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## Quantifying land use contributions to suspended sediment in a large cultivated catchment of Southern Brazil (Guaporé River, Rio Grande do Sul)

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1 **Quantifying land use contributions to suspended sediment in a large cultivated catchment**  
2 **of Southern Brazil (Guaporé River, Rio Grande do Sul)**

3  
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17  
18 **Abstract**

19 Cropland cultivated under no-tillage has dramatically increased in Brazil during the last three  
20 decades. However, soil degradation by water erosion remains excessive in the country.  
21 Furthermore, the impact of inappropriate agricultural practices on soil erosion is often neglected  
22 by farmers. Therefore, the contribution of potential sources of sediment should be quantified in  
23 order to raise awareness among rural communities on the need to improve land management for  
24 protecting soil and water resources. This study quantified the contribution of potential sources to  
25 sediment transiting the Guaporé River, draining a 2032-km<sup>2</sup> cultivated catchment, in Southern  
26 Brazil. Potential sediment source types were surface of cropland soils ( $n = 159$ ), unpaved roads  
27 ( $n = 58$ ), and stream channel banks ( $n = 46$ ). A total of 175 suspended sediment samples were  
28 collected following different sampling strategies (including sampling of river water during  
29 floods, installation of time-integrated suspended sediment samplers, and collection of bed  
30 sediment) in 10 sub-catchments, from January 2011 to March 2014. Discriminant properties  
31 were selected among the concentrations in 22 geochemical elements and total organic carbon.  
32 Results showed that sediment source contributions were similar for the different sediment  
33 sampling strategies. Although, the contributions of sediment sources varied in space across  
34 Guaporé catchment, they were dominated by cropland ( $91 \pm 15\%$ ), while stream channels ( $5 \pm 2\%$ )  
35 and unpaved roads ( $4 \pm 10\%$ ) were sources of minor importance. Cropland contribution increased  
36 with the drained cropland surface area. The unambiguous dominance of cropland as the main  
37 source supplying sediment to the Guaporé River justifies the urgent need to better plan land use  
38 and to promote the adoption of appropriate conservation farming practices in similar areas of  
39 Southern Brazil. Soil losses in cropland could be reduced by implementing crop rotation,  
40 mechanical runoff control strategies, and by avoiding the construction of unpaved roads in  
41 thalwegs.

42  
43 **Keywords:** Soil erosion, sediment fingerprinting, sediment tracing, conservational agriculture.

## 44 1. Introduction

45 In agricultural catchments characterized by high runoff coefficients and sediment yields,  
46 erosion processes need to be controlled to prevent an irreversible degradation of soil and water  
47 quality. In Brazil, although the cropland area under no-tillage has dramatically increased from 1  
48 million hectares in 1990 to 32 million hectares in 2012 (Casão Junior et al., 2012), soil  
49 degradation by water erosion remains excessive. In a literature review, Guerra et al. (2014)  
50 showed that total soil loss often exceeds  $50 \text{ Mg ha}^{-2} \text{ yr}^{-1}$ , which makes of Brazil one of the  
51 global erosion ‘hotspots’. Most fields in Southern Brazil are cultivated under a monoculture  
52 system of either soybeans, corn, or wheat. The advantages of crop rotation are neglected and  
53 cover crops are rarely sown after the harvest or during the plant growing period. Moreover, in  
54 most cropland areas, soil erosion is exacerbated by the absence of mechanical runoff control  
55 strategy. Furthermore, soil compaction due to the traffic of heavy agricultural machinery reduces  
56 water infiltration and increases runoff, facilitating the transfer of the uppermost soil layer rich in  
57 nutrients and pesticides to the water bodies (Merten et al., 2015). In addition, unpaved roads are  
58 built without concerted management at the catchment scale and they may concentrate runoff or  
59 increase erosion when they are located in the thalwegs (Didoné et al., 2015). All these factors  
60 have increased soil degradation and decreased agricultural profitability, which in turns  
61 aggravated poverty in rural areas. Therefore, there is a need to provide reliable estimations of  
62 soil erosion rates to raise awareness among farmers about the impact of applying inappropriate  
63 farming practices on the quality of soil and water resources.

64 There is also a need to identify and quantify the contribution of potential sources of  
65 sediment in order to guide the implementation of management measures to mitigate sediment  
66 transfer from cultivated hillslopes to water bodies. So far, sediment fingerprinting studies to trace  
67 land use contributions conducted in rural areas in Southern Brazil were restricted to small  
68 upstream catchments ( $<20 \text{ km}^2$ ) (Miguel et al., 2014a, 2014b; Minella et al., 2014, 2009, 2008,  
69 2007; Tiecher et al., 2017, 2016, 2015, 2014) (Table 1). Sediment tracing proved to be a  
70 powerful technique to identify sediment sources in Brazilian environmental conditions for  
71 catchments covered with Acrisols, Cambisols, Chernosols, Gleysols, and Leptosols (Table 1).  
72 Previous sediment apportionment studies indicated that cropland provides the main sediment  
73 source (mean:  $51 \pm 19\%$ , range: 11–68%,  $n = 12$ ), and that unpaved roads also supply significant  
74 loads of sediment to rivers (mean:  $33 \pm 10\%$ , range: 15–56%,  $n = 14$ ) (Table 1). However, the  
75 validity of these results obtained in small headwater areas should be verified in larger  
76 catchments, where the fluvial dynamics may affect the balance between sources and sinks of  
77 sediment. Accordingly, the erosion processes occurring on hillslopes may not reflect those

78 observed at the catchment outlet after the occurrence of sediment deposition in floodplains  
79 (Minella et al., 2014). In addition, the spatial and the temporal resolutions of source  
80 apportionment studies should be increased. For instance, information on changes in sediment  
81 sources that may occur during storm-events taking place during different periods of the  
82 hydrological year should be provided to improve our understanding of erosion processes in  
83 Southern Brazil and to propose effective management options for a wide range of hydrological  
84 conditions.

85 In sediment fingerprinting studies, one of the main difficulties is to collect sufficient and  
86 representative amounts of suspended sediments in rivers. Time-integrating samplers have been  
87 increasingly employed to achieve this objective (Gellis and Mukundan, 2013; Mukundan et al.,  
88 2012). However, this sampling strategy remains time-consuming as it requires frequent field  
89 surveys. Furthermore, samplers should be deployed for long periods (*i.e.* covering different  
90 seasons and events of different magnitudes) to provide samples that are fully representative of  
91 sediment exports from a given catchment (Walling, 2013). This problem is exacerbated when  
92 suspended sediment is sampled in river water during flood events (Navratil et al., 2012).  
93 Therefore, bed sediment was used as a surrogate for suspended sediment and it was shown to be  
94 representative of the sediment load transported by a river over a longer period of time (Horowitz  
95 et al., 2012; Wilkinson et al., 2013). Applying this strategy can provide faster results  
96 representative of the catchment behaviour over a longer period, and allows to sample both source  
97 and target material during a single campaign (Walling, 2013). Furthermore, the quantity of  
98 material necessary for the analyses can be directly collected in the river (Haddadchi et al., 2013).  
99 In this current research, these different sediment sampling strategies were used in order to  
100 compare their results and evaluate their respective advantages and drawbacks in the Brazilian  
101 context.

102 A large catchment heterogeneous in terms of soil type, relief, land use, and soil  
103 management and therefore representative of a large set of environmental conditions found in  
104 Southern Brazil was selected to conduct this study (Guaporé River, 2,032 km<sup>2</sup>). Recently, Le  
105 Gall et al. (2016) showed that soils found in lower parts of this catchment (Acrisols, Leptosols,  
106 and Luvisols, mean 92%) contributed much more sediment than those found in upper parts  
107 (Ferralsols and Nitisols, mean 8%). They attributed these results to the different farming  
108 practices implemented in both catchment areas. However, there remains a lack of information  
109 regarding the contribution of different land uses (cropland, unpaved roads, and stream channel  
110 banks) to sediment in this catchment, and the current research will fill this knowledge gap.  
111 Furthermore, as this catchment drains to the Jacuí River, which supplies water resources to the

112 metropolitan region of Rio Grande do Sul state inhabited by more than 2 million people, the  
113 implications of these results to improve land management and soil conservation in this region  
114 will also be discussed.

115

## 116 2. Study catchment

117 The Guaporé catchment is located along the border of the basaltic plateau, in Southern  
118 Brazil (Fig. 1). Climate is Cfa according to the Köppen climate classification, with average  
119 annual rainfall ranging from 1,400 to 2,000 mm yr<sup>-1</sup>, and the mean annual temperature is 17.4°C.  
120 Geology is characterized by volcanic lava flows (basalt and rhyodacite on the top) of the Serra  
121 Geral Formation, characterized by various facies (Caxias, Gramado, and Paranapanema),  
122 covering 72.2, 26.1, and 1.7% of total area, respectively (Fig. 2). Topography is undulating to  
123 hilly. Due to variations in landscape characteristics and parent material, several classes of soils  
124 are found in the catchment. Acrisols, Ferralsols, Luvisols, Leptosols, and Nitosols cover 16.6,  
125 31.2, 24.2, 6.6, and 21.4% of the total catchment surface area, respectively (IUSS Working  
126 Group WRB, 2007) (Fig. 2). Ferralsols and Nitosols dominate in the northern part of the  
127 catchment, where the altitude is higher, whereas Leptosols are mainly found in the southern part  
128 of the catchment where the topography is hilly.

129 Land use is heterogeneous in the Guaporé catchment (Fig. 2). The urbanization is sparse,  
130 covering about 0.60% of total area. Water bodies cover approximately 0.57%. Forest is the main  
131 land use and occupies 58% of the total area, while cropland and grassland cover 31 and 10% of  
132 the total area, respectively. In upper parts of the catchment where the terrain is characterized by  
133 gentle hillslopes, there is a clear dominance of soybean (*Glycine max*) and maize (*Zea mays*)  
134 crops that are cultivated in summer. In winter, wheat (*Triticum aestivum*) is cultivated under no-  
135 till. In the lower parts of the catchment, land use and soil management are very heterogeneous.  
136 The main land uses are tobacco (*Nicotiana tabacum*) and maize crops, areas afforested with  
137 Eucalyptus (*Eucalyptus* spp.), as well as pastures for dairy cattle. In these areas, soil  
138 management is very heterogeneous, although conventional tillage and minimum tillage practices  
139 are the main soil management techniques. In areas with steeper slopes, especially in the riparian  
140 zone, large portions of native forest areas as well as built-up areas are found. Riparian zone is  
141 either occupied by native forests of variable width or by perennial grasslands allowing cattle to  
142 access the river. Cropland is also found in very limited portions of the riparian zone. Proportions  
143 of cropland decrease from the North to the South (Table 2). Annual sediment yield (SY) at the  
144 Guaporé catchment outlet was estimated to 1.40 Mg ha<sup>-1</sup> yr<sup>-1</sup> based on 2 year records (2011–

145 2012) and a 10-year extrapolation using a sediment rating curve obtained by Didoné et al. (2014)  
146 based on water discharge.

147

148

149

### 150 **3. Methods**

#### 151 3.1. Hydro-sedimentological monitoring

152 The catchment was equipped with a monitoring station at the outlet. Rainfall was  
153 measured with a 10-min time step using 4-automatic meteorological station operated by the  
154 water resources national agency. The total depth estimated to the catchment was done by the  
155 interpolation using the Thiessen polygon method. Water level in the river was measured daily at  
156 a limnigraph by a local observer. It was also continuously recorded with a pressure transducer.  
157 Recorded values were converted into water discharge using rating curves.

158 Turbidity was recorded every 10 minutes and was used as a surrogate of suspended  
159 sediment concentration (SSC). Turbidimeters were calibrated using (i) various concentrations of  
160 a Formazin standard solution (between 0–3,000 Nephelometric Turbidity Units (NTU)), and (ii)  
161 suspended sediments samples collected during floods in this catchment. Suspended sediment  
162 yields (SSY) were then calculated by multiplying SSC and water discharge values.

163

#### 164 3.2. Sediment source sampling

165 Potential suspended sediment source types were collected in areas exposed to erosion and  
166 potentially connected to the river network. Sampling was concentrated in zones where sediment  
167 mobilization and transport processes were visible in the field during storm events. A total of 263  
168 samples were collected to characterize three main sediment sources: (i) surface of cropland soils  
169 (CF,  $n = 159$ ), (ii) unpaved roads (UR,  $n = 58$ ), and (iii) stream channel banks (SC,  $n = 46$ ).  
170 Areas under fallow, grassland and forest were not considered to provide potential sediment  
171 sources, as erosion was shown to be negligible under these land uses in this region (Didoné et al.,  
172 2014). Potential source material was collected using non-metallic trowels to avoid  
173 contamination. Samples were taken in the uppermost layer (0–0.05 m) of the soil under cropland  
174 and unpaved roads, and on exposed sites located along the river channel network (SC) by  
175 scraping the surface of river banks. Care was taken to avoid sampling material recently deposited  
176 on the channel bank. In order to obtain representative source material, each sample was  
177 composed of 10 sub-samples collected in the vicinity of the sampling point. Care was taken  
178 during sample collection to cover the entire range of soil types found in the catchment area.

179

180 

### 3.3. Sediment sampling

181 A total of 175 sediment samples were collected following four strategies (Table 2) from  
182 January 2011 to March 2014. The first strategy was employed to collect *flood suspended*  
183 *sediments (FSS)* ( $n = 11$ ), through the manual sampling of a large volume of water (50 to 200  
184 liters) at different periods during the rising and falling stages of floods, in order to evaluate the  
185 intra-event variation of sediment source contributions. This strategy was exclusively applied at  
186 the catchment outlet (Table 2). The second technique was to deploy *time-integrated suspended*  
187 *sediment samplers (TISS)* ( $n = 56$ ), by installing the device developed by Phillips et al. (2000) at  
188 10 sites within the catchment, with a duplication of the system to collect a sufficient quantity of  
189 sediment for the subsequent analyses. The third strategy was to collect *fine-bed sediment (FBS)*  
190 ( $n = 76$ ) with a suction stainless sampler limiting the loss of fine material at the sediment/water  
191 interface. Samples were composed of 20 to 30 subsamples collected across the river channel  
192 section at each sampling site. Finally, the fourth strategy was to collect storm-event suspended  
193 sediment by using US U-59 samplers (CEW-EH-Y, 1995) ( $n = 32$ ), installed on the streambed at  
194 9 sampling sites (coinciding with the locations where TISS were collected, except at the outlet  
195 where river flow was too high to deploy this type of collector – Table 2).

196

197 

### 3.4. Sources and sediment analyses

198 All sources and sediment samples were oven-dried at 50°C, and gently disaggregated  
199 using a pestle and a mortar. Source and sediment samples were sieved to 63 µm prior to  
200 laboratory analyses to compare similar particle size-fractions in both source and sediment  
201 samples. This 63-µm threshold was chosen to reduce uncertainties related to the effect of  
202 dilution of elemental concentrations that are depleted in coarser sand particles (Michelaki and  
203 Hancock, 2013). Moreover, this fraction is the most easily transferred in the rivers and it  
204 transports numerous pollutants, such as phosphorus, which may lead to eutrophication when  
205 concentrations are excessive.

206 All samples were analyzed for organic carbon and a range of geochemical properties.  
207 Total organic carbon (TOC) was estimated by wet oxidation with  $K_2Cr_2O_7$  and  $H_2SO_4$  (Walkley  
208 and Black, 1934). Total concentrations in several elements (Al, Ba, Be, Ca, Co, Cr, Cu, Fe, K,  
209 La, Li, Mg, Mn, Na, Ni, P, Pb, Sr, Ti, V, and Zn) were measured by ICP-OES after microwave  
210 assisted digestion for 9.5 min at 182°C with concentrated HCl and  $HNO_3$  following a ratio of 3:1  
211 (*aqua regia*).

212

### 213 3.5. Selection of optimum fingerprinting properties

214 In each source group, each tracer was tested for normality using the Shapiro-Wilk test  
215 ( $H_0$ =samples are random and follow a normal distribution). All variables that were not normally  
216 distributed were tested again for normality after transformation using log, power, square root,  
217 cube root, inverse, and inverse square root functions. The best transformation for normality was  
218 selected, and the variables were transformed accordingly. The average and standard deviation for  
219 each transformed variable were determined for each source group. Then, outliers were identified  
220 as suggested by Gellis and Noe (2013). When the value for a given source sample exceeded three  
221 times the standard deviation of the average value, this sample was considered to be an outlier and  
222 was removed from further analysis for all variables ( $n=31$ , including 18 crop field, 7 unpaved  
223 road, and 6 stream channel samples). This threshold was chosen because in normal distributions,  
224 99.7% of the values are assumed to lie within three standard deviations of the mean. The next  
225 steps of the statistical procedure were exclusively applied to the 232 remaining samples  
226 (including 141 cropland, 51 unpaved roads, and 40 stream channel bank samples). Then, a range  
227 test was conducted to exclude the variables with sediment concentrations lying outside the range  
228 of values found in sources, as recommended by Smith & Blake (2014). Concentrations in Ba, Be,  
229 Ca, K, Mg, Na, Sr, Ti, TOC, and Zn of most sediment samples (especially flood suspended  
230 sediments – FSS) were higher than the highest source concentrations (Table 3). In contrast,  
231 concentration in Fe and Pb were lower in most sediment samples than in the sources (Table 3).  
232 These elements were considered as non-conservative in the Guaporé catchment and were  
233 therefore excluded from further analysis. Several major elements (Ca, Mg, K, and Na) and trace  
234 elements (Sr, Ba) are mainly found in outer-sphere complexes with clay and organic matter in  
235 highly weathered soils (i.e. electrostatic attraction). Because ions adsorbed by outer-sphere  
236 complexes are subject to rapid exchange stoichiometric reactions, they may be less conservative  
237 during the erosion process (Essington, 2003; Sparks, 2003; Sposito, 2008).

238 Afterwards, the two-stage procedure proposed by Collins et al. (1997) was used to  
239 identify composite fingerprints capable of discriminating the sediment sources. The first step of  
240 the statistical analysis was performed to identify the set of properties with the optimal ability to  
241 discriminate between the sediment sources through the application of two sequential tests: (a) a  
242 non-parametric Kruskal-Wallis ( $H$ ) test and (b) a multivariate discriminant function. The  $H$  test  
243 verifies that the sources belong to the same population. It identifies the properties that are  
244 statistically different according to the source and that may provide tracers. The second step  
245 consists of a backwise multivariate discriminant function analysis (DFA) to determine the  
246 minimum number of variables that maximizes the discrimination between the sources. The DFA



247 analysis was exclusively performed on the variables showing differences between sources  
 248 according to the  $H$  test. The multivariate discriminant function is based on Wilks' Lambda ( $\Lambda^*$ )  
 249 value related to the analysis of variance, where the criterion used by the statistical model is the  
 250 minimization of  $\Lambda^*$ . A  $\Lambda^*$  value of 1 is obtained when all the group means are the same,  
 251 whereas a low  $\Lambda^*$  value means that the variability within the groups is small compared to the  
 252 total variability. At each step, the property which minimized the overall Wilks' Lambda was  
 253 introduced. Maximum significance of  $F$  to add a property was 0.01. Minimum significance of  $F$   
 254 to remove a property was 0.05.

255

### 256 3.6. Apportionment of sediment sources

257 After defining the set of discriminant variables, the contribution of each source to the  
 258 sediment samples was determined. Equation 1 describes the mathematical relationship between  
 259 the proportions of contribution of each source and the variables measured in the sources and in  
 260 suspended sediment (Walling and Woodward, 1995).

$$y_i = \sum_{s=1}^n a_{is}P_s \quad (s = 1, 2, \dots, n) \text{ and } (i = 1, 2, \dots, m) \quad (1)$$

261 where  $y_i$  is the value of the variable  $i$  measured in suspended sediment,  $a_{is}$  are the linear model  
 262 coefficients (concentration of property in source  $s_i$ ) and  $P_s$  is the contribution from the source  $s$ ,  
 263 which may be presented as a set of linear functions of  $m$  variables and  $n$  sources. To determine  
 264 the  $P_s$  values, an objective function was used (Walling and Woodward, 1995). The solution was  
 265 found through an iterative process with the objective to minimize the value of  $R$  ( $f$  mincon)  
 266 (Equation 2).

$$R = \sum_{i=1}^m \left\{ \frac{C_i - (\sum_{s=1}^n P_s C_{si})}{C_i} \right\}^2 \quad (2)$$

267 The mixing model was run using Matlab® software. During the minimization process,  $P$   
 268 values had to meet two constraints (Equations 3 and 4).

$$269 \quad 0 \leq P_s \leq 1 \quad (3)$$

$$\sum_{s=1} P_s = 1 \quad (4)$$

270 where  $m$  is the number of properties selected as tracers;  $n$  is the number of sources,  $C_i$  is the  
 271 concentration of tracer  $i$  in sediment;  $P_s$  is the contribution of source  $s$ ,  $C_{si}$  is the mean value of  
 272 tracer  $i$  in source  $s$ .

273 The evaluation of the results was made by comparing the elemental concentrations  
 274 (variables tracers) measured in suspended sediments and the value predicted by the model based  
 275 on the contribution calculated for each source. Then, based on relative errors for each variable,  
 276 the relative mean error (RME) was calculated to associate a unique error value with each  
 277 suspended sediment sample according to Equation 5.

$$RME = \sum_{i=1}^m \left\{ \frac{C_i - (\sum_{s=1}^n P_s C_{si})}{m} \right\} \quad (5)$$

278 Finally, sediment source contributions were compared for the different sampling  
 279 strategies and for the different sampling sites by using Kruskal-Wallis *H*-tests.

280

## 281 4. Results

### 282 4.1. Source discrimination

283 The concentrations of 10 geochemical tracers (Al, Co, Cr, Cu, La, Li, Mn, Ni, P, and V)  
 284 measured in sediments remained within the range of concentrations found in the source materials  
 285 (Table 3). From these 10 elements, 8 (Al, Co, Cr, La, Li, Mn, Ni, and P) were selected as  
 286 potential tracers through the application of the Kruskal-Wallis *H*-test ( $p < 0.1$ ) (Table 3). The  
 287 discriminant power of these tracers ranged from 22.4 to 62.9%, and no single variable was able  
 288 to correctly classify 100% of the samples in their respective source groups (Table 3). The  
 289 optimum set of tracers selected by DFA comprised seven tracers (Al, Co, Cr, La, Mn, Ni, and P)  
 290 (Table 4). The final value of the  $\Lambda^*$  parameter was 0.3537, showing that the set of selected  
 291 variables explained approximately 64.6% of the differences between the sources. The three  
 292 sediment sources (SC, UR, CF) were well separated by a Mahalanobis distance of  $4.9 \pm 1.7$   
 293 ( $p < 2.1E^{-16}$ ), resulting in a correct classification of 80.2% of the samples in their respective  
 294 groups (Table 5).

295

### 296 4.2. Sediment source apportionment

297 Suspended sediment collected at varying periods during floods was only sampled at the  
 298 catchment outlet (*i.e.* site 10). For both floods investigated, cropland contribution was dominant  
 299 during the rising stage (Figure 3). Then, during the recession phase, cropland contribution  
 300 decreased, while sediment supply from stream channel banks (Figure 3 c,f) and unpaved roads (3  
 301 f) increased.

302 Suspended sediment yield at the catchment outlet strongly varied throughout the study  
 303 period (Fig. 4 k). The monthly suspended sediment yield was correlated to the total amount of

304 rainfall ( $r = 0.567$ ,  $p=0.001$ ). However, source contributions did not show any significant  
305 seasonal variation trend at the sampling sites (Fig. 4, 5 and 6).

306 Results indicate that the different sediment sampling strategies (TISS, FBS, and FSS)  
307 provided similar results (Table 6 and Fig. 7). Flood sediment samples were not included in this  
308 comparison because of the low number of samples available ( $n = 11$ ). Overall, when grouping all  
309 sediment samples (TISS, FBS and FSS) and all sampling sites, on average, cropland was the  
310 main supply of sediment ( $78\pm 29\%$ ), followed by channel banks ( $20\pm 29\%$ ) and unpaved roads  
311 ( $2\pm 5\%$ ).

312 As no significant difference was found for the various sampling strategies, the entire set  
313 of sediment samples was used to compare the results obtained at the different sampling sites.  
314 Sediment source contributions varied in space across Guaporé catchment (Table 6) and were  
315 mainly characterized by changes in cropland and channel bank contributions to the river  
316 sediment ( $P < 0.0001$ ). Site 1 showed significantly different source contributions compared to all  
317 other sampling sites, with the exception of Site 7 (Table 6). The latter showed significantly  
318 different contributions compared to sites 4, 8, 9 and 10 (Table 6). Interestingly, cropland  
319 contribution to sediment was the lowest at Site 1 ( $20\pm 21\%$ ) and at Site 7 ( $55\pm 33\%$ ), whereas it  
320 was much higher and stable at the other sites ( $88\pm 19\%$ ). These results are consistent with the  
321 increasing cropland surface area drained by these sites (Table 2). In contrast, stream channel  
322 bank contributions were high at the sites characterized by low cropland contributions (i.e.  
323  $79\pm 20\%$  at site 1 and  $40\pm 30\%$  at site 7), and low in the rest of the catchment where they  
324 delivered  $11\pm 18\%$  of suspended sediment. Unpaved roads provided a very low contribution to  
325 sediment across the entire catchment ( $2\pm 6\%$ ).

326 At the catchment outlet (site 10), when calculating the mean for material collected  
327 following all sampling strategies (including TISS, FBS, and FSS samples,  $n = 29$ ), sediment was  
328 mainly supplied by cropland ( $91\pm 15\%$ ), with minor contributions from channel banks ( $5\pm 2\%$ )  
329 and unpaved roads ( $4\pm 10\%$ ). When weighting these source contributions with the sediment flux  
330 calculated by Didoné et al. (2014 –  $1.40 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ), the flux supplied by cropland was  
331 estimated to  $2.17 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ .

332

## 333 5. Discussion

334 The current research unambiguously showed that cropland is the main sediment source  
335 ( $91\pm 15\%$ ,  $n = 29$ ) in the Guaporé catchment. Source contributions modelled at the Guaporé  
336 catchment outlet remained similar to those found at most of the sites located on the main stem of  
337 the river, with the exception of sites 1 and 7, which drain less cultivated areas. At site 1, most of

338 cultivated areas are located in the uppermost part of the subcatchment and croplands are likely  
339 disconnected from the river network because of the presence of a wide band of riparian forest.  
340 When studying soil erosion in a very steep rural catchment cultivated with tobacco in this region  
341 of Southern Brazil, Pellegrini et al. (2010) reported that preserved riparian vegetation provided a  
342 barrier that decreased the amount of sediments and phosphorus transferred to water bodies, and  
343 consequently that mitigated off-site erosion impacts. In the same way, in the Chesapeake Bay  
344 watershed, USA, Massoudieh et al. (2012) found that the dense forest cover along streams  
345 reduced the contribution of sediment from agricultural areas located farther away from the river.  
346 The authors suggested that sediment generated by overland flow on the cultivated fields likely  
347 deposited in these forested areas and did not reach the stream network. In contrast, the dominant  
348 contribution of cropland calculated for site 7 agreed well with those obtained by a previous study  
349 conducted in a small headwater catchment (1.19 km<sup>2</sup>) draining to site 7 (Tiecher et al., 2016).  
350 The sampling site was characterized by a similar proportion of cropland in the drainage area  
351 (40% vs. 35% for site 7 in the current research), and contributions of farmland (57±14%) were  
352 found to be very similar (55±33%) with those calculated at site 7.

353 During floods, the slight increase in the contribution of channel banks during the later  
354 stages of the event may reflect the occurrence of bank collapse when the water level recedes  
355 (Carter et al., 2003). The occurrence of cattle trampling in Guaporé catchment may also have  
356 contributed, although to a much lower extent, to the input of channel bank material to the river.  
357 However, average contribution of channel banks remained low due to the presence of mature  
358 trees on the banks. Root reinforcement likely increased their stability against mass failure and  
359 oversteepening by lateral scour (Abernethy and Rutherford, 2001, 2000). Moreover, the low  
360 contribution of channel banks to suspended sediments may also reflect the high stability of the  
361 substrate found in the alluvial plains of this region and consisting of soils enriched in clay and  
362 iron oxides derived from volcanic lava flows (rhyodacite, basalt).

363 Although the contribution of unpaved roads remained low when considering the entire  
364 catchment, spatial variations of this supply may be found when considering a network of  
365 embedded sub-catchments. Accordingly, a scale effect is observed when moving from the  
366 headwater Arvorezinha catchment (Tiecher et al. 2016 – 1.19 km<sup>2</sup>) to site 7 (88 km<sup>2</sup>), and then  
367 site 10 (Guaporé outlet – 2,032 km<sup>2</sup>), with a decrease in unpaved road contributions in  
368 downstream direction (23±14, 5±8 and 4±10%, respectively). These results are consistent with  
369 those of Thomaz et al. (2014), who evaluated the local impacts of six unpaved road–stream  
370 crossings on suspended sediment concentrations in the rural Guabiroba River, in Southern  
371 Brazil. They demonstrated that the increase of suspended sediment concentration was strongly

372 scale-dependent. Unpaved road contribution was high for streams draining areas covering less  
373 than 3 km<sup>2</sup>, and it decreased in larger areas. In Southern Brazil, most of these rural roads are  
374 built without considering their potential impact on runoff and erosion. Several main roads and  
375 local paths are often damaged by rills and gullies, which complicates access for the farmers to  
376 their fields and increases maintenance costs for the municipalities (Thomaz et al., 2014).  
377 Furthermore, despite their low contribution to sediment in larger catchments, they represent  
378 perennial landscape features, and their construction should therefore be planned in the  
379 framework of integrated soil erosion control programs (Collins et al., 2010).

380 A good agreement was observed between the results obtained for the different sampling  
381 strategies implemented in Guaporé catchment (Fig. 7), which confirms previous results of  
382 Wilkinson et al. (2013). The similarity of these results indicates that source contributions are  
383 very stable in this catchment, although monitoring was conducted over a relatively short period.  
384 This increases the confidence in the sediment fingerprinting results and supports their use for  
385 guiding the design of efficient soil and water conservation programs in this region.

386 It is important to note that the value of 2.17 Mg ha<sup>-1</sup> yr<sup>-1</sup> corresponds to a sediment yield  
387 (SY; fraction of sediment exported from the catchment), and not to an erosion rate (SL; soil loss  
388 on the hillslopes). The difference between both values is explained by the fraction of sediment  
389 deposited between their source and the outlet (sediment delivery ratio [SDR] = SY / SL). For  
390 these same environmental conditions of the present study, Minella et al. (2014) have established  
391 a sediment budget for a small agricultural catchment by using <sup>137</sup>Cs measurements and sediment  
392 source fingerprinting, and they found a SDR of ~10%. When applying a SDR of 10% to the SY  
393 of cropland found in Guaporé, SL rates of 20 to 40 Mg ha<sup>-1</sup> yr<sup>-1</sup> can be estimated for cropfields,  
394 which exceed by far the tolerable erosion rates (max. 10 Mg ha<sup>-1</sup> yr<sup>-1</sup> according to Verheijen et  
395 al. (2009). Therefore, there is an urgent need to better plan land use and farming practices in  
396 Southern Brazil. Soil losses in cropland could be reduced by implementing crop rotation,  
397 mechanical runoff control strategies, and by avoiding the construction of unpaved road in the  
398 thalwegs. In other regions of the world, organizing the implementation of these measures at the  
399 catchment scale proved to be very efficient to mitigate erosion off-site impacts (Evrard et al.,  
400 2010). Often, these measures are not novel, and farmers, technicians and the academic  
401 community know them well. However, in practice, their benefits are widely neglected. The fact  
402 that decisions on land use planning and soil management have historically been taken  
403 independently by the farmers, who use their property as a basic unit for management and action,  
404 likely explains this situation. This complicates raising awareness among rural communities that,

405 to be efficient, soil erosion control measures should be planned and taken collectively, beyond  
 406 the rural property boundaries, at the catchment scale.

407

## 408 **6. Conclusions**

409 This sediment fingerprinting study demonstrated that cropland is unambiguously the  
 410 main source supplying sediment to the Guaporé River (91±15%) and that there is an urgent need  
 411 to better plan land use and farming practices in similar areas of Southern Brazil. These results  
 412 clearly indicate the high connectivity of erosive processes from hillslopes to the main river and  
 413 the limited deposition of sediment in floodplains. Soil management systems currently  
 414 implemented by the farmers proved to be inefficient to reduce runoff and erosion in cultivated  
 415 areas, and they resulted in a supply of 2.17 Mg ha<sup>-1</sup> yr<sup>-1</sup> sediment to the investigated river.  
 416 Measures for runoff interception in cropland should be installed to minimize the supply of  
 417 sediments and pollutants to rivers. The impact of agricultural activities in this river system  
 418 greatly affects the contamination and the eutrophication of the Taquari-Antas basin and,  
 419 consequently, the quality of the Guaíba lake, which supplies water resources to the majority of  
 420 the Rio Grande do Sul state population (approximately 2 million people). In the future, sediment  
 421 fingerprinting studies based on the measurement of other properties, such as fallout  
 422 radionuclides, could be applied to calculate the contributions of surface (*i.e.* cropland) and  
 423 subsurface (*i.e.* channel banks, unpaved roads) sources to sediment, and compare these  
 424 complementary results to those obtained in the current research. Moreover, the sediment  
 425 fingerprinting approach could be applied to floodplain overbank sediment cores to estimate  
 426 potential sediment source contribution changes over the last several decades.

427

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432

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562

**Table 1** Summary results of source contributions found in previous sediment fingerprinting studies conducted in Brazil.

Catchment	Area (km <sup>2</sup> )	Soil type <sup>1</sup>	Period	Sediment source contribution (%)					Reference
				Crop field	Unpaved road	Stream channel	Grassland	Topsoil <sup>d</sup>	
Agudo	1.68	<b>Ch</b> , L	Apr/2003–Jun/2004	68	28	4	-	-	Minella et al. (2007)
Arvorezinha	1.19	<b>A</b> , C, L	Apr/2003–Jun/2004	55	38	7	-	-	Minella et al. (2007)
Arvorezinha sub-catchment	0.57	<b>A</b> , C, L	Apr/2002–Oct/2002	64	36	-	-	-	Minella (2009a)
Arvorezinha pre-treatment period	1.19	<b>A</b> , C, L	May/2002–Jul/2003	61	37	2	-	-	Minella (2009b, 2008)
Arvorezinha post-treatment period	1.19	<b>A</b> , C, L	Oct/2003–Mar/2006	53	29	18	-	-	Minella (2009b, 2008)
Arvorezinha	1.19	<b>A</b> , C, L	May/2002–Jul/2003	63	36	2	-	-	Minella (2014)
Arvorezinha	1.19	<b>A</b> , C, L	Oct/2009-Jul/2011	57	23	20	-	-	Tiecher et al. (2016) <sup>a</sup>
Arvorezinha	1.19	<b>A</b> , C, L	Oct/2009-Jul/2011	58	23	20	-	-	Tiecher et al. (2016) <sup>b</sup>
Arvorezinha	1.19	<b>A</b> , C, L	Oct/2009-Jul/2011	62	36	6	-	-	Tiecher et al. (2015) <sup>c</sup>
Júlio de Castilhos I	0.80	<b>A</b> , C, G, L	May/2009–Apr/2011	44	56	-	-	-	Tiecher et al. (2014)
Júlio de Castilhos I	0.80	<b>A</b> , C, G, L	Apr/2011–Oct/2013	16	15	49	20	-	Tiecher et al. (2017)
Júlio de Castilhos II	1.40	<b>A</b> , C, G, L	Apr/2011–Oct/2013	11	41	23	25	-	Tiecher et al. (2017)
Vacacaí-Mirim	20.0	<b>L</b> , A, P	May/2011–Dec/2011	-	35	3	-	62	Miguel et al. (2014a)
Vacacaí-Mirim	20.0	<b>L</b> , A, P	May/2011–Dec/2011	-	31	35	-	34	Miguel et al. (2014b)

<sup>1</sup> IUSS Working Group WRB (2007)

A, Acrisol. C, Cambisol. Ch, Chernosol. G, Gleysol. L, Leptosol. Bold soil types indicate the predominance.

<sup>a</sup> Results from geochemical approach. <sup>b</sup> Results from near-infrared spectroscopy approach. <sup>c</sup> Results from ultra-violet-visible spectroscopy approach. <sup>d</sup> Topsoil from planted and natural forest.

1 **Table 2** Land use in the drainage area and number of sediment samples collected at  
 2 each site following different strategies in sub-catchments of Guaporé River.

Variable	Sub-catchment										Total
	1	2	3	4	5	6	7	8	9	10	
Area (km <sup>2</sup> )	3.3	269	532	257	1,043	1,441	99	145	1,698	2,032	2,032
Area (%)	0.2	13.3	26.2	12.7	51.4	71.0	4.9	7.1	83.6	100	100
<i>Land use (%)</i>											
Cropland	34.4	70.6	70.0	69.1	68.8	66.3	34.7	49.5	61.5	58.5	-
Forest	57.9	17.4	18.7	20.1	21.3	24.2	50.0	37.0	28.5	31.2	-
Silviculture	0.7	5.1	3.4	1.8	2.5	2.3	3.0	8.7	2.4	3.2	-
Grassland	7.0	4.2	4.9	5.7	5.6	5.8	11.0	4.6	6.2	5.9	-
Water body	0.0	1.9	1.0	0.1	0.6	0.5	0.1	0.1	0.5	0.5	-
Urban	0.0	0.8	2.0	3.2	1.2	0.9	1.2	0.1	0.9	0.7	-
<i>Number of sediment samples collected following each sediment sampling strategy</i>											
TISS	4	4	5	6	6	4	5	5	7	10	56
FSS	-	-	-	-	-	-	-	-	-	11	11
FSS U-59	4	4	3	1	5	4	3	3	5	-	32
FBS	7	7	8	7	9	7	7	7	9	8	76
Total	15	15	16	14	20	15	15	15	21	29	175

3 TISS, time-integrated suspended sediment; FSS-U59, flood suspended sediment collected with US-U59  
 4 sampler; FSS, flood suspended sediment; FBS, fine-bed sediment.  
 5

6 **Table 3** Geochemical element concentrations in sediment sources and suspended sediments, results of the Kruskal–Wallis *H*-test and the Discriminant  
7 Function Analysis (DFA) used to identify the optimum composite fingerprint for distinguishing the source types supplying sediment to the Guaporé  
8 River. SD, standard deviation; TISS, time-integrated suspended sediment; FSS, flood suspended sediment; FSS-U59, flood suspended sediment  
9 collected with US-U59 sampler; FBS, fine-bed sediment.

Fingerprint property	Sediment sources						Kruskal-Wallis test		DFA  Correctly classified samples (%)	Sediment samples							
	Stream channels ( <i>n</i> = 40)		Unpaved roads ( <i>n</i> = 51)		Cropland ( <i>n</i> = 141)		<i>H</i> -value	<i>p</i> -value		TISS ( <i>n</i> = 56)		FSS ( <i>n</i> = 11)		FSS-U59 ( <i>n</i> = 32)		FBS ( <i>n</i> = 76)	
	Mean	SD	Mean	SD	Mean	SD				Mean	SD	Mean	SD	Mean	SD	Mean	SD
	Al (g kg <sup>-1</sup> )	46.0	8.4	66.3	20.5	48.8	11.8	35.2		<0.0001	43.1	37.5	11.0	42.9	3.3	36.4	5.0
Ba (mg kg <sup>-1</sup> )	212.7	45.3	169.5	67.4	199.7	60.5	13.2	0.0013	33.2	289.9	89.4	418.8	43.7	313.5	106.3	330.8	101.8
Be (mg kg <sup>-1</sup> )	3.5	1.0	3.0	1.1	3.2	1.5	2.9	0.2308	-	4.1	3.2	8.3	0.5	1.9	1.9	4.3	2.9
Ca (g kg <sup>-1</sup> )	1.7	0.9	1.6	1.5	2.0	1.1	9.4	0.0090	45.7	3.1	1.5	10.1	4.9	3.8	1.4	3.3	0.9
Co (mg kg <sup>-1</sup> )	44.0	26.5	33.3	21.5	42.3	27.6	5.5	0.0647	22.8	40.9	17.1	49.9	5.9	44.0	19.2	52.5	20.7
Cr (mg kg <sup>-1</sup> )	24.6	9.8	28.4	13.1	24.9	13.5	5.9	0.0525	22.4	31.6	16.9	31.9	4.7	31.1	11.0	36.7	19.3
Cu (mg kg <sup>-1</sup> )	156.4	99.5	201.9	120.1	186.5	138.9	3.4	0.1833	-	135.4	49.7	138.1	19.1	164.7	45.0	176.4	62.6
Fe (g kg <sup>-1</sup> )	69.8	26.8	78.2	24.2	74.7	35.7	1.5	0.4719	-	48.7	14.6	50.3	5.8	51.5	9.1	59.7	16.2
K (g kg <sup>-1</sup> )	1.3	0.6	1.5	0.8	1.4	0.7	1.2	0.5525	-	1.7	1.0	6.4	3.5	2.4	1.0	1.5	0.5
La (mg kg <sup>-1</sup> )	38.0	14.0	33.5	14.3	31.7	12.4	6.0	0.0495	44.8	34.2	9.9	36.8	5.7	32.8	8.7	32.1	8.8
Li (mg kg <sup>-1</sup> )	40.5	9.0	53.0	21.3	40.9	13.1	16.4	0.0003	28.0	33.6	7.7	38.1	4.3	34.4	6.5	33.4	3.4
Mg (g kg <sup>-1</sup> )	3.7	1.3	4.1	1.9	3.4	1.4	5.7	0.0565	53.9	4.1	1.1	7.2	1.5	4.8	1.1	4.2	1.1
Mn (g kg <sup>-1</sup> )	2.0	1.0	1.4	0.7	2.0	0.9	15.5	0.0004	27.2	1.8	0.6	1.8	0.3	1.9	0.4	2.0	0.7
Na (mg kg <sup>-1</sup> )	78.2	52.8	136.9	176.8	64.4	98.7	21.4	<0.0001	60.8	442.8	835.7	2095.6	1317.2	517.8	569.8	280.2	232.7
Ni (mg kg <sup>-1</sup> )	17.0	9.8	25.4	15.8	19.7	15.4	7.4	0.0250	28.0	19.1	7.8	23.0	2.0	22.2	9.5	23.2	8.6
P (mg kg <sup>-1</sup> )	267.3	77.7	253.4	98.3	437.2	123.1	101.8	<0.0001	62.9	452.5	251.2	502.4	42.7	431.9	102.0	427.8	128.7
Pb (mg kg <sup>-1</sup> )	27.1	8.4	19.6	8.6	24.0	6.9	21.8	<0.0001	39.7	19.1	6.4	15.7	3.2	20.5	5.6	19.3	7.4
Sr (mg kg <sup>-1</sup> )	30.9	8.4	26.1	16.3	26.2	10.8	11.4	0.0034	26.3	41.9	16.4	104.9	39.6	47.7	16.3	44.0	12.9
Ti (g kg <sup>-1</sup> )	4.0	0.9	3.4	1.2	3.6	1.0	9.9	0.0071	31.5	7.1	5.1	10.8	1.1	4.5	2.1	7.3	5.5
V (mg kg <sup>-1</sup> )	256.5	147.2	252.1	133.9	281.7	196.0	0.9	0.6395	-	245.8	118.2	289.0	42.5	268.6	107.5	343.7	139.0
Zn (mg kg <sup>-1</sup> )	12.6	3.7	12.8	3.7	14.3	5.1	4.8	0.0905	40.1	32.9	28.7	14.2	1.5	38.2	15.8	33.5	20.1
TOC (g kg <sup>-1</sup> )	13.3	2.7	8.9	3.9	21.5	6.2	127.5	<0.0001	74.1	39.2	15.4	41.1	8.8	38.3	15.7	30.8	13.2

10 Bold values indicate *p*-value <0.1.

11 **Table 4** Results of the discriminant function analysis (DFA) as indicated by the Wilks'  
 12 Lambda values using three and four sediment sources in Guaporé catchment.

Step	Fingerprint property selected	Wilks' Lambda	<i>p</i> to remove	Cumulative % of source type samples correctly classified
1	P	0.6184	0.0E+00	62.9
2	Al	0.4587	4.6E-09	68.1
3	Cr	0.4489	2.8E-04	68.1
4	Ni	0.4048	1.2E-02	73.3
5	Co	0.3722	3.4E-02	78.4
6	La	0.3628	5.7E-02	78.9
7	Mn	0.3537	6.0E-02	80.2

13

14 **Table 5** Discriminant function analysis (DFA) parameters in Guaporé River catchment.

DFA parameters	Output
Wilks' Lambda	0.3537
Variance explained by the variables (%)	64.6
Degrees of freedom	14;446
$F_{\text{calculated}}$	21.71
$F_{\text{critical}}$	1.71
<i>p</i> -value	<0.00001
<i>F-values</i>	
Degrees of freedom	7;223
$F_{\text{critical}}$	2.1
Unpaved roads vs. Stream channels	13.9
Cropland vs. Stream channels	15.4
Unpaved roads vs. Cropland	35.2
<i>p-levels</i>	
Unpaved roads vs. Stream channels	6.4E-15
Cropland vs. Stream channels	2.1E-16
Unpaved roads vs. Cropland	0.0E+00
<i>Squared Mahalanobis distances</i>	
Unpaved roads vs. Stream channels	4.5
Cropland vs. Stream channels	3.6
Unpaved roads vs. Cropland	6.8

15

16

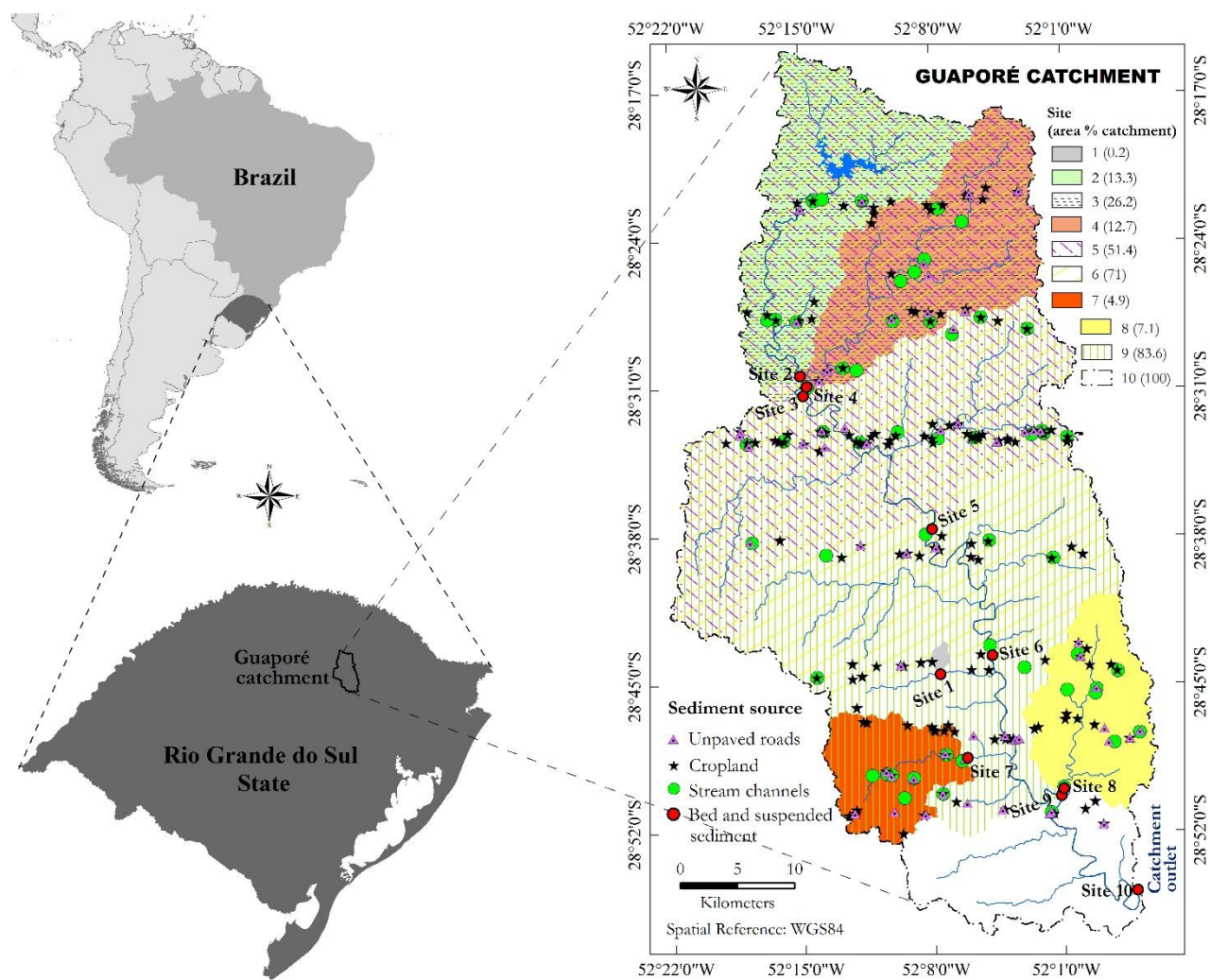
17 **Table 6** Comparison of sediment source contribution depending on sediment sampling  
 18 strategy and variations between sampling sites.

Comparison <sup>1</sup>	Cropland	Stream channels
<i>Sampling strategy</i>		
Kruskal-Wallis test (2; n= 164)	ns	ns
TISS (n=56) × FSS-U-59 (n=32)	ns	ns
TISS (n=56) × FBS (n=76)	ns	ns
FSS-U-59 (n=32) × FBS (n=76)	ns	ns
<i>Sampling site</i> <sup>2</sup>		
Kruskal-Wallis test (9; n= 164)	<0.0001	<0.0001
Site 1 (n=15) × Site 2 (n=15)	0.0067	0.0076
Site 1 (n=15) × Site 3 (n=16)	0.0009	0.0009
Site 1 (n=15) × Site 4 (n=14)	0.0001	<0.0001
Site 1 (n=15) × Site 5 (n=20)	0.0035	0.0023
Site 1 (n=15) × Site 6 (n=15)	0.0001	0.0002
Site 1 (n=15) × Site 7 (n=15)	ns	ns
Site 1 (n=15) × Site 8 (n=15)	<0.0001	<0.0001
Site 1 (n=15) × Site 9 (n=21)	<0.0001	<0.0001
Site 1 (n=15) × Site 10 (n=18)	<0.0001	<0.0001
Site 2 (n=15) × Site 3 (n=16)	ns	ns
Site 2 (n=15) × Site 4 (n=14)	ns	ns
Site 2 (n=15) × Site 5 (n=20)	ns	ns
Site 2 (n=15) × Site 6 (n=15)	ns	ns
Site 2 (n=15) × Site 7 (n=15)	ns	ns
Site 2 (n=15) × Site 8 (n=15)	ns	ns
Site 2 (n=15) × Site 9 (n=21)	ns	ns
Site 2 (n=15) × Site 10 (n=18)	ns	ns
Site 3 (n=16) × Site 4 (n=14)	ns	ns
Site 3 (n=16) × Site 5 (n=20)	ns	ns
Site 3 (n=16) × Site 6 (n=15)	ns	ns
Site 3 (n=16) × Site 7 (n=15)	ns	ns
Site 3 (n=16) × Site 8 (n=15)	ns	ns
Site 3 (n=16) × Site 9 (n=21)	ns	ns
Site 3 (n=16) × Site 10 (n=18)	ns	ns
Site 4 (n=14) × Site 5 (n=20)	ns	ns
Site 4 (n=14) × Site 6 (n=15)	ns	ns
Site 4 (n=14) × Site 7 (n=15)	ns	0.0952
Site 4 (n=14) × Site 8 (n=15)	ns	ns
Site 4 (n=14) × Site 9 (n=21)	ns	ns
Site 4 (n=14) × Site 10 (n=18)	ns	ns
Site 5 (n=20) × Site 6 (n=15)	ns	ns
Site 5 (n=20) × Site 7 (n=15)	ns	ns
Site 5 (n=20) × Site 8 (n=15)	ns	ns
Site 5 (n=20) × Site 9 (n=21)	ns	ns
Site 5 (n=20) × Site 10 (n=18)	ns	ns
Site 6 (n=15) × Site 7 (n=15)	ns	ns
Site 6 (n=15) × Site 8 (n=15)	ns	ns
Site 6 (n=15) × Site 9 (n=21)	ns	ns
Site 6 (n=15) × Site 10 (n=18)	ns	ns
Site 7 (n=15) × Site 8 (n=15)	0.0064	0.0274
Site 7 (n=15) × Site 9 (n=21)	0.0851	ns
Site 7 (n=15) × Site 10 (n=18)	ns	0.0845
Site 8 (n=15) × Site 9 (n=21)	ns	ns
Site 8 (n=15) × Site 10 (n=18)	ns	ns
Site 9 (n=21) × Site 10 (n=18)	ns	ns

<sup>1</sup>Comparisons of unpaved roads for different sampling strategies and sampling sites are not presented because they were all not significant at  $P<0.1$ . ns = not significant at  $P<0.1$ .

# Figure

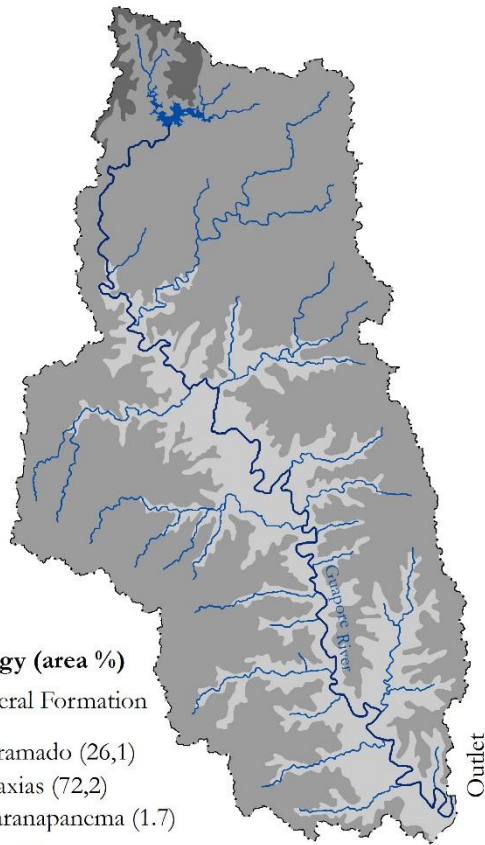
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**Fig. 1.** Location of the Guaporé catchment in Brazil and the soil/sediment sampling sites.

### A

## LITHOLOGY



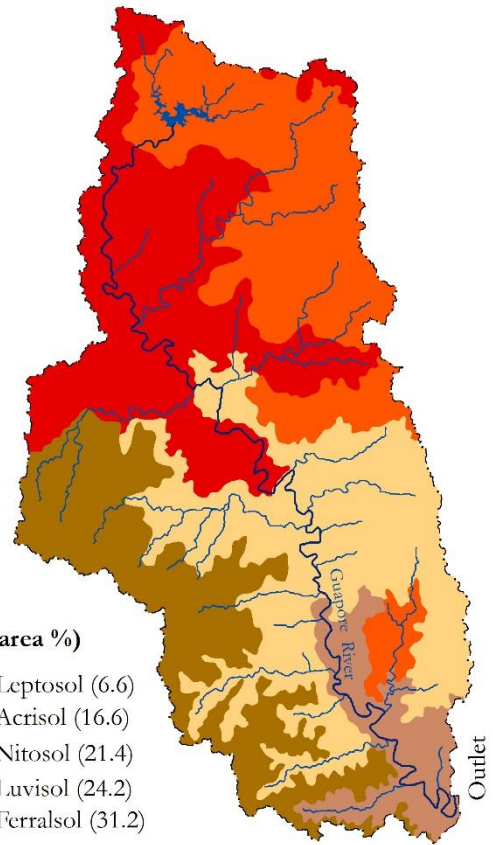
**Lithology (area %)**  
 Serra Geral Formation

Gramado	(26,1)
Caxias	(72,2)
Paranapanema	(1,7)

Source: CPRM

### B

## SOIL



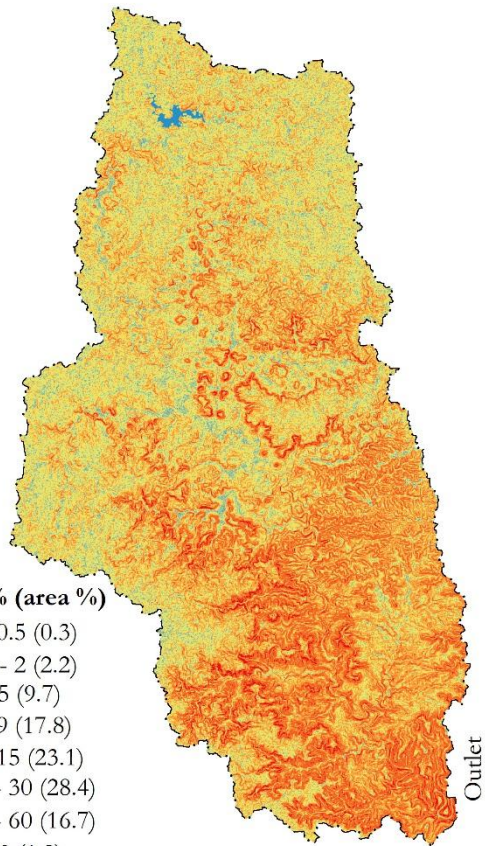
**Soil (area %)**

Leptosol	(6.6)
Acrisol	(16.6)
Nitosol	(21.4)
Luvisol	(24.2)
Ferralsol	(31.2)

Source: Embrapa

### C

## SLOPE



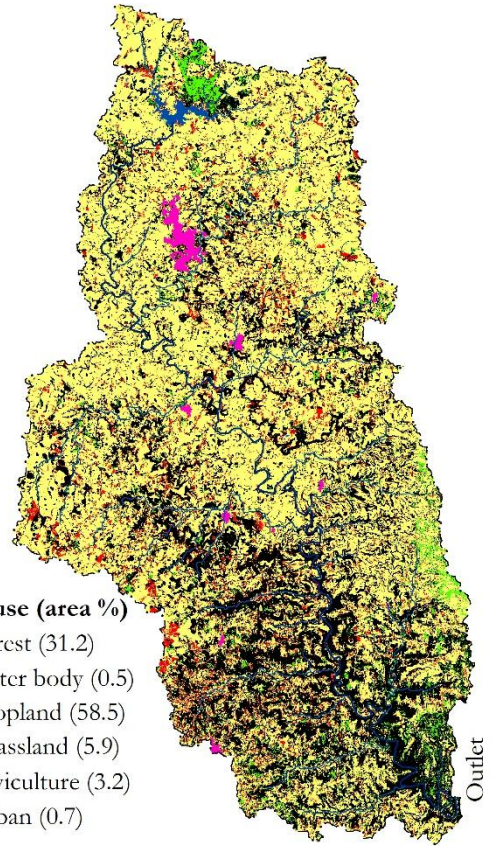
**Slope % (area %)**

0 - 0.5	(0.3)
0.5 - 2	(2.2)
2 - 5	(9.7)
5 - 9	(17.8)
9 - 15	(23.1)
15 - 30	(28.4)
30 - 60	(16.7)
> 60	(1.8)

Source: SRTM 30 m

### D

## LAND USE



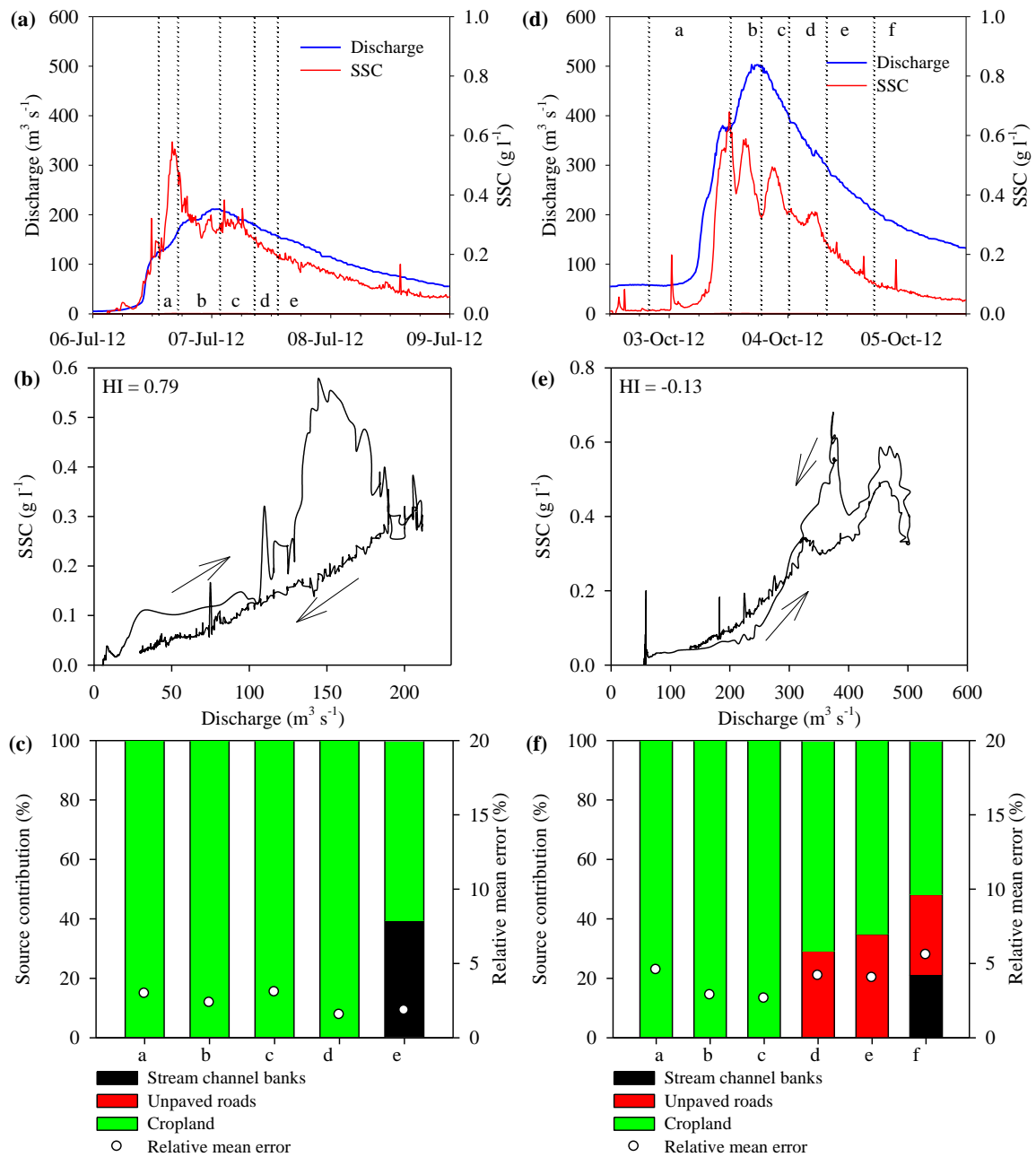
**Land use (area %)**

Forest	(31.2)
Water body	(0.5)
Cropland	(58.5)
Grassland	(5.9)
Silviculture	(3.2)
Urban	(0.7)

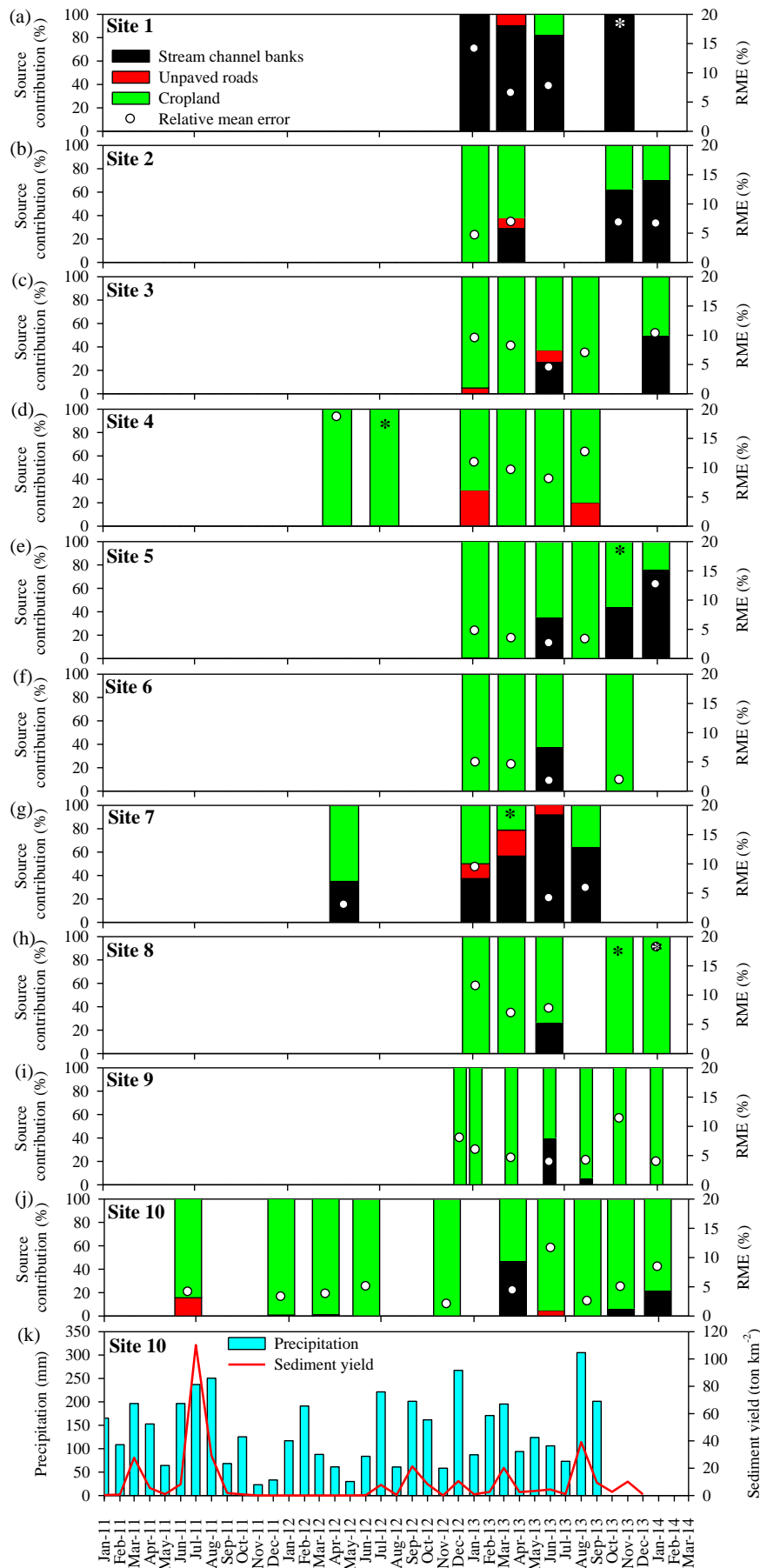
Source: RapidEye satellite images (5 m)

**Fig. 2.** Lithology, soil types, slope and land use in Guaporé catchment.

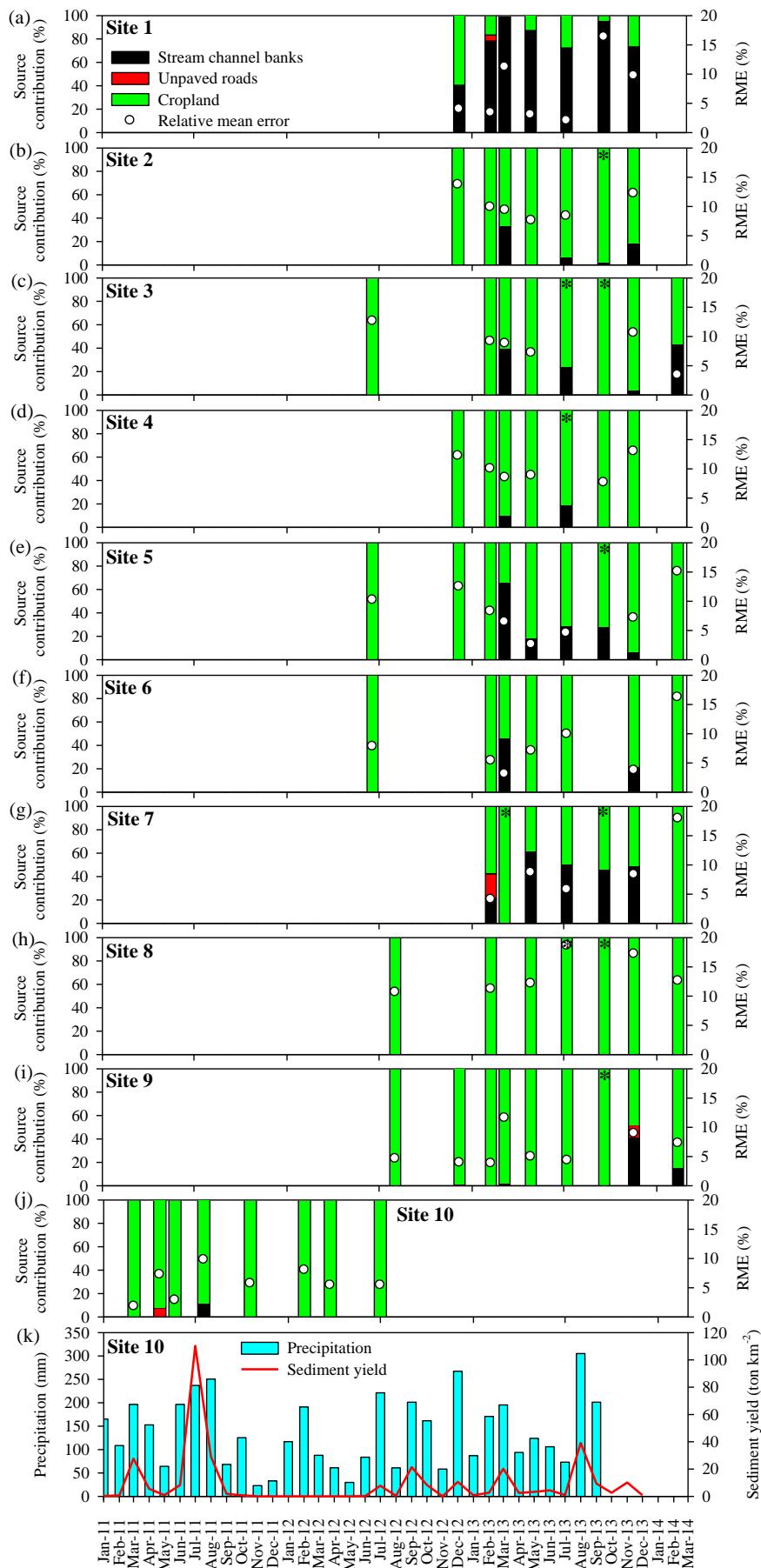




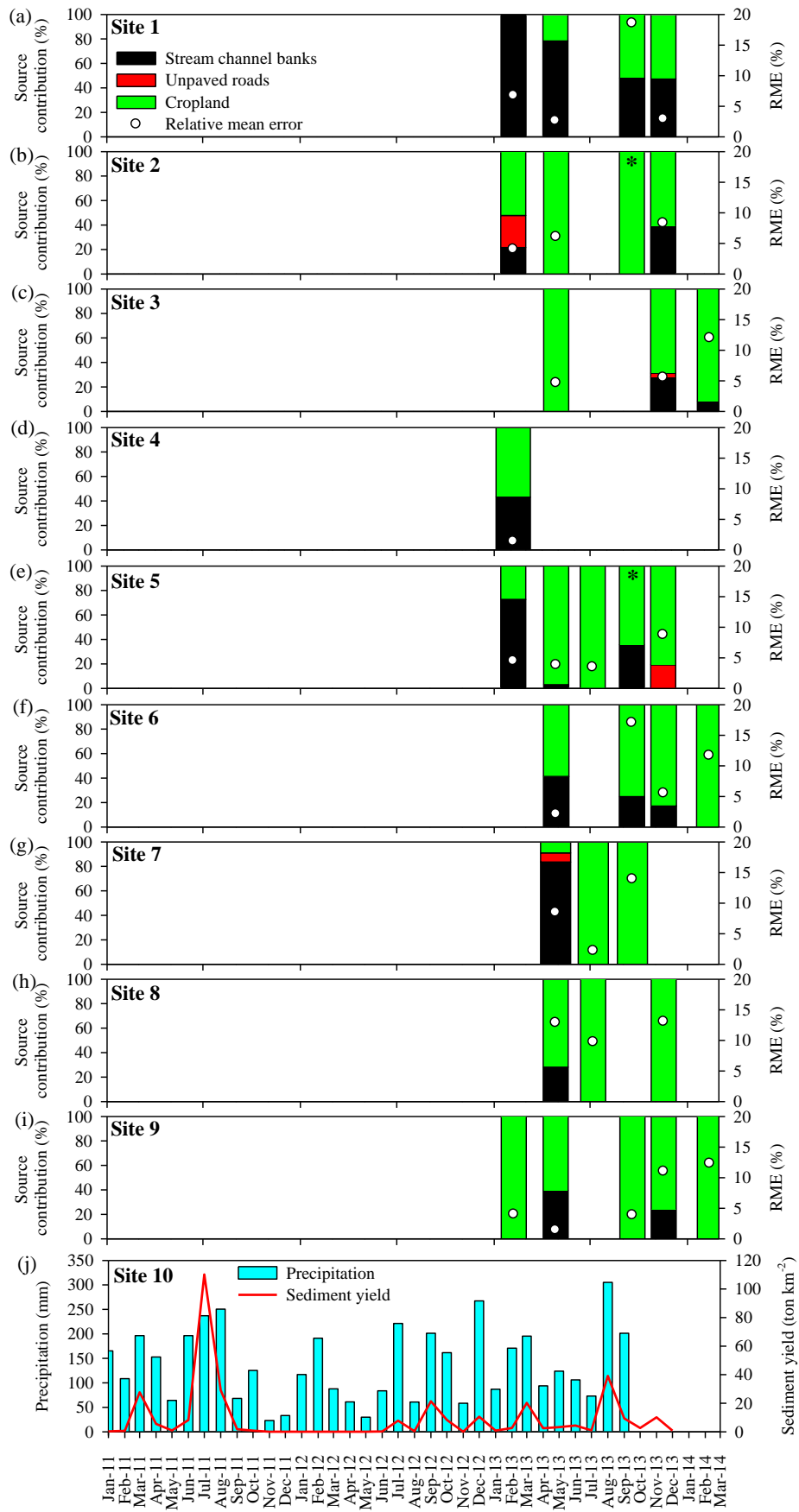
**Fig. 3.** Records of precipitation, discharge, suspended sediment concentration (SSC), hysteresis pattern, and the sediment source contribution during the floods that occurred on 6 July 2012 (a, b, c) and 2 October 2012 (d, e, f) in Guaporé catchment.



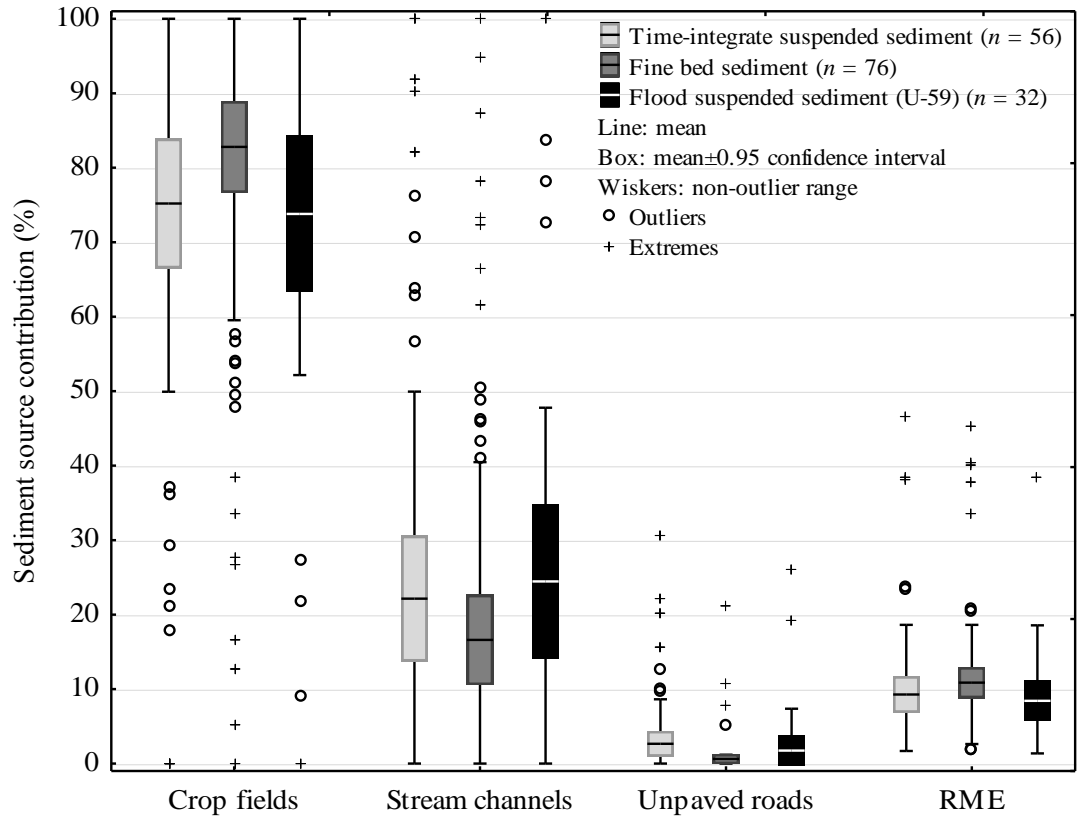
**Fig. 4.** Spatial and temporal variation in source contributions for suspended sediment samples collected with time-integrate samplers in Guaporé catchment (a, b, c, d, e, f, g, h, i, j), and records of monthly precipitation and sediment yield at the catchment outlet (k). Stars indicate relative mean error for prediction higher than 20%.



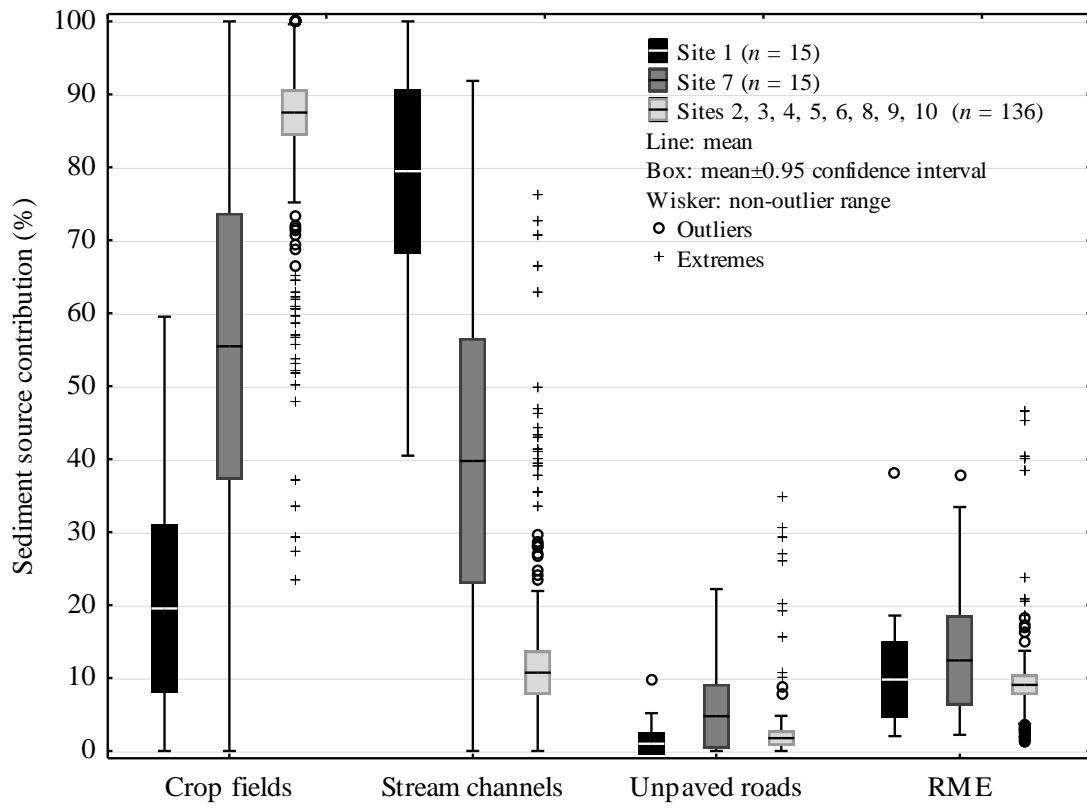
**Fig. 5.** Spatial and temporal variation in source contributions for fine-bed sediment samples collected in Guaporé catchment (a, b, c, d, e, f, g, h, i, j), and records of monthly precipitation and sediment yield at the catchment outlet (k). Stars indicate relative mean error for prediction higher than 20%.



**Fig. 6.** Spatial and temporal variation in source contributions for flood suspended sediment samples collected with US-U59 in Guaporé catchment (a, b, c, d, e, f, g, h, i), and records of monthly precipitation and sediment yield at the catchment outlet (j). Stars indicate relative mean error for prediction higher than 20%.



**Fig. 7.** Box plot of the sediment source contribution for different sediment sampling strategies.



**Fig. 8.** Box plot of the sediment source contribution for different sediment sampling sites.