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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Abstract

Cropland cultivated under no-tillage has dramatically increased in Brazil during the last three decades. However, soil degradation by water erosion remains excessive in the country. Furthermore, the impact of inappropriate agricultural practices on soil erosion is often neglected by farmers. Therefore, the contribution of potential sources of sediment should be quantified in order to raise awareness among rural communities on the need to improve land management for protecting soil and water resources. This study quantified the contribution of potential sources to sediment transiting the Guaporé River, draining a 2032-km² cultivated catchment, in Southern Brazil. Potential sediment source types were surface of cropland soils ($n = 159$), unpaved roads ($n = 58$), and stream channel banks ($n = 46$). A total of 175 suspended sediment samples were collected following different sampling strategies (including sampling of river water during floods, installation of time-integrated suspended sediment samplers, and collection of bed sediment) in 10 sub-catchments, from January 2011 to March 2014. Discriminant properties were selected among the concentrations in 22 geochemical elements and total organic carbon. Results showed that sediment source contributions were similar for the different sediment sampling strategies. Although, the contributions of sediment sources varied in space across Guaporé catchment, they were dominated by cropland ($91 \pm 15\%$), while stream channels ($5 \pm 2\%$) and unpaved roads ($4 \pm 10\%$) were sources of minor importance. Cropland contribution increased with the drained cropland surface area. The unambiguous dominance of cropland as the main source supplying sediment to the Guaporé River justifies the urgent need to better plan land use and to promote the adoption of appropriate conservation farming practices in similar areas of Southern Brazil. Soil losses in cropland could be reduced by implementing crop rotation, mechanical runoff control strategies, and by avoiding the construction of unpaved roads in thalwegs.

Keywords: Soil erosion, sediment fingerprinting, sediment tracing, conservational agriculture.

1. Introduction

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

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

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

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

A large catchment heterogeneous in terms of soil type, relief, land use, and soil management and therefore representative of a large set of environmental conditions found in Southern Brazil was selected to conduct this study (Guaporé River, 2,032 km²). Recently, Le Gall et al. (2016) showed that soils found in lower parts of this catchment (Acrisols, Leptosols, and Luvisols, mean 92%) contributed much more sediment than those found in upper parts (Ferralsols and Nitisols, mean 8%). They attributed these results to the different farming practices implemented in both catchment areas. However, there remains a lack of information regarding the contribution of different land uses (cropland, unpaved roads, and stream channel banks) to sediment in this catchment, and the current research will fill this knowledge gap. Furthermore, as this catchment drains to the Jacuí River, which supplies water resources to the

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

2. Study catchment

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

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

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

3. Methods

3.1. Hydro-sedimentological monitoring

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

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

3.2. Sediment source sampling

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

3.3. Sediment sampling

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

3.4. Sources and sediment analyses

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

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

3.5. Selection of optimum fingerprinting properties

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

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

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

3.6. Apportionment of sediment sources

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

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

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

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

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

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

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

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

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

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

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

4. Results

4.1. Source discrimination

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

4.2. Sediment source apportionment

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

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

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

Results indicate that the different sediment sampling strategies (TISS, FBS, and FSS) provided similar results (Table 6 and Fig. 7). Flood sediment samples were not included in this comparison because of the low number of samples available ($n = 11$). Overall, when grouping all sediment samples (TISS, FBS and FSS) and all sampling sites, on average, cropland was the main supply of sediment ($78\pm29\%$), followed by channel banks ($20\pm29\%$) and unpaved roads ($2\pm5\%$).

As no significant difference was found for the various sampling strategies, the entire set of sediment samples was used to compare the results obtained at the different sampling sites. Sediment source contributions varied in space across Guaporé catchment (Table 6) and were mainly characterized by changes in cropland and channel bank contributions to the river sediment ($P<0.0001$). Site 1 showed significantly different source contributions compared to all other sampling sites, with the exception of Site 7 (Table 6). The latter showed significantly different contributions compared to sites 4, 8, 9 and 10 (Table 6). Interestingly, cropland contribution to sediment was the lowest at Site 1 ($20\pm21\%$) and at Site 7 ($55\pm33\%$), whereas it was much higher and stable at the other sites ($88\pm19\%$). These results are consistent with the increasing cropland surface area drained by these sites (Table 2). In contrast, stream channel bank contributions were high at the sites characterized by low cropland contributions (i.e. $79\pm20\%$ at site 1 and $40\pm30\%$ at site 7), and low in the rest of the catchment where they delivered $11\pm18\%$ of suspended sediment. Unpaved roads provided a very low contribution to sediment across the entire catchment ($2\pm6\%$).

At the catchment outlet (site 10), when calculating the mean for material collected following all sampling strategies (including TISS, FBS, and FSS samples, $n = 29$), sediment was mainly supplied by cropland ($91\pm15\%$), with minor contributions from channel banks ($5\pm2\%$) and unpaved roads ($4\pm10\%$). When weighting these source contributions with the sediment flux calculated by Didoné et al. (2014 – $1.40 \text{ Mg ha}^{-1} \text{ yr}^{-1}$), the flux supplied by cropland was estimated to $2.17 \text{ Mg ha}^{-1} \text{ yr}^{-1}$.

5. Discussion

The current research unambiguously showed that cropland is the main sediment source ($91\pm15\%$, $n = 29$) in the Guaporé catchment. Source contributions modelled at the Guaporé catchment outlet remained similar to those found at most of the sites located on the main stem of the river, with the exception of sites 1 and 7, which drain less cultivated areas. At site 1, most of

cultivated areas are located in the uppermost part of the subcatchment and croplands are likely disconnected from the river network because of the presence of a wide band of riparian forest. When studying soil erosion in a very steep rural catchment cultivated with tobacco in this region of Southern Brazil, Pellegrini et al. (2010) reported that preserved riparian vegetation provided a barrier that decreased the amount of sediments and phosphorus transferred to water bodies, and consequently that mitigated off-site erosion impacts. In the same way, in the Chesapeake Bay watershed, USA, Massoudieh et al. (2012) found that the dense forest cover along streams reduced the contribution of sediment from agricultural areas located farther away from the river. The authors suggested that sediment generated by overland flow on the cultivated fields likely deposited in these forested areas and did not reach the stream network. In contrast, the dominant contribution of cropland calculated for site 7 agreed well with those obtained by a previous study conducted in a small headwater catchment (1.19 km²) draining to site 7 (Tiecher et al., 2016). The sampling site was characterized by a similar proportion of cropland in the drainage area (40% vs. 35% for site 7 in the current research), and contributions of farmland (57±14%) were found to be very similar (55±33%) with those calculated at site 7.

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

Although the contribution of unpaved roads remained low when considering the entire catchment, spatial variations of this supply may be found when considering a network of embedded sub-catchments. Accordingly, a scale effect is observed when moving from the headwater Arvorezinha catchment (Tiecher et al. 2016 – 1.19 km²) to site 7 (88 km²), and then site 10 (Guaporé outlet – 2,032 km²), with a decrease in unpaved road contributions in downstream direction (23±14, 5±8 and 4±10%, respectively). These results are consistent with those of Thomaz et al. (2014), who evaluated the local impacts of six unpaved road–stream crossings on suspended sediment concentrations in the rural Guabiroba River, in Southern Brazil. They demonstrated that the increase of suspended sediment concentration was strongly

scale-dependent. Unpaved road contribution was high for streams draining areas covering less than 3 km², and it decreased in larger areas. In Southern Brazil, most of these rural roads are built without considering their potential impact on runoff and erosion. Several main roads and local paths are often damaged by rills and gullies, which complicates access for the farmers to their fields and increases maintenance costs for the municipalities (Thomaz et al., 2014). Furthermore, despite their low contribution to sediment in larger catchments, they represent perennial landscape features, and their construction should therefore be planned in the framework of integrated soil erosion control programs (Collins et al., 2010).

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

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

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

6. Conclusions

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

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

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

¹ IUSS Working Group WRB (2007)

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

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

Table 2 Land use in the drainage area and number of sediment samples collected at 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	
<i>Area (km²)</i>	3.3	269	532	257	1,043	1,441	99	145	1,698	2,032	2,032
<i>Area (%)</i>	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

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

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 ⁻¹)	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	36.0	6.5
Ba (mg kg ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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 ⁻¹)	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

Bold values indicate *p*-value <0.1.

Table 4 Results of the discriminant function analysis (DFA) as indicated by the Wilks' 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

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_{critical}	1.71
<i>p</i> -value	<0.00001
<i>F-values</i>	
Degrees of freedom	7;223
F_{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

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

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

¹Comparisons 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 $P<0.1$.

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

A

LITHOLOGY

B

SOIL

C

SLOPE

D

LAND USE

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.