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1 FINGERPRINTING SEDIMENT SOURCES IN A LARGE AGRICULTURAL
2 CATCHMENT UNDER NO-TILLAGE IN SOUTHERN BRAZIL (CONCEIÇÃO RIVER)

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17
18 ABSTRACT

19 Brazil is a leader in the adoption of conservation agriculture practices and technologies.
20 However, the impact of these practices on sediment sources at the catchment scale has not been
21 quantified yet, particularly in grain growing regions, where a conservationist no-tillage system is
22 implemented to protect soils. To address this knowledge gap, a sediment fingerprinting study
23 based on elemental geochemistry was carried out in a large agricultural catchment (804 km²) of
24 Southern Brazil where no-tillage practices dominate. A total of 156 soil samples were taken to
25 characterize the three main potential sediment sources: cropland ($n=79$), unpaved roads ($n=41$),
26 and channel banks ($n=36$). Sediment sampling was performed using a time-integrated sampler
27 ($n=33$) and by collecting fine-bed material ($n=34$) at five locations across the catchment.
28 Sediment was also sampled during flood events at the catchment outlet ($n=20$). Sediment source
29 contributions were calculated using an optimal suite of geochemical properties and a mixing
30 model. Results showed that although the catchment is not particularly sensitive to soil erosion
31 (*i.e.* deep clayey soils with gentle slopes), the amount of sediment supplied by cropland to the
32 river network remains very high (up to 1.63 Mg ha⁻¹ yr⁻¹). Sediment fingerprinting results
33 showed that even when no-tillage is implemented, cropland remains an important source of
34 sediment, supplying up to 70% of the material transiting the Conceição River. Accordingly, the
35 current conservation farming system in this catchment needs to be improved to further reduce
36 soil erosion and sediment yield.

37
38 **KEY WORDS:** land use, soil erosion, best management practices, sediment sources, suspended
39 sediment.

INTRODUCTION

40
41 In Brazil, soil erosion is considered as the main factor of land degradation in agricultural
42 areas. In the 1990s, Brazil was one of the few countries in the world where the agricultural area
43 expanded. By 2000, farmland was estimated to cover 250 million hectares, and it currently
44 occupies 27.6% of the national territory, whilst protected areas cover only 55 million hectares
45 (Manzatto *et al.*, 2002). According to Merten and Minella (2013), during the next 10 years,
46 Brazil's agricultural area will expand to meet increased domestic and worldwide demand for
47 food, fuel, and fiber. The current land use allocation choices will determine the magnitude of the
48 adverse effects induced by this expansion. These impacts include soil erosion, reservoir siltation,
49 streambed sediment clogging, flooding, decrease in water quality, loss of biodiversity and social
50 conflicts, especially in zones of indigenous lands.

51 The intensification of agriculture in Brazil was strongly influenced by the technologies
52 developed in countries of Northern Europe due to the occurrence of successive phases of
53 immigration (Casão Junior *et al.*, 2012). In the 1950s and 1960s, conventional tillage with
54 plowing and heavy harrowing were generally conducted after residue burning to reduce biomass
55 volume and facilitate mechanical operations. This production system caused soil erosion losses
56 of up to 10 Mg ha⁻¹ per ton of grain produced, resulting in deleterious environmental impacts
57 and massive losses of cultivated land (Casão Junior *et al.*, 2012). As a consequence, several
58 initiatives emerged in the 1970s in Southern Brazil in order to improve the soil management
59 system and to implement progressively a more conservationist approach.

60 Currently, Brazil is a worldwide leader in the adoption of conservation agriculture
61 practices and technologies (Freitas and Landers, 2014). It has encouraged the dissemination of
62 conservation agriculture in South America through the development of an effective and
63 innovative network of farmers' associations, in the framework of private and public partnerships
64 (Speratti *et al.*, 2015). The No-Tillage System (NTS) is based on basic principles as the reduction
65 or removal of soil disturbance, the maintenance of permanent soil cover with plant residues or
66 living plants as long as possible, the diversification of crops by growing multiple species, in
67 rotation, succession and/or in intercropping, and the implementation of mechanical runoff control
68 measures. This management system is sustainable and highly productive, and it improves the
69 structure, the quality of aggregates and the porosity of the soil. It maximizes nutrient cycling and
70 stimulates soil biological activity, which contributes to its protection against erosion.
71 Furthermore, NTS promotes soil carbon sequestration and offers a strategy to achieve food
72 security through the improvement of soil quality. The widespread adoption of NTS (no-tillage,
73 crop rotation, soil cover/cover crops) was one of the main factors responsible for the evolution

74 of Brazilian agriculture, especially in the last two decades, characterized by an increase of
75 farmers' incomes and sustainability in the intensively cultivated regions of Brazil (Casão Junior
76 *et al.*, 2012).

77 Although the NTS is considered to be the best approach to minimize soil loss, few
78 Brazilian farmers respect the NTS guidelines, and, as a rule, the only principle widely
79 implemented by farmers is to avoid soil disturbance with plowing and harrowing, because sowing
80 without tilling the soil is less labor intensive. This practice is referred to as "no-till" (NT – and it
81 differs from the no-till 'system' because it does not comprise the implementation of the additional
82 conservation measures recommended.) Overall, areas under no-till (including both NT and NTS
83 areas) exponentially increased in Brazil, from 1 million hectares in the early 1990s to 31.8 million
84 hectares in 2011/12 (Figure 1), representing approximately 25% of the area under NT in the
85 world (FEBRAPDP, 2016).

86 The general farmer's perception in Rio Grande do Sul is that there is no soil degradation
87 in areas under NT although soil losses remain significant. In the southernmost Brazilian State
88 (Rio Grande do Sul), most farmers neglect soil and water losses occurring in cultivated areas
89 under NT. This perception is even more strongly rooted for those who participated in the
90 transition from the conventional soil management including soil plowing to the no-till system.
91 During this transition, the erosion of arable layers as thick as 20–30 cm during a single storm
92 was reported after soil plowing, and they resulted in the siltation of local streams. As they supply
93 large quantities of fertilizers to the soil, local farmers erroneously consider that soil losses under
94 NT are negligible because their crop yields remain satisfactory.

95 The soil degradation problem in Southern Brazil is complex as it results from a
96 combination of environmental, economic, social and political factors. However, to raise farmers'
97 awareness, consistent data demonstrating the impact of their practices on land and water
98 resources are currently lacking. Merten *et al.* (2015) showed that soil erosion decreased by more
99 than 70% on plots (38.5 to 10,000 m²) cultivated under NTS compared to those where traditional
100 tillage was implemented. Furthermore, the impact of no-tillage systems on sediment yields was
101 investigated in two large catchments of Southern Brazil (Didoné *et al.*, 2014). This preliminary
102 study based on hydrological and sedimentological monitoring showed that runoff and erosion
103 remained excessive in these cultivated areas (1.40 Mg ha⁻¹ year⁻¹). These results suggest that
104 additional control measures are needed at the hillslope scale in order to avoid runoff
105 concentration and the formation of rills and gullies, as it was observed in other cultivated
106 environments of the world, such as in northwestern Europe (Delmas *et al.*, 2012).

107 In addition to modelling and monitoring studies, the sediment fingerprinting technique
108 was shown to provide a powerful tool to identify sediment sources in Brazil (Minella *et al.*, 2007,
109 2008, 2009, 2014; Miguel *et al.*, 2014; Tiecher *et al.*, 2014, 2015a, 2015b, 2016, 2017a, 2017b),
110 and elsewhere in the world, such as in France (Navratil *et al.*, 2012b; Poulenard *et al.*, 2012;
111 Legout *et al.*, 2013; Foucher *et al.*, 2015), Mexico (Evrard *et al.*, 2013), South Africa (Foster *et al.*
112 *et al.*, 2007), Zambia (Walling *et al.*, 2001), Canada (Koiter *et al.*, 2013; Stone *et al.*, 2014; Barthod
113 *et al.*, 2015), United States of America (Devereux *et al.*, 2010), UK (Collins *et al.*, 2010; Smith
114 and Blake, 2014; Pulley *et al.*, 2015), Spain (Brosinsky *et al.*, 2014), Luxemburg (Martínez-
115 Carreras *et al.*, 2010), Turkey (D'Haen *et al.*, 2013), Tunisia (Ben Slimane *et al.*, 2013), Iran
116 (Haddadchi *et al.*, 2014), and Australia (Olley *et al.*, 2013; Wilkinson *et al.*, 2013; Lacey *et al.*,
117 2015). Therefore, the objective of the current study is to quantify the contribution of sources
118 supplying sediment to the river in a catchment characterised by the widespread implementation
119 of no-tillage since the 1990s in Southern Brazil. The implications of these results for catchment
120 management will then be discussed.

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122

MATERIAL AND METHODS

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Study site

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The Conceição catchment is located in the northwestern part of Rio Grande do Sul, and
it drains a surface area of approximately 804 km² (Figure 2). According to Köppen's
classification, the climate is of Cfa type, i.e. subtropical humid without a dry season, with an
average annual rainfall amount comprised between 1,750 and 2,000 mm and an average
temperature of 18.6°C. The main lithological substrate is composed of basic volcanic rocks (Serra
Geral Formation - 94% of total area) and, to a lesser extent, sedimentary rocks (Tupanciretã
Formation - 6%, Figure 3a). The soils are deep, highly weathered, and enriched in iron oxides
and kaolinite. Ferralsols are the dominant soil class in the catchment (80.3% of total area – Figure
3b), whereas Nitisols and Acrisols cover 17.6 and 2.1% of the total surface area, respectively.
The topography of the region is gentle (6–9%) in the top and middle parts of the 300 to 500-m
long hillslopes, whereas steeper gradients (10–14%) are observed near the drainage channels
(Figure 3c).

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Land use and soil management are quite homogeneous in the Conceição catchment (Table
1 and Figure 3d), although farm size increases in a North-South direction. The main land use in
the catchment is cropland (73.1%). Grasslands and scrublands cover 18.1% of the total surface
area, whereas forest is found on only 7.7% of the surface. In summer, cropland areas are mainly
cultivated with soybean (*Glycine max*) under no-tillage. Corn used to feed dairy cattle (silage) is

141 also planted in cropland areas, although in much lower proportions. During winter, cropland
142 areas are occupied by wheat (*Triticum aestivum*) for grain production, but also with black oat
143 (*Avena strigosa*), and ryegrass (*Lolium multiflorum*) with the objective of producing straw for
144 mulching in summer and for providing a pasture for dairy cattle in winter. No-tillage is
145 implemented on more than 80% of the cultivated area. However, these areas are devoid of
146 additional measures to control runoff, such as terraces, strip cropping, vegetated ridges, or
147 seeding perpendicular to the slope line. In the Conceição catchment, the annual sediment yield
148 was estimated to $1.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ (Didoné *et al.*, 2014).

149

150 *Hydro-sedimentological monitoring*

151 Rainfall was monitored by an automatic meteorological station (volumes recorded every
152 10 minutes) and by rain gauges. Surface runoff was estimated from gauge height readings
153 coupled with a rating curve. The water level was measured every day using two approaches: (i)
154 local observing, and (ii) using a 10-min intervals records on a limnigraph (pressure sensor) model
155 OTT-Thalimedes.

156 The suspended-sediment concentration (SSC) was also estimated based on a combination
157 of two approaches: (i) systematic manual daily sampling and (ii) specific manual sampling
158 performed during heavy rainfall–runoff events. Additionally, *in situ* turbidity (Solar® Brand,
159 model SL-2000) data with 10-min intervals were collected. Then, SSC was estimated using an
160 equation based on data from rainfall–runoff events establishing the relationship between turbidity
161 (nephelometric turbidity units - NTU) and SSC (mg L^{-1}). The sediment discharge (kg s^{-1}) was
162 obtained by multiplying water discharge (L s^{-1}) by the SSC (mg L^{-1}). Suspended sediment yield
163 (SSY) (Mg year^{-1}) was then calculated integrating these values over time.

164 SSY was calculated for each sampling period using the time-integrated suspended
165 sediment samplers and then SSY for each source was calculated using their relative contribution.
166 To better characterize temporal variations, sediment source contributions to each sediment
167 sample collected at the outlet were weighted with SSY and mean daily fluxes exported during
168 each monitoring period.

169

170 *Sediment source sampling*

171 Composite samples of potential sediment sources were collected to characterize the three
172 main sediment sources types found in the Conceição catchment, namely: (i) cropland ($n = 79$),
173 (ii) unpaved roads ($n = 41$), and (iii) stream channel banks ($n = 36$). Other land uses such as
174 grassland and forest were not considered to provide potential sediment sources. Sediment source

175 samples were taken from the surface soil layer (0–0.05 m) of cropland and unpaved roads, and
176 on exposed sites located along the river channel network. The unpaved road samples were taken
177 in places where there was evident erosion. Areas that might have accumulated sediment
178 originating from other sources (e.g. nearby cropland) were excluded during sampling to avoid
179 collecting transiting material. Each sample was composed of at least 10 sub-samples in order to
180 obtain representative source material. Samples were always taken at sites sensitive to erosion and
181 connected to the river network. Sampling was performed to collect the entire range of soil types
182 found in the catchment. Care was taken to avoid collecting transiting material or sediment
183 deposits from other primary sources.

184

185 *Sediment sampling*

186 Sediment sampling was performed following three strategies ($n = 78$, Table 1). First, at
187 the catchment outlet, *flood suspended sediments (FSS)* ($n = 20$) were obtained by the manual
188 sampling of a large volume of water (~50 liters) at varying intervals during floods. Second, at
189 five different sites across the catchment, *time-integrated suspended sediment samplers (TISS)* (n
190 $= 33$) (Phillips *et al.*, 2000) that remained immersed in the river during 28 to 102 days were
191 deployed. In order to compare the different samples, the mean daily flux of suspended sediment
192 was calculated for each period. Finally, the third strategy was to collect *fine-bed sediment (FBS)*
193 ($n = 34$) with a suction stainless sampler to minimize the loss of fine material at the
194 sediment/water interface. The sampler used was a malleable plastic bottle. Sediment sampling
195 required diving and placing the open side of the bottle on the bottom of the river channel with
196 the bottle completely pressed. When the pressure released, it created a vacuum pumping the
197 sediment from the bottom of the river channel into the bottle. FBS samples were composed of 20
198 to 30 subsamples collected from river channel cross-sections of 10 to 25 m.

199

200 *Source and sediment analyses*

201 Source and sediment samples were oven-dried at 50°C, and gently disaggregated using a
202 pestle and mortar, and then sieved to 63 μm to compare similar grain size-fractions, as
203 recommended in previous sediment fingerprinting studies to avoid any bias resulting from the
204 higher affinity/content in some elements in the smaller particle size fractions (Walling, 2013;
205 Laceby *et al.*, 2017).

206 The geochemical tracers evaluated included: total organic carbon (TOC) estimated by wet
207 oxidation ($\text{K}_2\text{Cr}_2\text{O}_7 + \text{H}_2\text{SO}_4$) and the total concentration of several elements (Al, Ba, Be, Ca,

208 Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Na, Ni, P, Pb, Sr, Ti, V, and Zn) using ICP-OES after
209 microwave assisted digestion with concentrated HCl and HNO₃ (ratio 3:1) for 9.5 min at 182°C.

210

211 *Selection of optimum fingerprinting properties*

212 Prior to tracer selection, outliers were identified and removed from the sample set as
213 suggested by Gellis and Noe (2013). A total of 15 source sediment samples with one or more
214 outliers (values exceeding three times the standard deviation of the average value) were detected
215 and excluded from the further steps of source discrimination analysis (cropland = 6, unpaved
216 roads = 6, channel banks = 3). In addition, the variables for which concentrations measured in
217 sediment fell outside the range of those measured in sources were excluded from further analyses
218 (“*range test*”) as suggested by Gellis and Noe (2013) to test the conservative behavior of the
219 tracers.

220 Then, composite fingerprints were established based on a non-parametric mean test
221 (Kruskal-Wallis *H*) followed by a multivariate discriminant function. The *H*-test identifies
222 geochemical properties showing significant differences between the various sediment sources.
223 These properties can, therefore, be used as potential tracers. Afterwards, a multivariate
224 discriminant function analysis (DFA) was performed to select the minimum number of variables
225 that maximize the discrimination between the sources. DFA was performed in the backward
226 mode, using $p < 0.01$ to enter a property and $p < 0.05$ to remove a property.

227

228 *Apportionment of sediment sources*

229 To estimate the contribution of the sources in each sediment sample, the tracers selected
230 in the previous steps were then entered into a multivariate mixing model based on a system of
231 linear equations using Matlab® software. The model used had only two boundary conditions,
232 wherein: (i) the sum of the sources contribution should be equal to 100%, and (ii) the contribution
233 of each source may not be less than 0% and not higher than 100%. Further details on this
234 procedure can be found in Tiecher et al. (2017b).

235

236

RESULTS

237 *Source discrimination*

238 Concentrations of Ca, K, Mg, Na, Sr, and Ti exceeded in most sediment samples the
239 highest concentration measured in sources. In the same way, concentrations of Al, Li, Pb, and
240 TOC in most sediment samples were lower than the lowest source concentration. These elements

241 were considered non-conservative in the Conceição catchment and excluded from further
242 analysis.

243 The concentrations in the remaining 12 geochemical tracers (Ba, Be, Co, Cr, Cu, Fe, La,
244 Mn, Ni, P, V, and Zn) measured in sediment remained in the same range as the sources and were
245 used in the next steps. Eleven geochemical tracers (Ba, Be, Co, Cr, Fe, La, Mn, P, Sr, V, and Zn)
246 were selected as potential tracers after applying the Kruskal-Wallis H -test ($p < 0.1$) (Table 2). The
247 discriminatory power of these tracers ranged from 31.2 to 62.4%. No single tracer was able to
248 correctly classify 100% of the source samples in their respective source groups.

249 Six tracers were selected by DFA as the optimum set of tracers (P, La, V, Mn, Be, and Ba
250 – Table 3). The final value of the Wilk's lambda parameter in the DFA was 0.2702, meaning that
251 these six tracers were able to explain approximately 73.0% of the differences between the
252 sediment sources (Table 3). All three sediment sources were well separated by a Mahalanobis
253 distance of 6.0 ± 1.1 ($p < 2.50E-14$) (Table 4). Moreover, 84.4% of sediment sources were
254 correctly classified in their respective groups (Table 3).

255

256 *Source apportionment*

257 All four floods monitored at the outlet were characterized by clockwise hysteresis (Figure
258 4 and 5). The source contributions obtained with FSS technique was strongly different during the
259 flood event that occurred in July (winter), compared to the other events occurring in September
260 and October (beginning of spring). Cropland contribution increased with discharge during the
261 last three floods (Fig. 4f, Fig. 5c, Fig. 5f), while the supply of sediment from stream channel
262 banks decreased during the rising limb before increasing again during the recession limb.
263 Moreover, the contribution of cropland during the first flood event (July) was much higher than
264 during the other floods. These differences are likely explained by various rainfall characteristics.
265 For instance, the weather station located at the catchment outlet did not record any rainfall during
266 the July 2012 event, which likely indicates that rainfall exclusively occurred in upper catchment
267 parts. This is also likely reflected by the maximum water discharges observed during these
268 events, with $24 \text{ m}^3 \text{ s}^{-1}$ in July 2012 vs. a range of $61\text{--}178 \text{ m}^3 \text{ s}^{-1}$ during the other flood events.
269 For the events occurring in 19 September, 2 October, and 23 October 2012, the total precipitation
270 was 70, 119, and 63 mm, with a mean intensity of 4.5, 4.8, and 5.9 mm h^{-1} , corresponding to a
271 return period (based on total precipitation and rainfall intensity) of 13, 321, and 12 days.

272 Unpaved road contributions were similar and very low ($1 \pm 1\%$) for all the sediment
273 sampling strategies (Table 5). The contribution of sources delivering suspended sediment to the
274 river showed no significant differences between the sampling sites for both sediments collected

275 with time-integrate samplers (TISS) and the fine material collected on the riverbed (FBS) (Table
 276 5, see Figure 1 and 2 in the supplementary material). However, when grouping all sediment
 277 samples collected at the five sampling sites (Table 5), stream channel bank contribution was
 278 higher in FBS ($90\pm 17\%$) than in material collected with the time-integrated samplers ($56\pm 22\%$).
 279 In contrast, cropland contribution was higher for TISS ($44\pm 22\%$) than for FBS ($8\pm 16\%$) (Table
 280 5 and Figure 6).

281 At the catchment outlet, cropland and stream channel banks contribution also varied
 282 depending on the sediment sampling strategy (Table 5). Contribution of cropland increased
 283 according to the following sequence: FBS ($8\pm 20\%$) < TISS ($45\pm 22\%$) < FSS ($70\pm 21\%$) (Figure
 284 7). In contrast, contribution of stream channels decreased in a similar way: FBS ($90\pm 17\%$) >
 285 TISS ($55\pm 12\%$) > FSS ($30\pm 21\%$) (Figure 7). Moreover, the relative mean errors (RME)
 286 associated with sediment source contributions decreased as follows: FBS ($19\pm 7\%$) > TISS
 287 ($10\pm 6\%$) > FSS ($6\pm 4\%$) (Figure 7).

288

289 *Weighted source contributions*

290 Total sediment discharge for the monitored period was 75,124 Mg. Sediment flux was
 291 higher for the first and third sampling periods (Figure 8a). Sediment yield from cropland ranged
 292 from 0.05 to 1.63 Mg ha⁻¹ yr⁻¹ in the second and third periods, respectively (Figure 8b).

293 Weighted contributions (Figure 8 e, g) were compared to raw results (Figure 8 d, f).
 294 Similar trends were observed for sediment collected in time-integrated samplers. However,
 295 weighted contributions of cropland were about 10% lower than modeling results during floods,
 296 whereas stream channel banks exhibited an opposite behaviour.

297

298 DISCUSSION

299 *Dominant erosion processes*

300 Overall, the results show a dominant supply of sediment from cropland (9–70%) and
 301 channel banks (30–90%), with minor contributions of material from unpaved roads (~1%). The
 302 flood events were associated with an increase in sediment transfer from cultivated topsoil, as
 303 found by Cooper et al. (2015). The dominance of sediment originating from cropland during the
 304 rising limb likely indicates the rapid transfer of runoff and sediment from cultivated fields which
 305 are well connected to the stream network. These results are also supported by field observations
 306 during storms. Moreover, the relationship between Q and SSC demonstrates a clockwise pattern
 307 in most cases with a clear anticipation of sediment peak, indicating the mobilization of the
 308 material near to the outlet of the basin and a process of sediment exhaustion throughout the

309 events. The delayed sediment inputs from channel banks during the floods triggered by higher
310 rainfall that occurred in September and October 2012 (Fig. 4 and 5) may reflect the occurrence
311 of bank failure during the water level recession (Carter *et al.*, 2003), which was not observed
312 during the low rainfall event that occurred in July 2012. Intra-storm contribution of unpaved
313 roads showed no clear pattern because these roads are constantly redesigned and damaged by the
314 traffic of heavy agricultural machinery mainly under wet conditions.

315 Relative contributions of the different sources to fine sediment deposited on the stream
316 bed (FBS) and suspended sediment (TISS) were not similar. The lower mean relative errors
317 obtained with the TISS technique indicate that this sediment sampling strategy is likely the most
318 appropriate in Conceição catchment because its results were associated with the lowest
319 uncertainty. Other studies have also reported that source contributions to FBS and suspended
320 sediment may be different (Lamba *et al.*, 2015). For instance, Navratil *et al.* (2012) found similar
321 source contribution differences between flood deposits and suspended sediment collected in the
322 Alpine Bleone River. Suspended sediments are primarily composed of finer sediment ($<63\mu\text{m}$),
323 while sediment originating from eroded channel banks can be transported as individual coarser
324 particles or as a mix of aggregates due to mass failures, which are one of the main erosion
325 processes in Conceição catchment. The aggregates are more likely to deposit on the stream bed
326 than individual fine particles (*i.e.* suspended sediments). Furthermore, sediments eroded during
327 the recession stage, when most failures occur after the flood peak, are more likely to deposit on
328 the stream bed.

329

330 *Source contributions*

331 The high channel bank contributions (ranging from 30 to 90% depending on the sediment
332 sampling strategy – Figure 7) found in Conceição catchment could be explained by the sparse
333 riparian forest cover found in this area. Riparian vegetation was shown to have a significant
334 impact on stream stability and morphology because mature trees increase bank stability against
335 mass failure by reinforcing the bank sediment with roots, preventing banks from failing due to
336 oversteepening from lateral toe scour (Abernethy and Rutherford, 2000). Moreover, riparian
337 forest acts as barrier for sediment originating from cropland, by decreasing connectivity between
338 the hillslopes and the stream.

339 In soils under no-till there is less erosion, but there are larger quantities of runoff produced
340 (Merten *et al.*, 2015). This clear water flow has a greater ability to erode the drainage channels.
341 This process may explain the frequent occurrence of gully erosion observed in thalwegs (see
342 Figure 3 in the supplementary material). In these landscapes, there is the convergence of flow

343 with low sediment concentrations that propagates in the thalweg where it generates concentrated
344 erosion (zero-order channel). This type of process is also likely to occur in the river channel (see
345 Figure 4 in the supplementary material). These results agree with those of Minella *et al.* (2008),
346 who demonstrated that sediment mobilization from the channel system increased after the
347 implementation of improved land management on cropland (such as minimum tillage and winter
348 cover crops) due to channel scour and bank collapse associated with reduced sediment inputs and
349 increased transport capacity.

350 Rural road networks may provide a continuous sediment source to rivers during the entire
351 year in wet tropical regions (Thomaz *et al.*, 2014). Sediment fingerprinting studies conducted in
352 small rural catchments from southern Brazil where soils are frequently plowed showed that
353 unpaved roads contribute on average 25–50% of suspended sediments (Minella *et al.*, 2009;
354 Tiecher *et al.*, 2014, 2015b, 2016). However, according to Didoné *et al.* (2014), the values
355 obtained in these small catchments (<1.5 km²) might not necessarily be extrapolated to larger
356 catchments. Although severe erosion processes can be observed along the roads in Conceição
357 catchment (Didoné *et al.*, 2014), the contribution of unpaved roads was shown to remain very
358 low (<1%) by the current research. Pictures taken at different times in Conceição catchment
359 clearly show that the current road level compared to the nearby cropland is significantly lower
360 than in the 1960s/1970s (see Figure 5 in supplementary material). Although erosion is low in
361 roads compared to that occurring in cropland and in channel banks, its impacts are clearly visible
362 when they are cumulated over several decades. Despite the current low contribution of unpaved
363 roads compared to cropland and channel banks in Conceição catchment, roads are perennial
364 landscape features. Therefore, their construction should be planned in the framework of
365 integrated soil erosion control programs designed at the catchment scale (Evrard *et al.*, 2010).
366 Future sediment fingerprinting studies could usefully incorporate additional tracers with greater
367 potential for discrimination between surface and subsurface sources, such as fallout
368 radionuclides, in order to provide better differentiation of unpaved roads contribution (depleted
369 in ¹³⁷Cs) and the cropland surface and river channel (enriched in ¹³⁷Cs) (Ben Slimane *et al.*, 2013;
370 Foucher *et al.*, 2015).

371

372 *Management implications*

373 In Brazil, quantitative data on sediment sources and fluxes at the catchment scale are still
374 scarce particularly in cash crop regions, where the implementation of a conservationist no-tillage
375 system is promoted to protect soils (Didoné *et al.*, 2014). Cropland in Conceição catchment is
376 characterized by a low sensitivity to erosion, because (*i*) soils are deep, clayey, and rich in iron

377 oxides, which limits the detachment of particles by raindrop impact and runoff; (ii) average
378 topography is characterized by gentle slopes; and (iii) the no-tillage (NT) is applied on most of
379 the cultivated area (>80%). However, the current research shows that, even in these favorable
380 conditions, the amount of sediment supplied by cropland to the river network remains very high.
381 When weighting source contributions with the sediment flux calculated at the Conceição
382 catchment outlet by Didoné et al. (2014) ($1.40 \text{ Mg ha}^{-1} \text{ yr}^{-1}$), the flux supplied by cropland was
383 estimated $1.3 \pm 0.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for TISS and $0.8 \pm 0.2 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for FSS. Several characteristics
384 of the agricultural production system that are reducing infiltration and increasing runoff and
385 erosion may explain the high sediment delivery from these fields despite their relatively low
386 erosion potential, such as (i) the absence of crop rotation; (ii) grazing of winter biomass (oat and
387 ryegrass) reducing soil covering; (iii) sowing parallel to the main slope lines, increasing runoff
388 speed and erosion potential; (iv) degradation of the soil structure and occurrence of soil
389 compaction due to the traffic of heavy machinery under inadequate moisture conditions; and (v)
390 the absence of additional soil conservation measures to control runoff as crop leveling, strip
391 cropping, terraces, and grassed channel sinks.

392 Despite the above-mentioned on-site erosion problems (loss of fertility, farmland and soil
393 water storage), the soils from Conceição catchment remain rich in clay and Fe-iron oxides that
394 are good sorbents of nutrients, especially P (Bortoluzzi *et al.*, 2015), and of several types of
395 contaminants such as heavy metals, pesticides and other persistent organic pollutants. Erosion of
396 these soils can then generate off-site problems such as eutrophication and fish kills. Furthermore,
397 it increases the cost of water treatment and the exposure of the human population to potentially
398 hazardous substances.

399

400

CONCLUSION

401 This study shows that cropland was the main source of sediment in the Conceição
402 catchment characterized by the widespread implementation of no-tillage since the 1990s.
403 Although channel banks also provided a significant source of fine-grained material to the river
404 system, the contribution of unpaved roads was shown to be negligible. The contribution of these
405 sediment sources varied during flood events with cropland supplying more material during the
406 rising stage. In contrast, the channel bank contribution tended to increase during the recession
407 stage. The contribution of these sources remained similar for various sampling sites within the
408 investigated catchment. In contrast, sediment sources varied depending on the sediment sampling
409 strategy.

410 The effect of applying no-tillage without implementing additional runoff control
 411 measures could be quantified using the sediment fingerprinting approach. The amount of
 412 sediment supplied by cropland to the river network remains excessive to be sustainable, and
 413 additional efforts are necessary to further reduce soil erosion. To improve this situation,
 414 mechanical practices for runoff control and crop rotations should be reintroduced. Furthermore,
 415 higher biomass inputs should be supplied to soils to increase soil cover by vegetation, and farmers
 416 should refrain from using heavy agricultural machinery during wet periods, because it causes soil
 417 compaction, decreasing water infiltration and leading to a gradual increase in runoff and erosion.
 418 Accordingly, there is an urgent need to better plan land cover and farming practices in agricultural
 419 areas where no-till is applied in southern Brazil.

420

421

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604

605 Figure 1. Evolution of the area under no-till in Brazil.

606

607 Figure 2. Location of the Conceição catchment in Brazil, the soil/sediment sampling sites, and
608 the proportion of the area in each sub-section of sediment sampling.

609

610 Figure 3. Lithology (a), soil types (b), slope (c), and land use (d) in Conceição catchment.

611

612 Figure 4. Records of precipitation, discharge, suspended sediment concentration (SSC) (a);
613 hysteresis pattern (b); and the sediment source contributions – and relative mean error – (c),
614 during the floods that occurred on 6 July and 19 September 2012 in Conceição catchment. Letters
615 under the bars (c) correspond to sampling periods (a) during the floods. Precipitation on 6 July
616 2012 was very small and it was not recorded by the meteorological station that is positioned in the
617 basin outlet. The rainfall of this event may have occurred more upstream of the basin.

618

619 Figure 5. Records of precipitation, discharge, suspended sediment concentration (SSC) (a);
620 hysteresis pattern (b); and the sediment source contributions – and relative mean error – (c),
621 during the floods that occurred on 2 and 23 October 2012 in Conceição catchment. Letters under
622 the bars (c) correspond to sampling periods (a) during the floods.

623

624 Figure 6. Box plot of the sediment source contribution for time-integrated suspended sediments
625 and fine-bed sediments collected in all sites of Conceição catchment. RME = relative mean
626 error.

627

628 Figure 7. Box plot of the sediment source contribution for time-integrated suspended
629 sediments, fine-bed sediments, and flood suspended sediments collected at Conceição
630 catchment outlet. RME = relative mean error.

631

632 Figure 8. Weighted sediment yield (a) and mean daily flux of sediments (b) using time
633 integrated suspended sediments, and weighted sediment yield for each individual flood sampled
634 (c). The unweighted results and weighted contributions are also presented in pie charts for time
635 integrated suspended sediments (d, e) and flood suspended sediments (f, g).

636

637

638

Figure 1

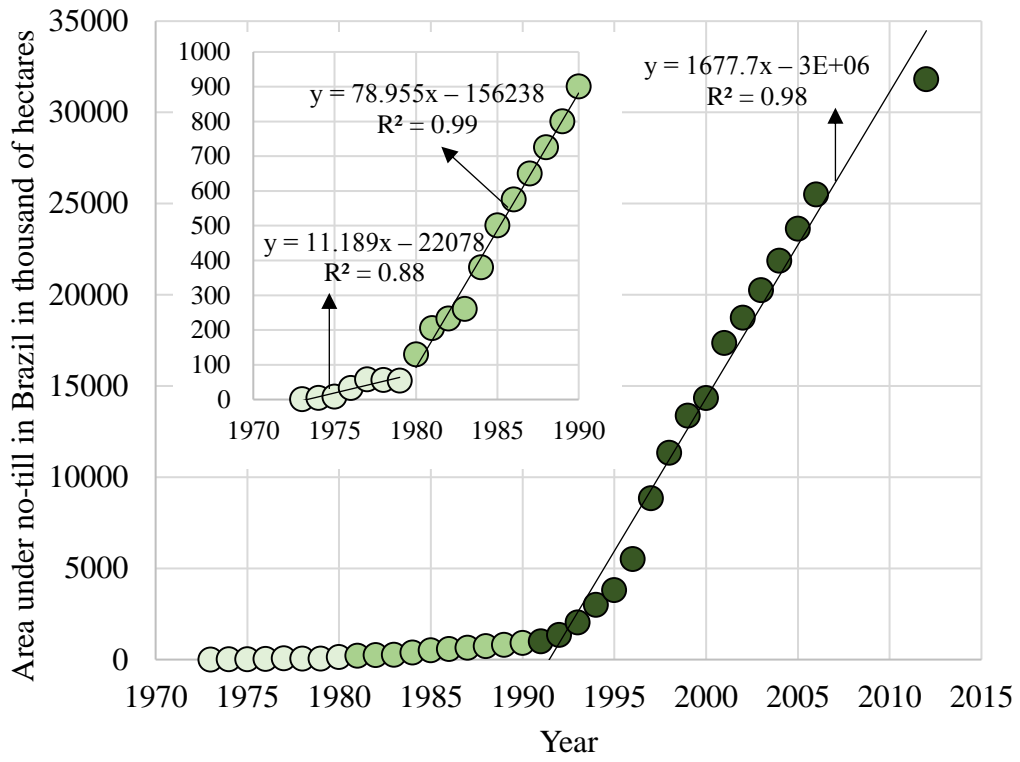


Figure 2

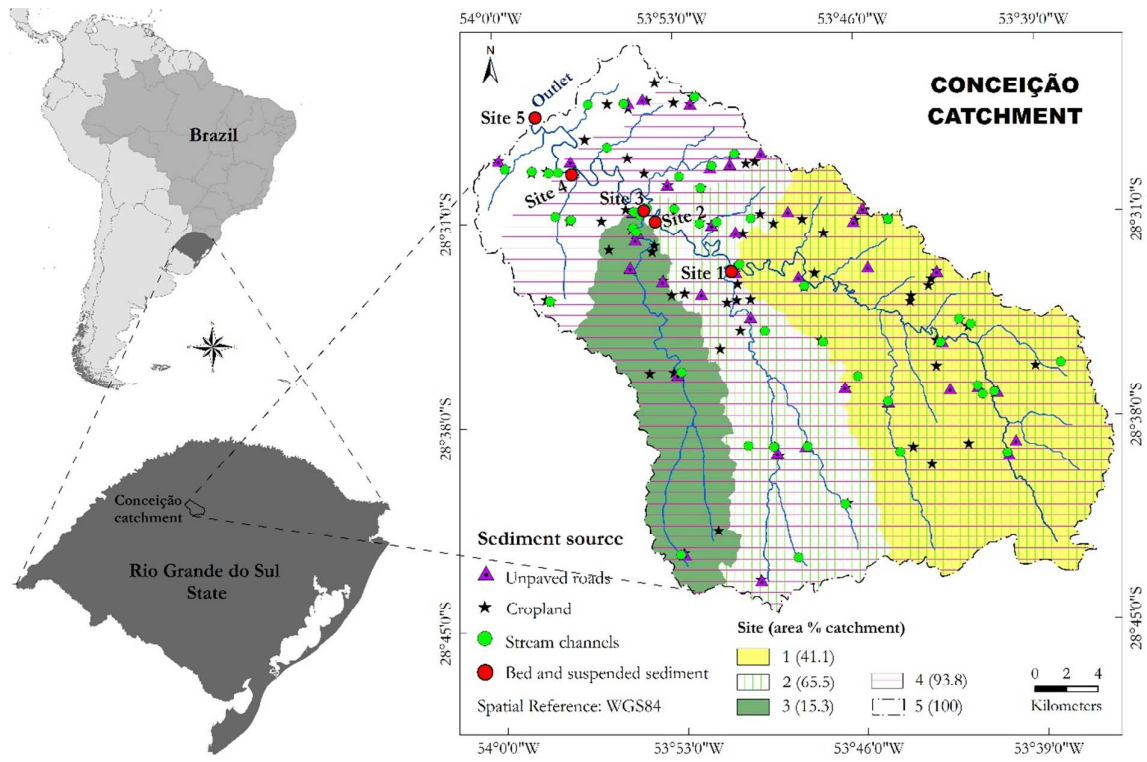


Figure 3

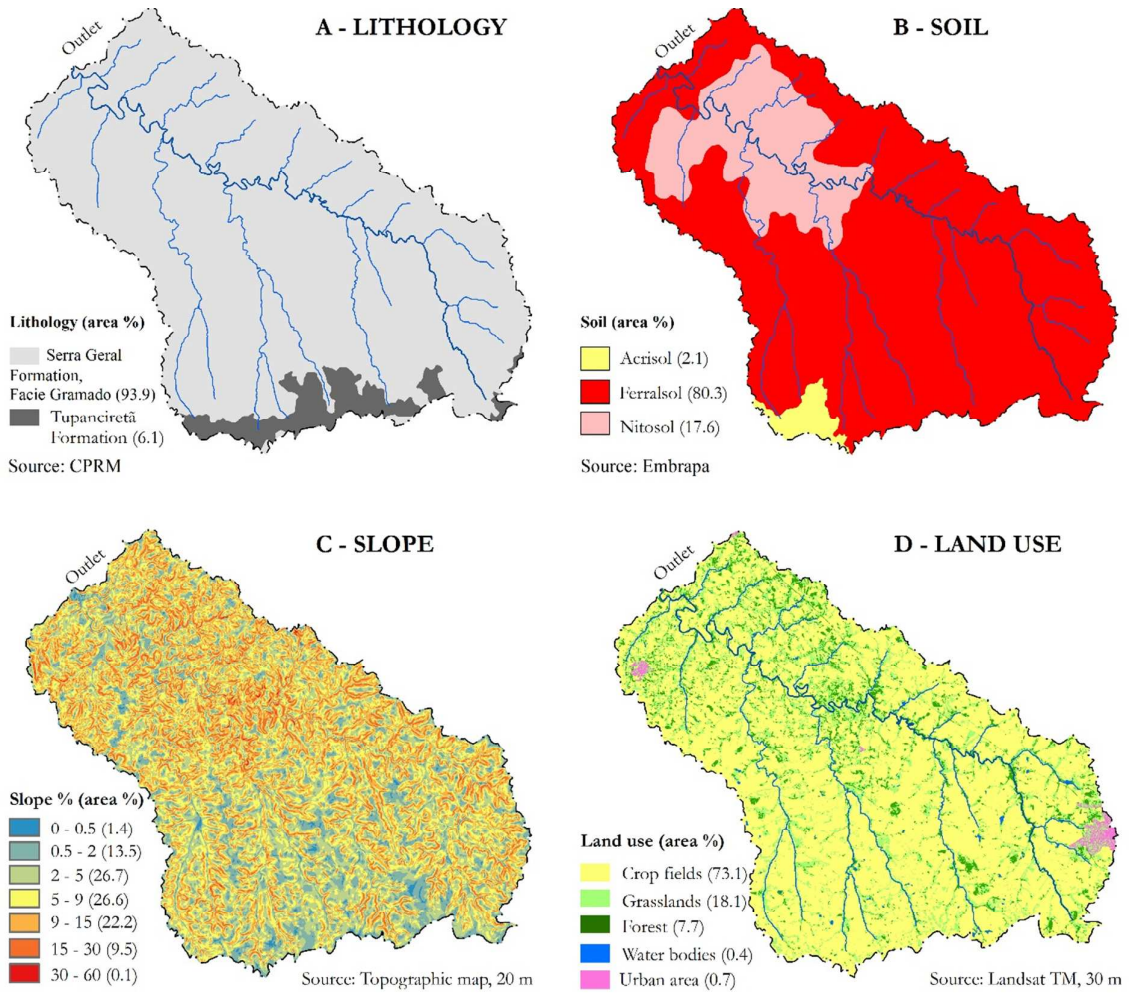


Figure 4 (1/2)

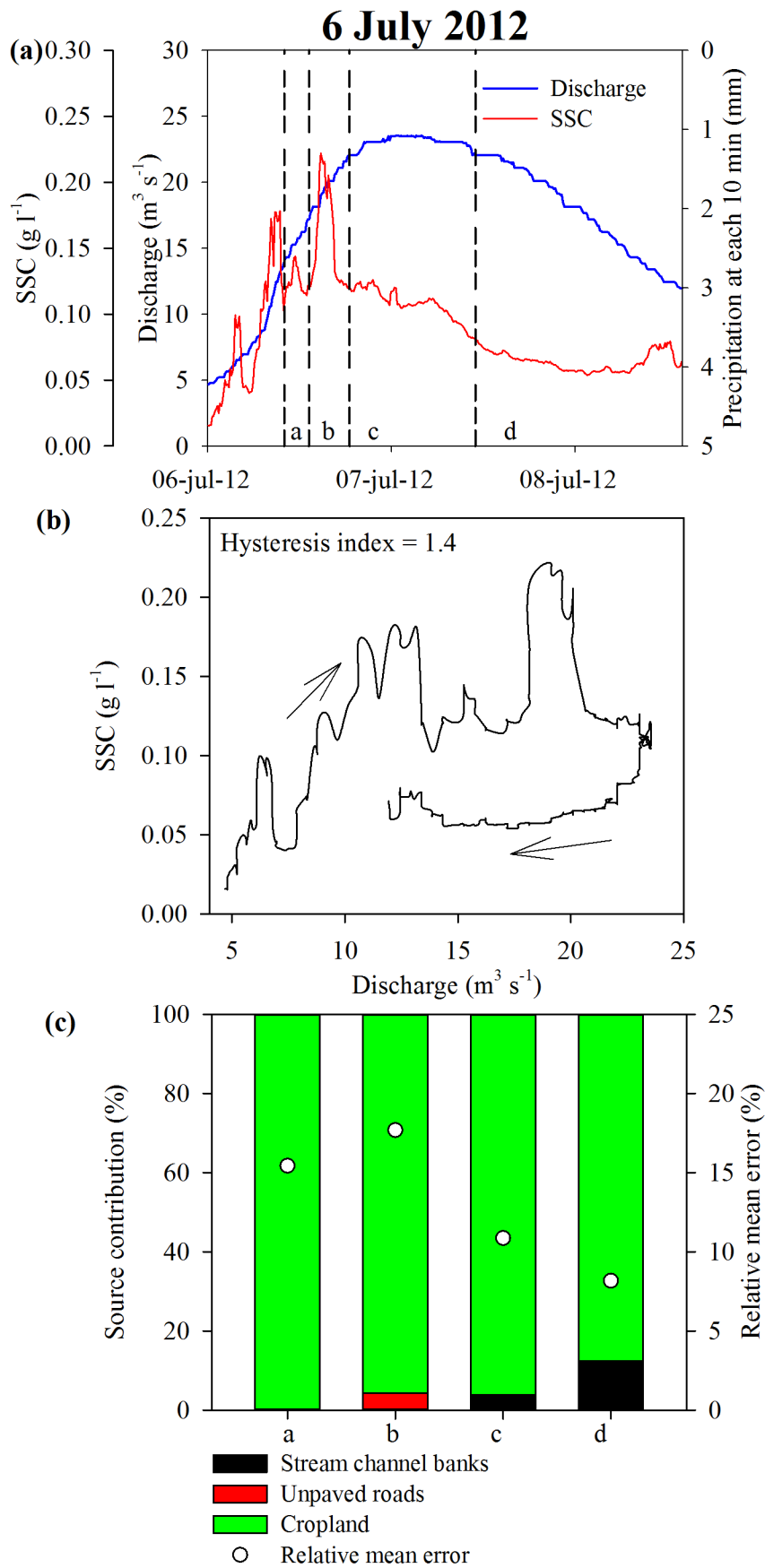


Figure 4 (2/2)

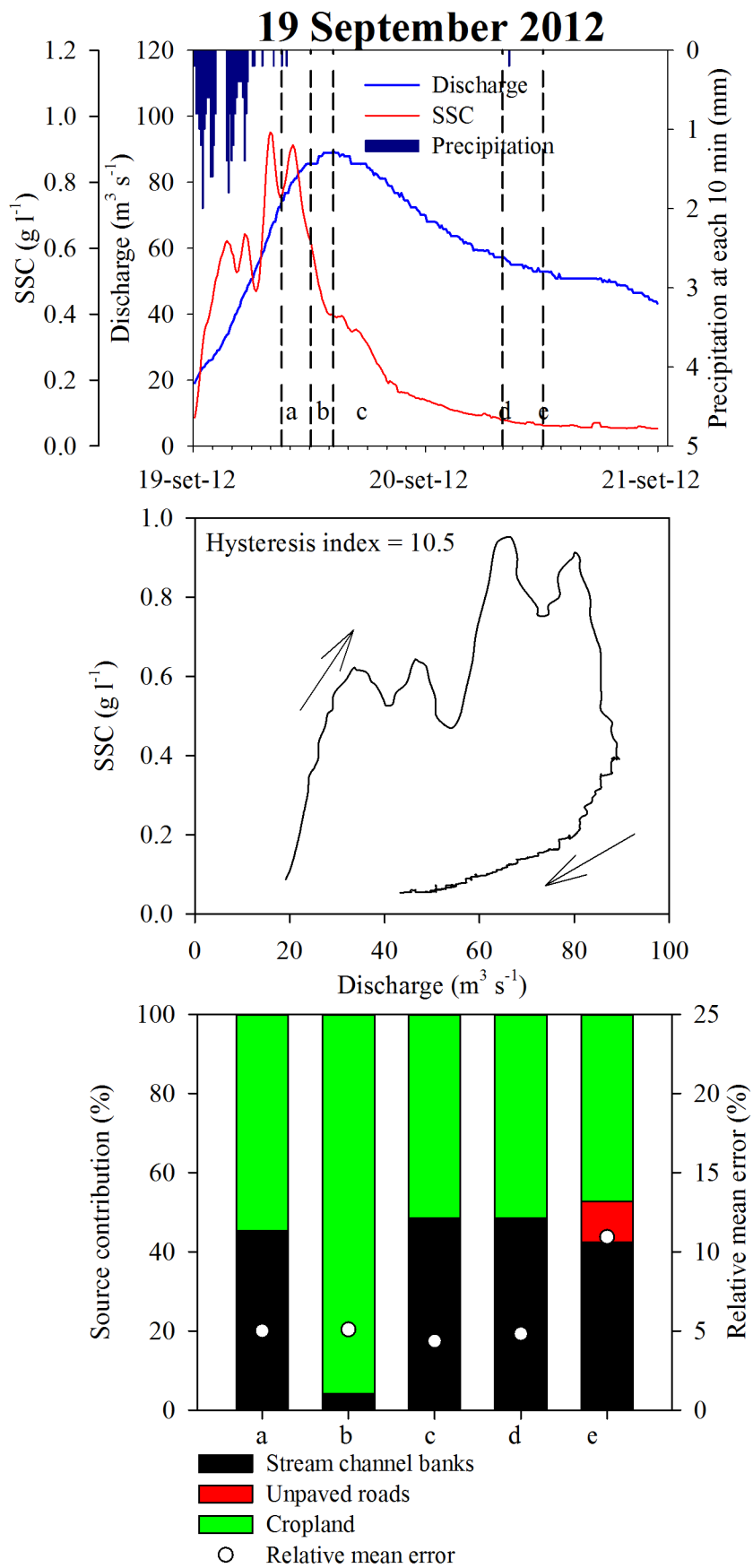


Figure 5 (1/2)

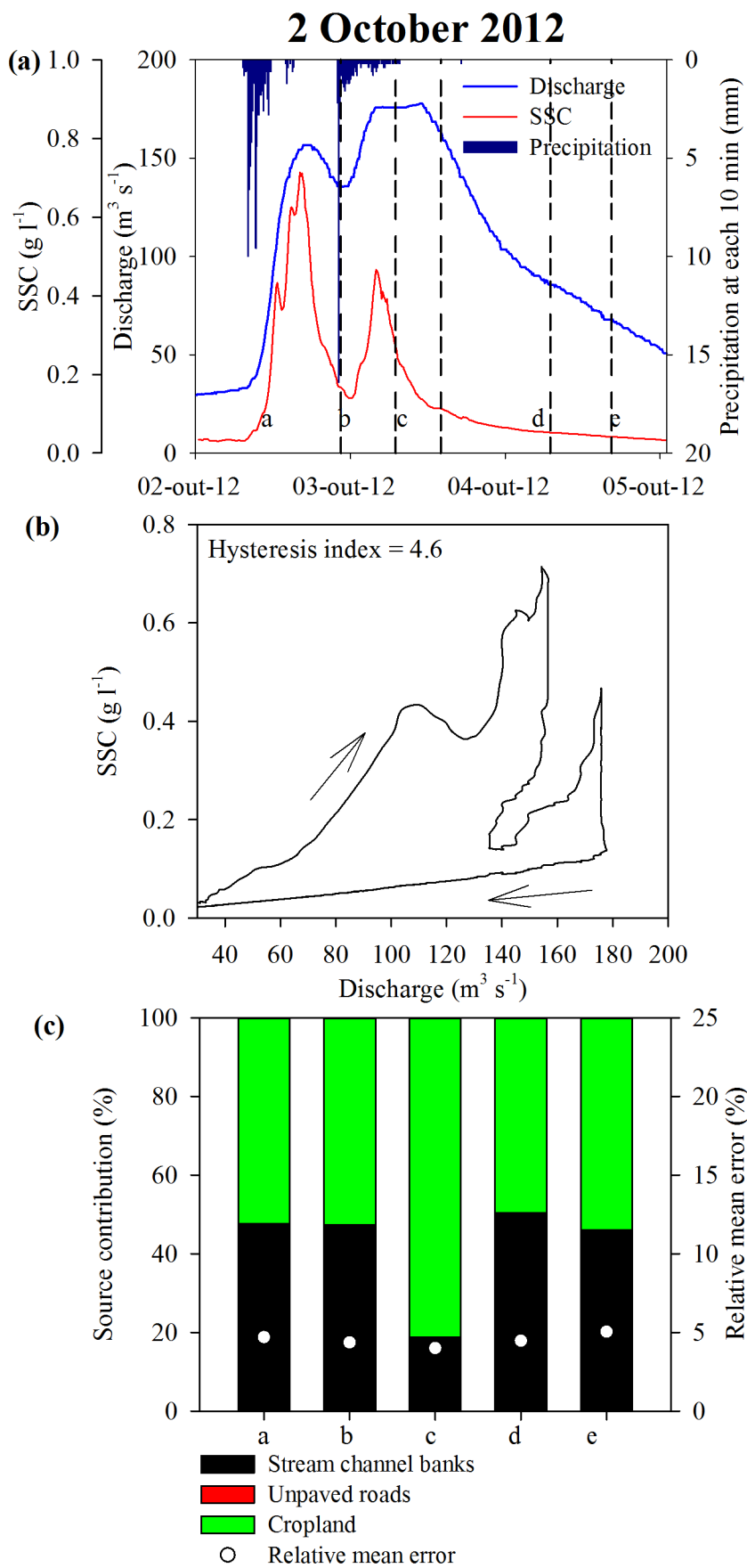


Figure 5 (2/2)

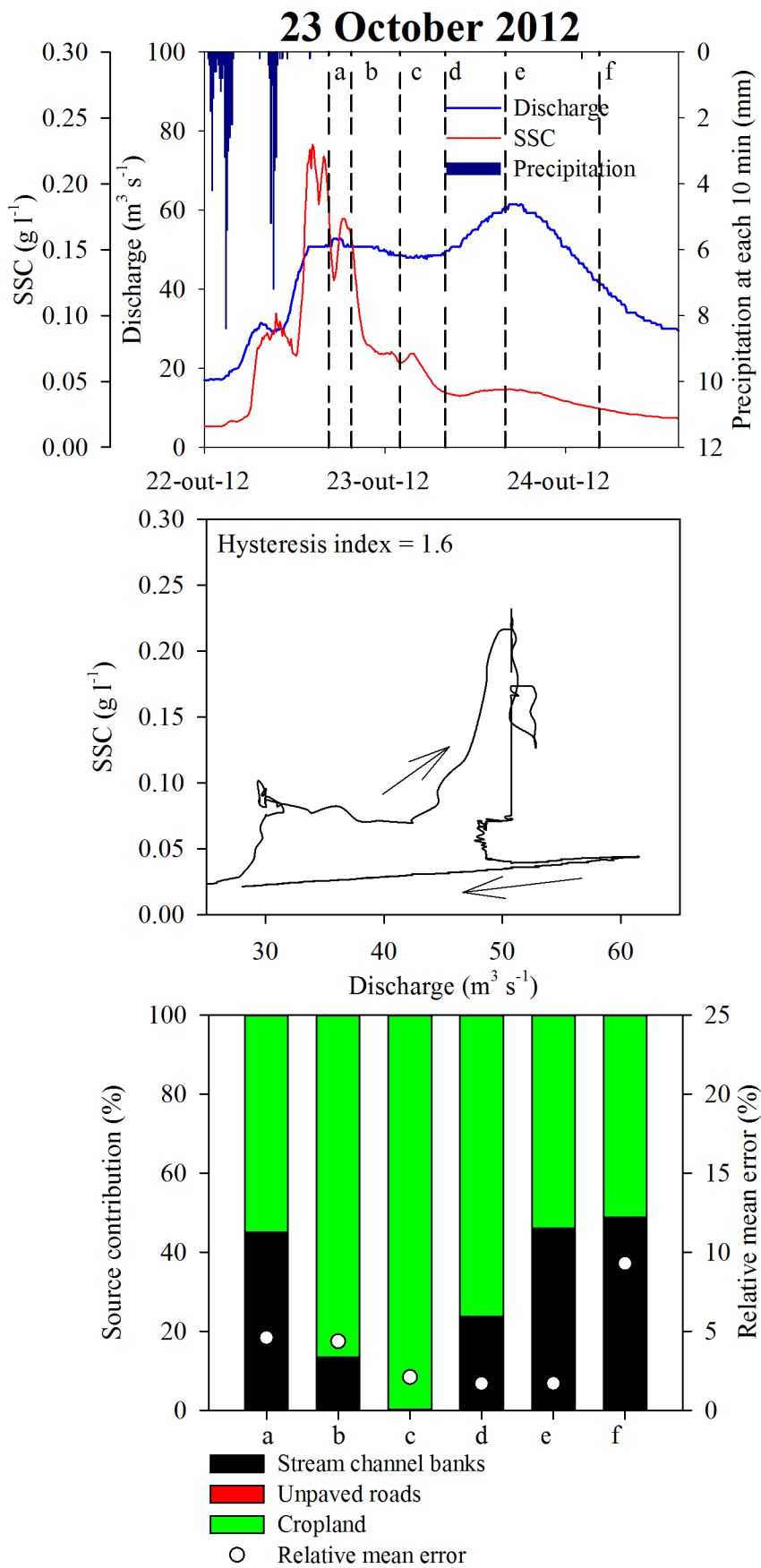


Figure 6

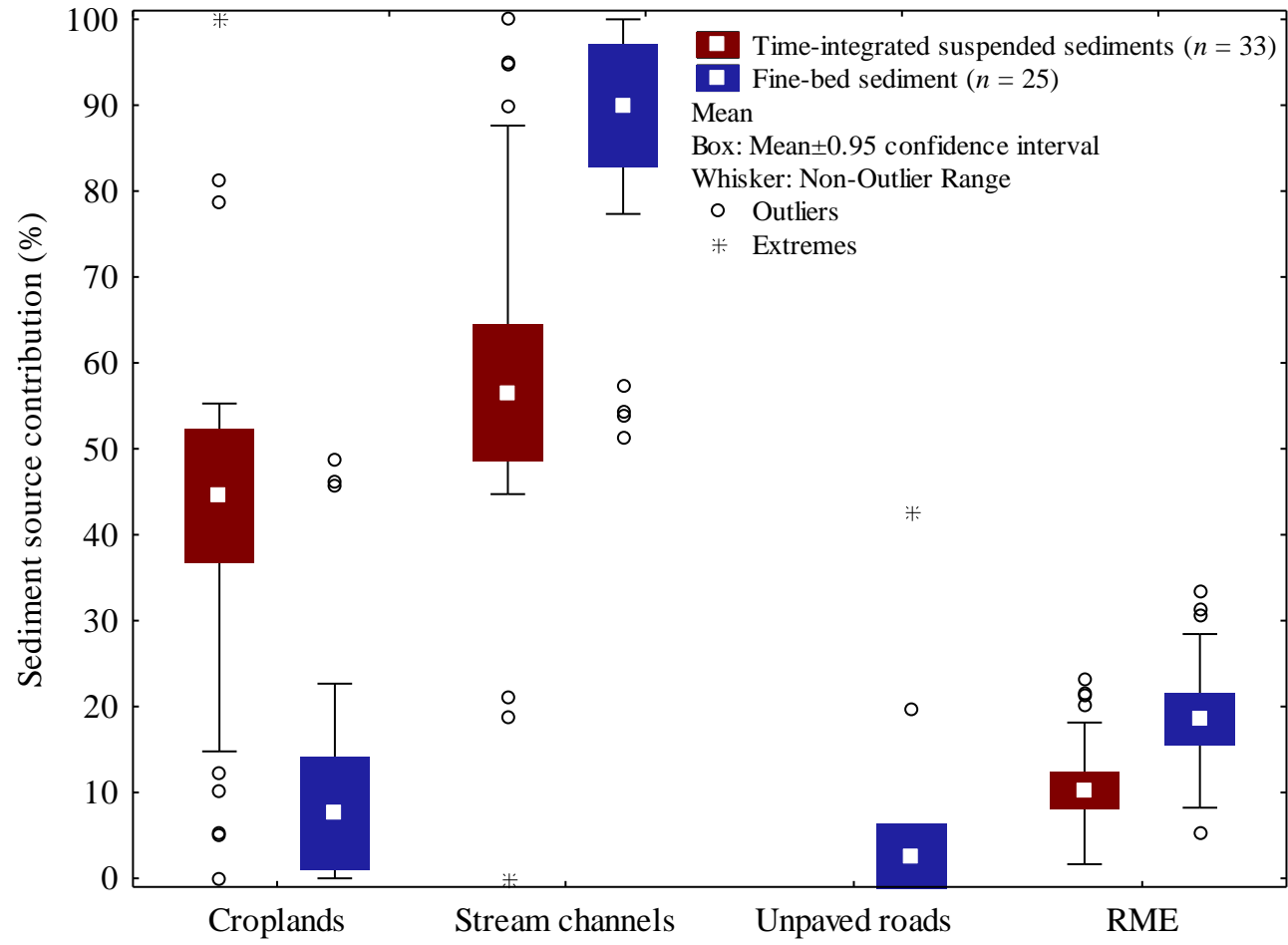


Figure 7

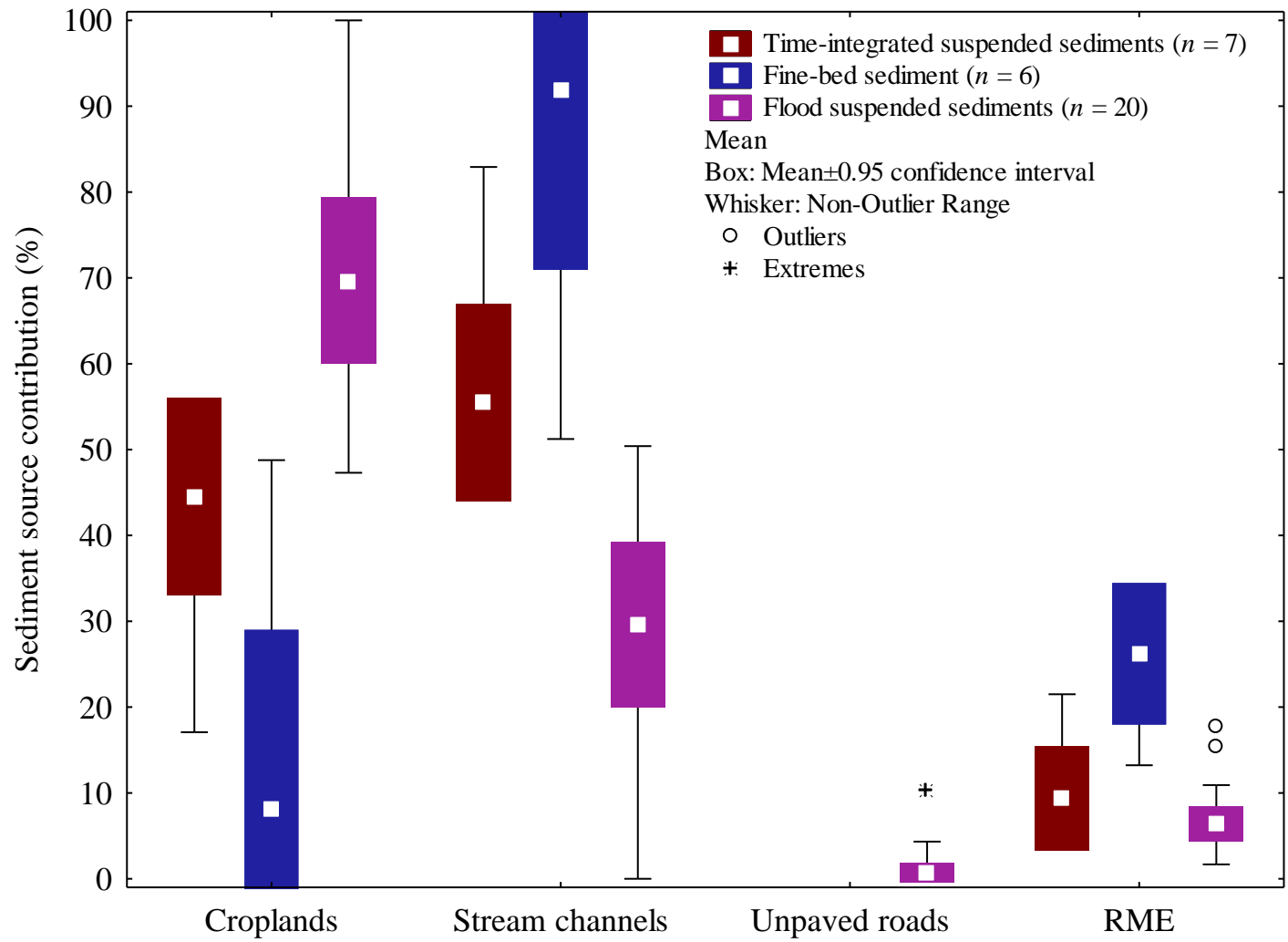
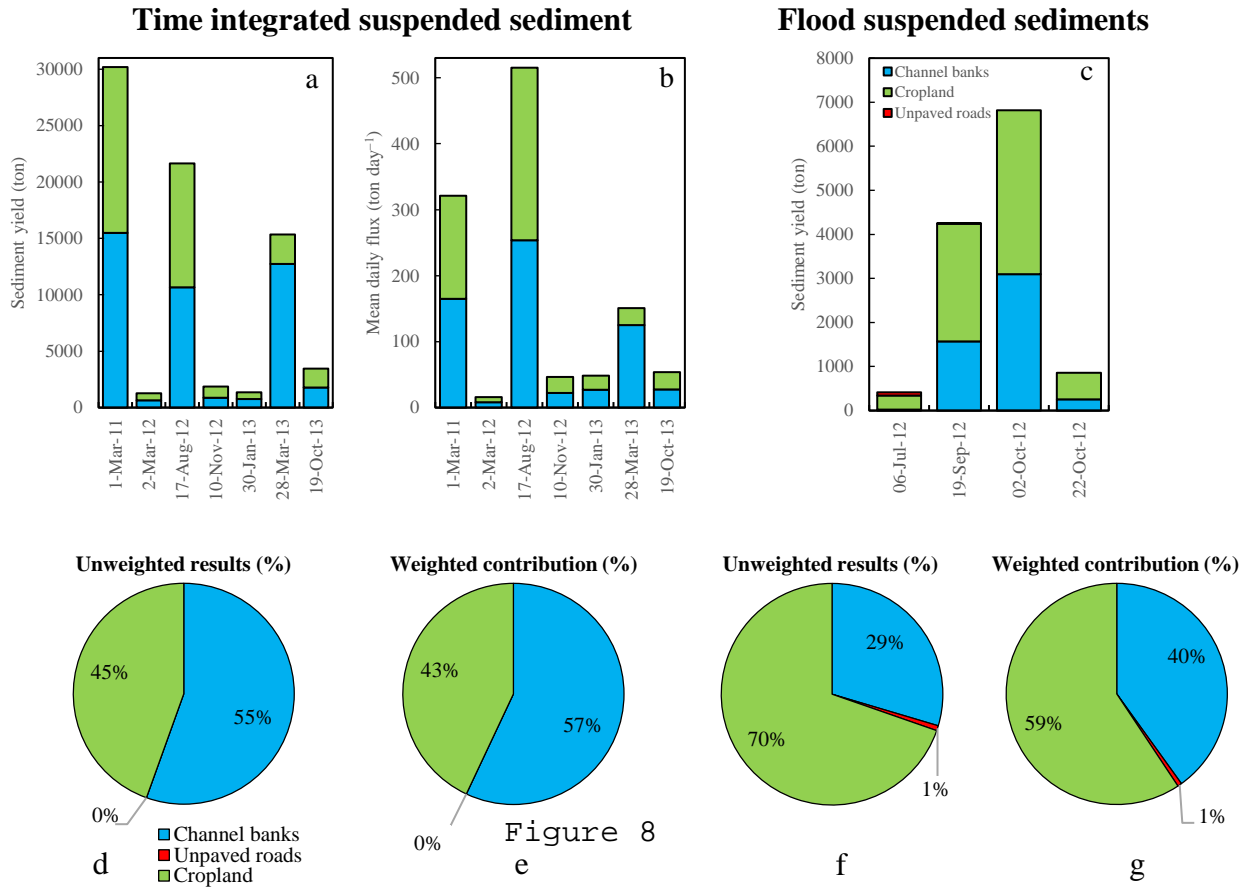


Figure 8



639 Table 1. Percentage distribution of land use in the drainage area and number of sediment samples collected at each
 640 site following different strategies in sub-catchments of Conceição River.

Land use (%)	Sub-catchment					Total
	1	2	3	4	5	
Cropland	73.1	73.8	78.6	74.7	73.8	-
Grasslands	18.1	17.7	16.0	17.0	17.0	-
Forest	7.7	7.4	5.2	7.0	7.4	-
Water body	0.4	0.4	0.3	0.4	0.4	-
Urban	0.7	0.7	0.0	0.9	1.4	-

Number of sediment samples collected following each sediment sampling strategy

TISS	7	6	7	6	7	33
FBS	5	3	8	3	6	25
FSS	-	-	-	-	20	20
Total	12	9	15	9	33	78

641 TISS, time-integrated suspended sediment; FSS, flood suspended sediment; FBS, fine-bed sediment
 642

Table 2. Geochemical element concentrations in sediment sources and suspended sediments, results of the Kruskal–Wallis H -test and the Discriminant Function Analysis (DFA) used to identify the optimum composite fingerprint for distinguishing the source types supplying sediment to the Conceição River. SD, standard deviation; TISS, time-integrated suspended sediment; FSS, flood suspended sediment; FBS, fine-bed sediment.

Fingerprint property	Stream channel banks ($n = 33$)		Unpaved roads ($n = 35$)		Cropland ($n = 73$)		Kruskal-Wallis test			DFA – correctly classified samples (%)	Sediment samples					
							H -value	p -value	Signif.		TISS ($n = 33$)		FSS ($n = 20$)		FBS ($n = 25$)	
	Mean	SD	Mean	SD	Mean	SD					Mean	SD	Mean	SD	Mean	SD
Al (g kg^{-1})	59.9	12.5	91.6	13.2	71.5	13.8	57.1	<0.001	****	53.2	51.3	8.5	53.7	8.6	41.1	8.0
Ba (mg kg^{-1})	210.9	55.3	123.2	79.0	191.7	79.4	31.5	<0.001	****	45.4	350.6	84.4	337.7	38.5	404.4	211.4
Be (mg kg^{-1})	3.9	0.6	3.4	0.5	3.7	0.6	12.6	0.002	***	34.8	6.1	3.3	4.6	1.3	5.8	3.2
Ca (g kg^{-1})	1.8	0.9	0.6	1.0	2.1	1.1	54.9	<0.001	****	50.4	4.1	2.5	13.0	6.5	3.2	0.6
Co (mg kg^{-1})	58.9	19.5	25.6	17.4	45.5	20.6	37.0	<0.001	****	45.4	76.6	14.6	53.1	8.5	126.1	48.8
Cr (mg kg^{-1})	79.2	14.0	67.0	12.5	75.3	18.9	12.7	0.002	***	36.2	97.6	23.8	70.8	7.7	141.0	54.0
Cu (mg kg^{-1})	323.8	71.7	315.7	73.5	321.7	60.4	1.7	0.421	ns	-	293.0	58.1	240.5	40.0	441.3	130.5
Fe (g kg^{-1})	92.1	20.7	88.1	10.2	92.5	11.9	4.6	0.099	*	41.8	70.5	13.7	64.2	11.9	98.6	19.7
K (g kg^{-1})	0.4	0.4	0.7	0.6	0.9	0.6	19.1	<0.001	****	46.8	0.9	0.5	3.1	2.5	0.6	0.4
La (mg kg^{-1})	36.8	7.3	32.3	8.4	35.1	10.1	4.7	0.090	*	31.2	40.7	6.3	29.8	5.3	30.1	5.3
Li (mg kg^{-1})	50.4	13.4	75.1	24.5	57.6	19.2	22.0	<0.001	****	42.6	37.8	9.3	43.7	6.0	30.3	5.0
Mg (g kg^{-1})	2.9	0.9	2.1	0.9	3.0	1.4	24.4	<0.001	****	41.8	4.2	1.4	10.2	3.8	3.8	0.7
Mn (g kg^{-1})	2.3	0.9	1.0	0.4	1.9	0.6	47.4	<0.001	****	58.2	2.9	0.6	2.3	0.4	3.8	1.6
Na (mg kg^{-1})	82.5	35.1	79.2	101.6	74.2	69.9	6.7	0.036	*	45.4	896.4	1277.2	1847.2	1811.4	412.7	447.3
Ni (mg kg^{-1})	46.8	13.6	49.4	14.7	49.1	15.0	0.5	0.775	ns	-	60.1	16.3	44.5	6.5	74.0	22.1
P (mg kg^{-1})	327.6	104.5	291.2	76.6	476.2	105.8	67.5	<0.001	****	62.4	549.2	130.3	512.0	62.3	368.8	110.1
Pb (mg kg^{-1})	16.3	3.6	11.9	5.5	13.9	4.7	14.1	<0.001	****	35.5	9.9	12.4	4.1	4.3	14.3	16.1
Sr (mg kg^{-1})	25.2	8.8	14.2	9.7	22.4	9.1	45.7	<0.001	****	51.1	48.5	24.5	108.9	44.0	38.7	7.8
Ti (g kg^{-1})	3.5	1.0	2.4	0.8	3.0	0.8	20.2	<0.001	****	41.1	11.5	5.6	12.5	1.8	14.7	9.6
V (mg kg^{-1})	377.1	62.1	301.0	59.9	362.4	56.8	30.0	<0.001	****	48.2	473.6	99.5	359.9	57.8	726.6	142.7
Zn (mg kg^{-1})	14.8	3.1	12.1	2.4	13.4	2.6	13.6	0.001	***	32.6	18.1	4.7	15.8	10.5	24.5	8.3
TOC (g kg^{-1})	15.6	4.9	7.3	4.6	22.2	4.2	87.8	<0.001	****	73.0	30.8	6.0	44.3	12.3	15.0	6.6

ns = not significant, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, **** $p < 0.001$.

1 Table 3. Results of the stepwise discriminant function analysis (DFA) as indicated by the Wilks' Lambda values.

Step	Fingerprint property selected	Wilks' Lambda	<i>p</i> to remove	Cumulative % of source type samples correctly classified
1	P	0.5733	0.0E+00	62.4
2	La	0.5284	1.9E-05	66.7
3	V	0.4126	8.1E-05	76.6
4	Mn	0.3092	1.0E-04	81.6
5	Be	0.2871	5.3E-03	83.0
6	Ba	0.2702	1.8E-02	84.4

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3 Table 4. Discriminant function analysis (DFA) output.

DFA parameters	Output
Wilks' Lambda	0.2702
Variance explained by the variables (%)	73.0
Degrees of freedom	12;226
$F_{\text{calculated}}$	20.47
F_{critical}	1.80
<i>p</i> -value	<0.00001
<i>F-values</i>	
Degrees of freedom	6;133
F_{critical}	2.17
Unpaved roads vs. Stream channel banks	16.75
Cropland vs. Stream channel banks	17.84
Unpaved roads vs. Cropland	26.53
<i>p-levels</i>	
Unpaved roads vs. Stream channel banks	2.5E-14
Cropland vs. Stream channel banks	4.2E-15
Unpaved roads vs. Cropland	1.3E-20
<i>Squared Mahalanobis distances</i>	
Unpaved roads vs. Stream channel banks	6.1
Cropland vs. Stream channel banks	4.9
Unpaved roads vs. Cropland	7.0

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5 Table 5. Comparison of sediment source contribution depending on sediment sampling strategy and variations
6 between sampling sites.

	<i>p</i> -values		
	Stream channels	Unpaved roads	Cropland
<i>Comparison of sampling sites</i>			
TISS	ns	ns	ns
FBS	ns	ns	ns
<i>Comparison sediment sampling strategy</i>			
TISS × FBS for all sampling sites	0.0005	ns	0.0001
TISS × FBS × FSS for outlet only	<0.0001	ns	<0.0001
TISS × FBS for outlet only	0.0076	ns	0.0076
TISS × FSS for outlet only	0.0003	ns	0.0007
FBS × FSS for outlet only	0.0001	ns	0.0002

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