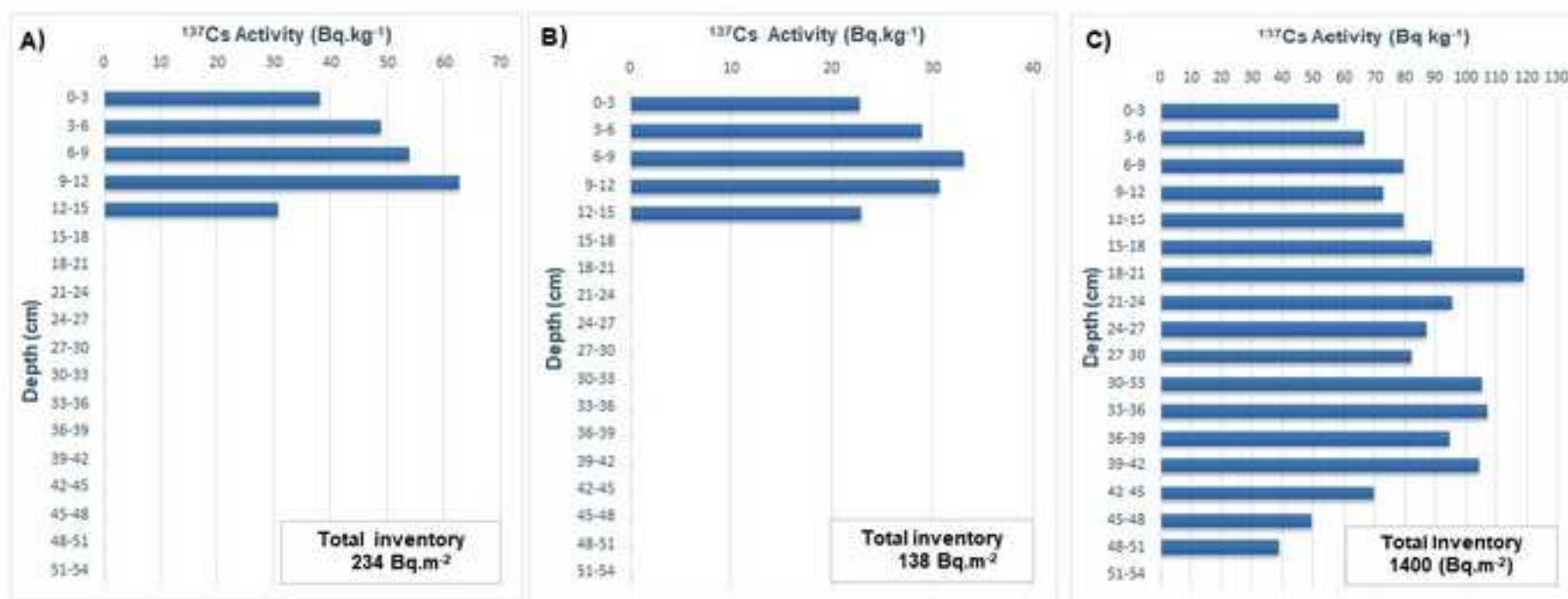


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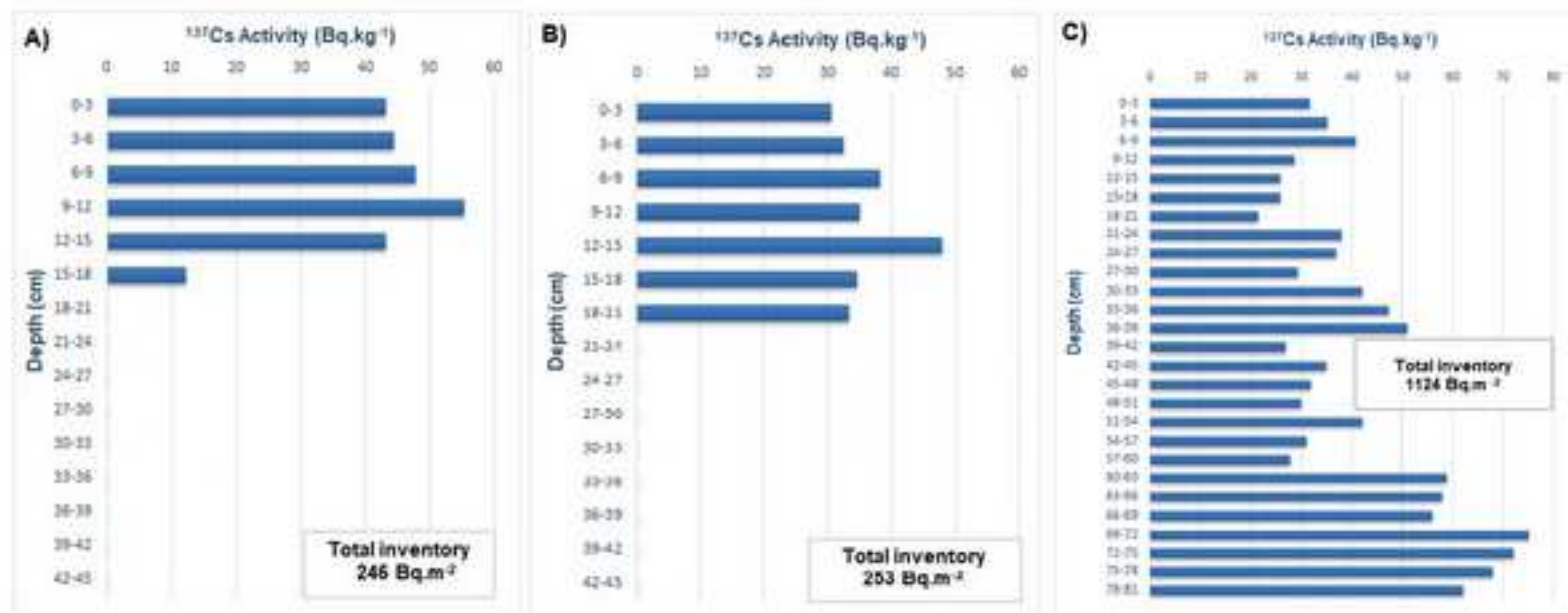
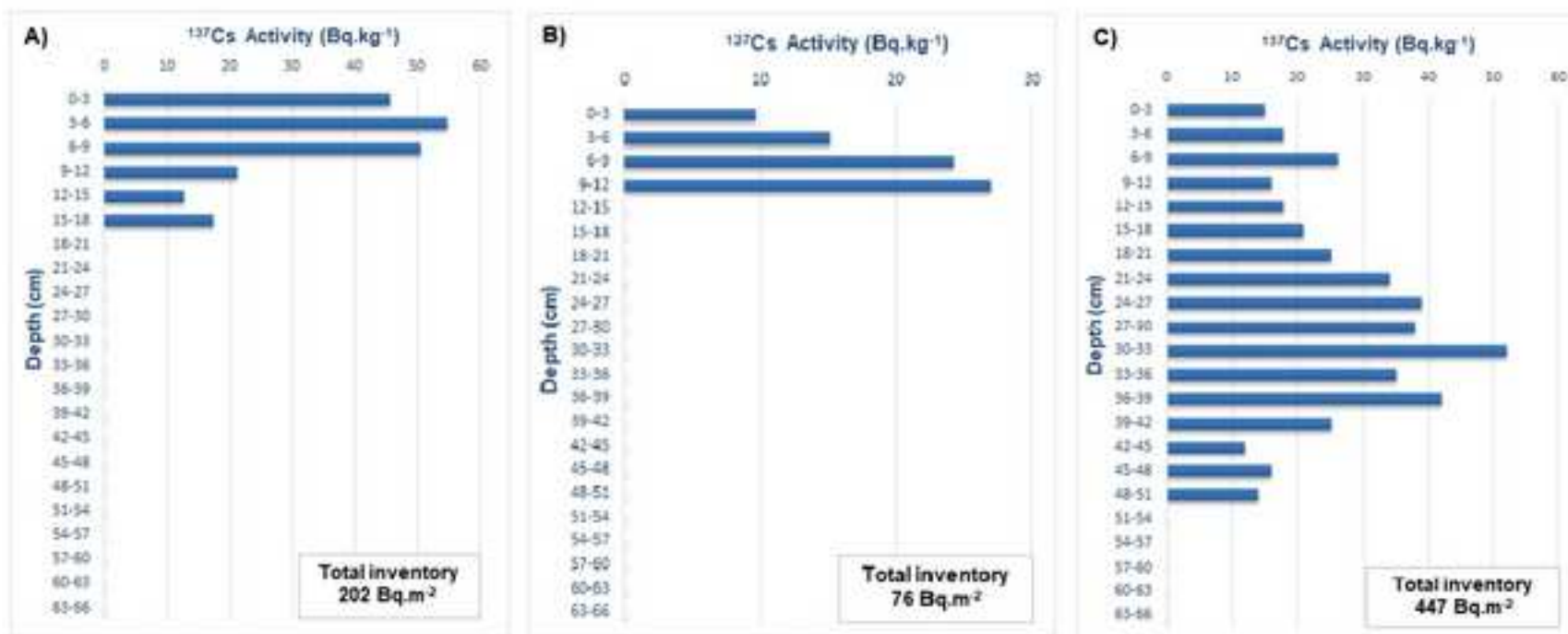


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^{137}Cs technique for evaluation of erosion and deposition rates

