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

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ABSTRACT

Brazil is a leader in the adoption of conservation agriculture practices and technologies. However, the impact of these practices on sediment sources at the catchment scale has not been quantified yet, particularly in grain growing regions, where a conservationist no-tillage system is implemented to protect soils. To address this knowledge gap, a sediment fingerprinting study based on elemental geochemistry was carried out in a large agricultural catchment (804 km^2) of Southern Brazil where no-tillage practices dominate. A total of 156 soil samples were taken to characterize the three main potential sediment sources: cropland (n=79), unpaved roads (n=41), and channel banks (n=36). Sediment sampling was performed using a time-integrated sampler (n=33) and by collecting fine-bed material (n=34) at five locations across the catchment. Sediment was also sampled during flood events at the catchment outlet (n=20). Sediment source contributions were calculated using an optimal suite of geochemical properties and a mixing model. Results showed that although the catchment is not particularly sensitive to soil erosion (*i.e.* deep clayey soils with gentle slopes), the amount of sediment supplied by cropland to the river network remains very high (up to 1.63 Mg ha^{-1} yr^{-1}). Sediment fingerprinting results showed that even when no-tillage is implemented, cropland remains an important source of sediment, supplying up to 70% of the material transiting the Conceição River. Accordingly, the current conservation farming system in this catchment needs to be improved to further reduce soil erosion and sediment yield.

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

INTRODUCTION

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

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

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

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

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

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

The soil degradation problem in Southern Brazil is complex as it results from a combination of environmental, economic, social and political factors. However, to raise farmers' awareness, consistent data demonstrating the impact of their practices on land and water resources are currently lacking. Merten et al. (2015) showed that soil erosion decreased by more than 70% on plots (38.5 to 10,000 m^2) cultivated under NTS compared to those where traditional tillage was implemented. Furthermore, the impact of no-tillage systems on sediment yields was investigated in two large catchments of Southern Brazil (Didoné *et al*., 2014). This preliminary study based on hydrological and sedimentological monitoring showed that runoff and erosion remained excessive in these cultivated areas (1.40 Mg ha^{-1} $year^{-1}$). These results suggest that additional control measures are needed at the hillslope scale in order to avoid runoff concentration and the formation of rills and gullies, as it was observed in other cultivated environments of the world, such as in northwestern Europe (Delmas *et al.*, 2012).

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

MATERIAL AND METHODS

Study site

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

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

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

Hydro-sedimentological monitoring

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

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

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

Sediment source sampling

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

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

Sediment sampling

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

Source and sediment analyses

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

The geochemical tracers evaluated included: total organic carbon (TOC) estimated by wet oxidation ($K_2Cr_2O_7$ + H_2SO_4) and the total concentration of several elements (Al, Ba, Be, Ca,

Co, Cr, Cu, Fe, K, La, Li, Mg, Mn, Na, Ni, P, Pb, Sr, Ti, V, and Zn) using ICP-OES after microwave assisted digestion with concentrated HCl and HNO_3 (ratio 3:1) for 9.5 min at 182ºC.

Selection of optimum fingerprinting properties

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

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

Apportionment of sediment sources

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

RESULTS

Source discrimination

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

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

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

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

Source apportionment

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

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

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

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

Weighted source contributions

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

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

DISCUSSION

Dominant erosion processes

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

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

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

Source contributions

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

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

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

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

Management implications

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

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

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

CONCLUSION

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

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

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

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

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

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

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

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

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

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

Figure 1

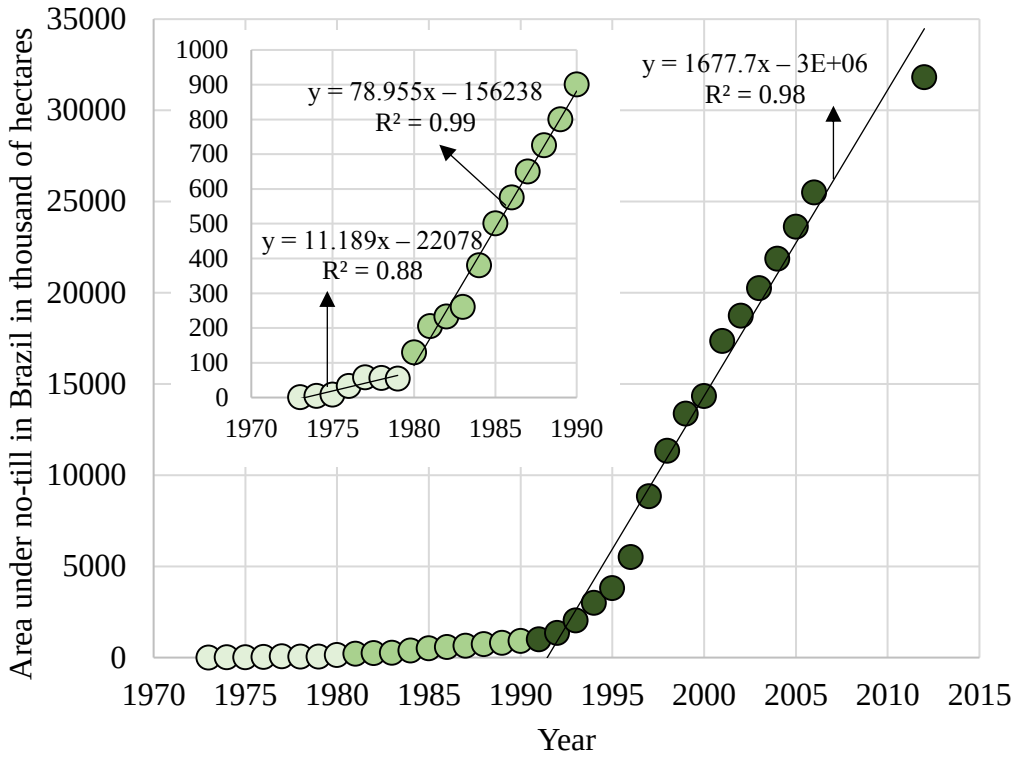
Area under no-till in Brazil in thousand of hectares
35000
30000
25000
20000
15000
10000
5000
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year
y = 1677.7x – 3E+06
R² = 0.98
y = 78.955x – 156238
R² = 0.99
y = 11.189x – 22078
R² = 0.88
1000
900
800
700
600
500
400
300
200
100
0
1970
1975
1980
1985
1990

Figure 2

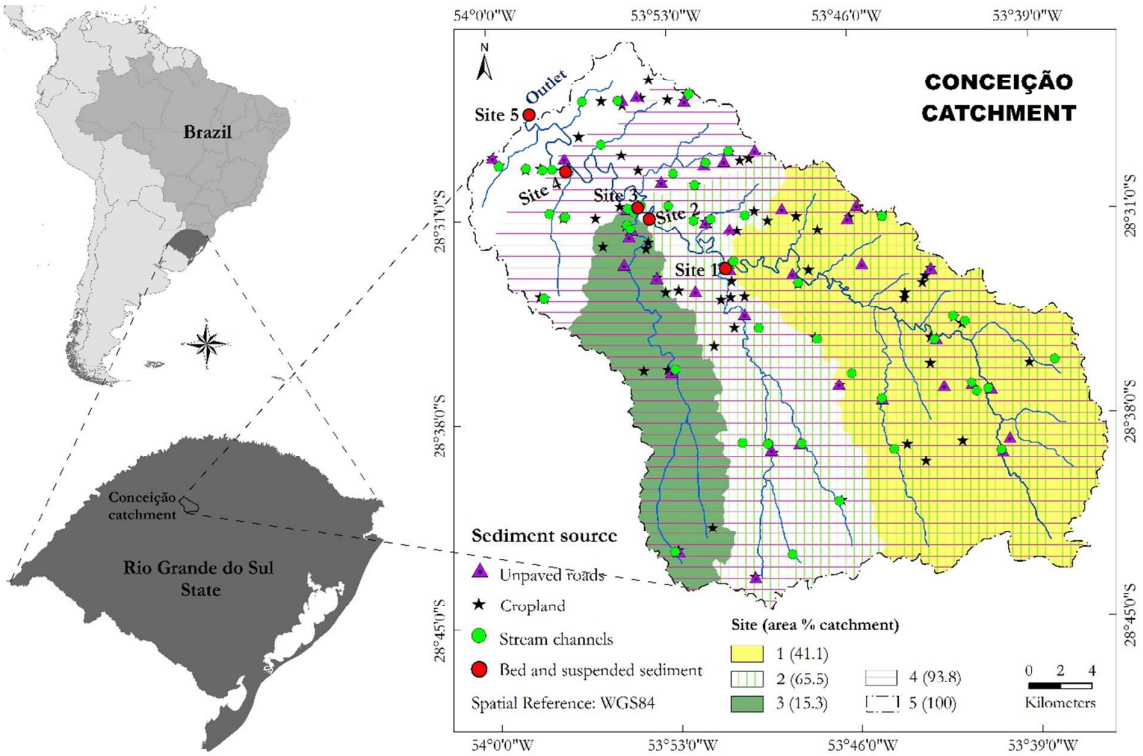
Brazil
Conceição catchment
Rio Grande do Sul State
CONCEIÇÃO CATCHMENT
Outlet
Site 5
Site 4
Site 3
Site 2
Site 1
54°0'0"W
53°53'0"W
53°46'0"W
53°39'0"W
28°31'0"S
28°38'0"S
28°45'0"S
Sediment source
Unpaved roads
Cropland
Stream channels
Bed and suspended sediment
Spatial Reference: WGS84
Site (area % catchment)
1 (41.1)
2 (65.5)
3 (15.3)
4 (93.8)
5 (100)
0 2 4
Kilometers

Figure 3

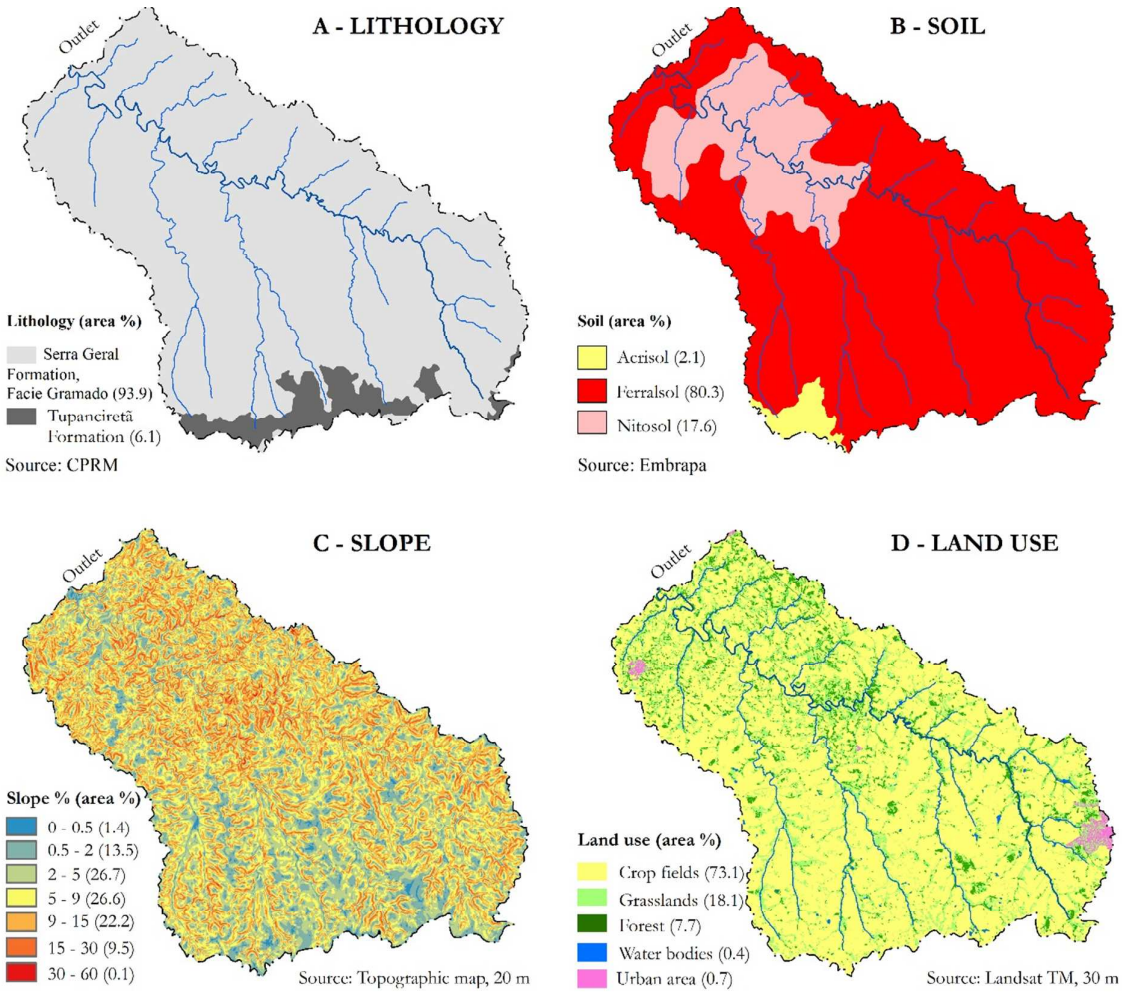
A - LITHOLOGY
Outlet
Lithology (area %)
Serra Geral Formation, Facie Gramado (93.9)
Tupanciretã Formation (6.1)
Source: CPRM
B - SOIL
Outlet
Soil (area %)
Acrisol (2.1)
Ferralsol (80.3)
Nitosol (17.6)
Source: Embrapa
C - SLOPE
Outlet
Slope % (area %)
0 - 0.5 (1.4)
0.5 - 2 (13.5)
2 - 5 (26.7)
5 - 9 (26.6)
9 - 15 (22.2)
15 - 30 (9.5)
30 - 60 (0.1)
Source: Topographic map, 20 m
D - LAND USE
Outlet
Land use (area %)
Crop fields (73.1)
Grasslands (18.1)
Forest (7.7)
Water bodies (0.4)
Urban area (0.7)
Source: Landsat TM, 30 m

Figure 4 (1/2)

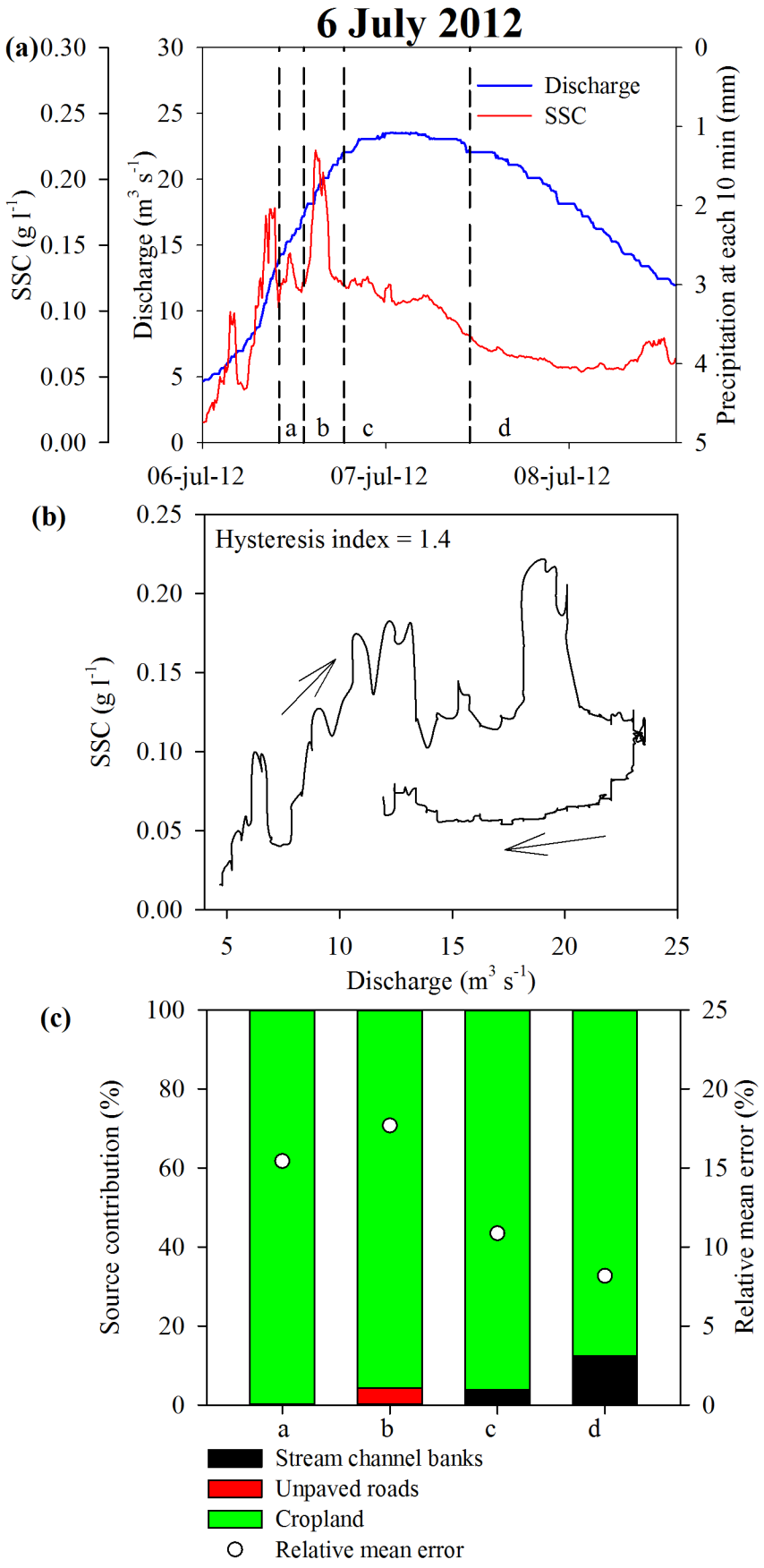
6 July 2012
(a)
SSC (g l-1)
Discharge (m3 s-1)
Precipitation at each 10 min (mm)
Discharge
SSC
a
b
c
d
06-jul-12
07-jul-12
08-jul-12
(b)
Hysteresis index = 1.4
SSC (g l-1)
Discharge (m3 s-1)
(c)
Source contribution (%)
Relative mean error (%)
a
b
c
d
Stream channel banks
Unpaved roads
Cropland
Relative mean error

Figure 4 (2/2)

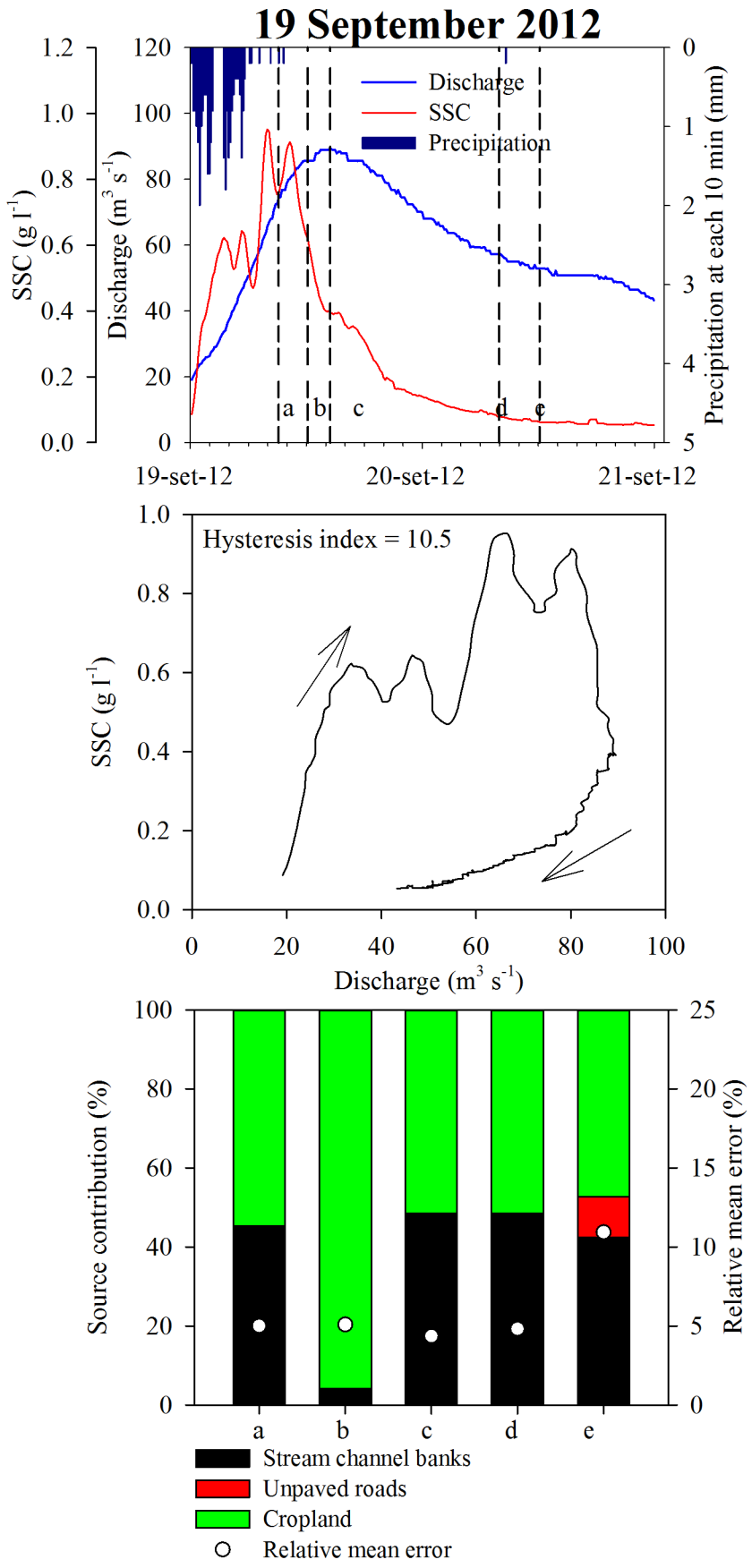
19 September 2012
Discharge
SSC
Precipitation
SSC (g l-1)
Discharge (m3 s-1)
Precipitation at each 10 min (mm)
a
b
c
d
e
19-set-12
20-set-12
21-set-12
Hysteresis index = 10.5
SSC (g l-1)
Discharge (m3 s-1)
Source contribution (%)
Relative mean error (%)
a
b
c
d
e
Stream channel banks
Unpaved roads
Cropland
Relative mean error

Figure 5 (1/2)

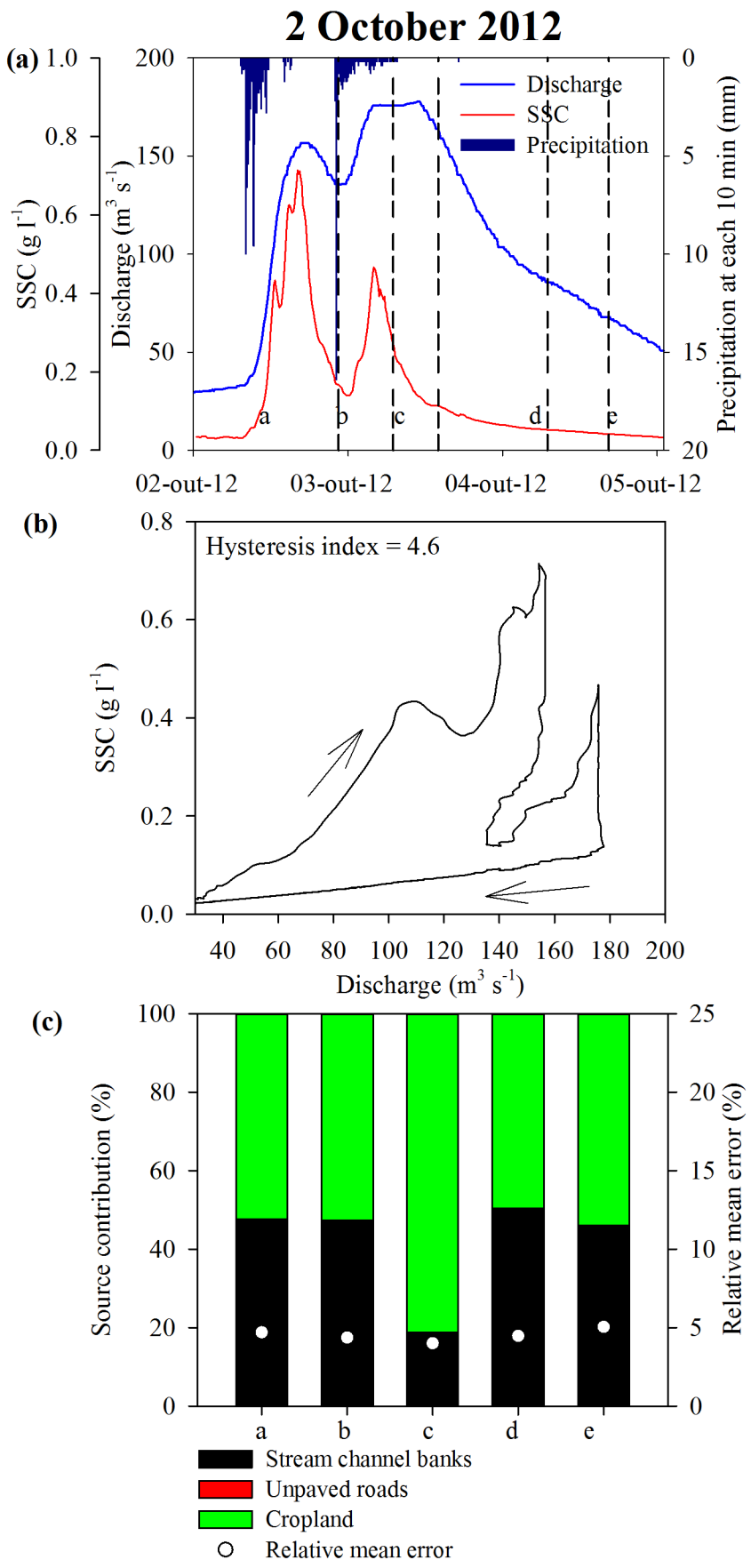
2 October 2012
(a)
SSC (g l-1)
Discharge (m3 s-1)
Precipitation at each 10 min (mm)
Discharge
SSC
Precipitation
a
b
c
d
e
02-out-12
03-out-12
04-out-12
05-out-12
(b)
Hysteresis index = 4.6
SSC (g l-1)
Discharge (m3 s-1)
(c)
Source contribution (%)
Relative mean error (%)
a
b
c
d
e
Stream channel banks
Unpaved roads
Cropland
Relative mean error

Figure 5 (2/2)

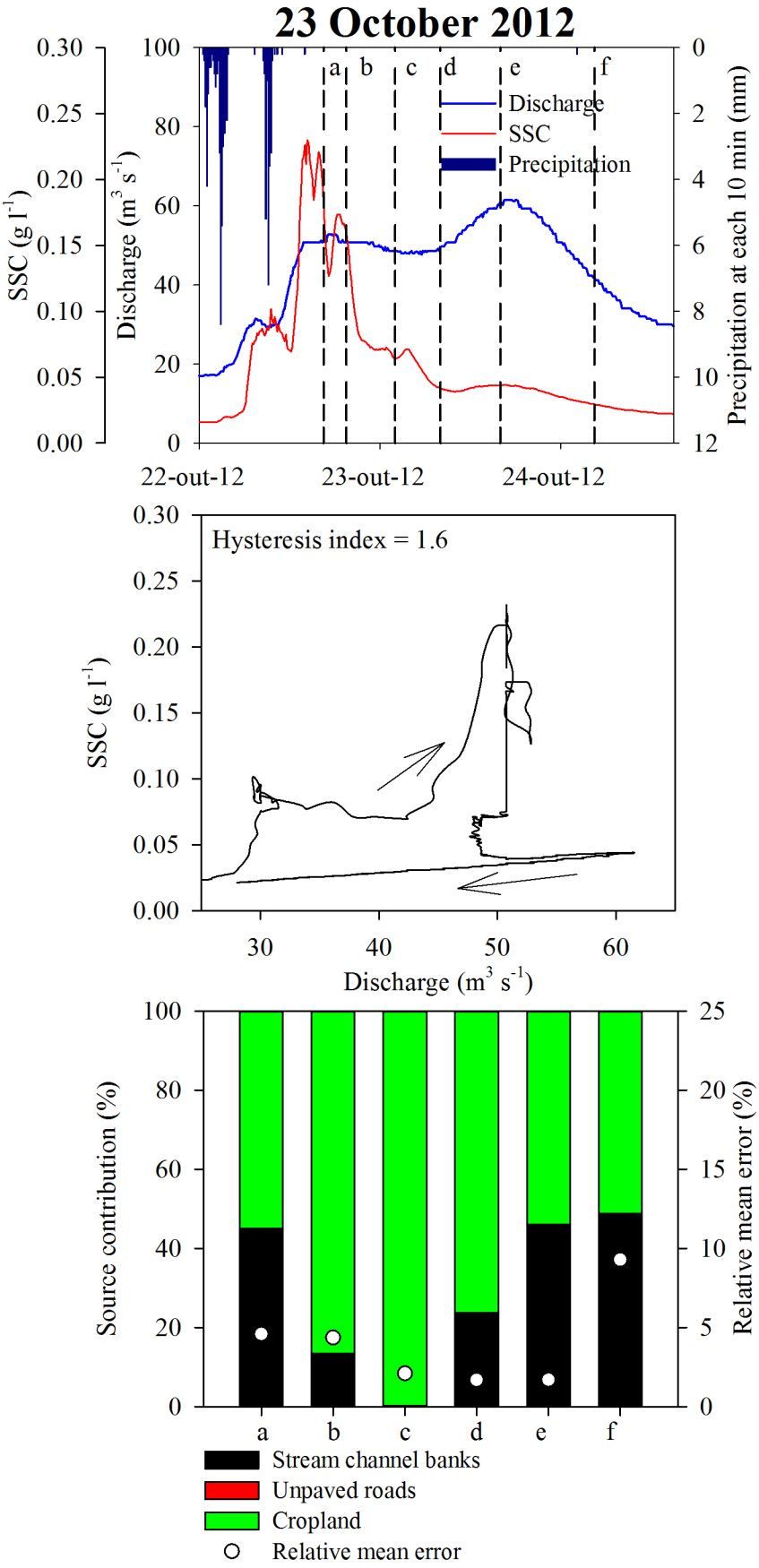
23 October 2012
SSC (g l-1)
Discharge (m3 s-1)
Precipitation at each 10 min (mm)
a
b
c
d
e
f
Discharge
SSC
Precipitation
22-out-12
23-out-12
24-out-12
Hysteresis index = 1.6
SSC (g l-1)
Discharge (m3 s-1)
Source contribution (%)
Relative mean error (%)
Stream channel banks
Unpaved roads
Cropland
Relative mean error

Figure 6

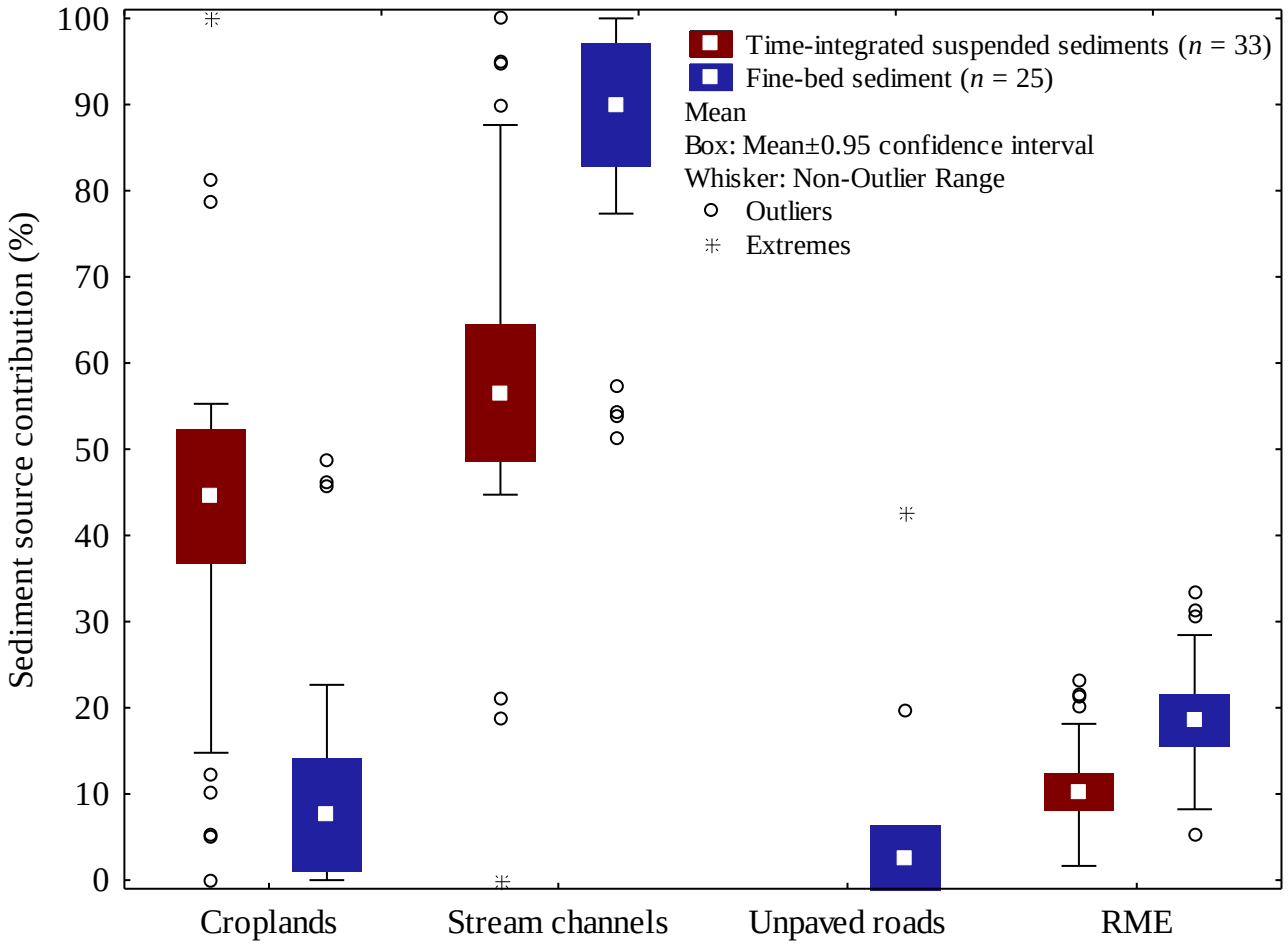
Sediment source contribution (%)
100
90
80
70
60
50
40
30
20
10
0
Croplands
Stream channels
Unpaved roads
RME
Time-integrated suspended sediments (n = 33)
Fine-bed sediment (n = 25)
Mean
Box: Mean±0.95 confidence interval
Whisker: Non-Outlier Range
Outliers
Extremes

Figure 7

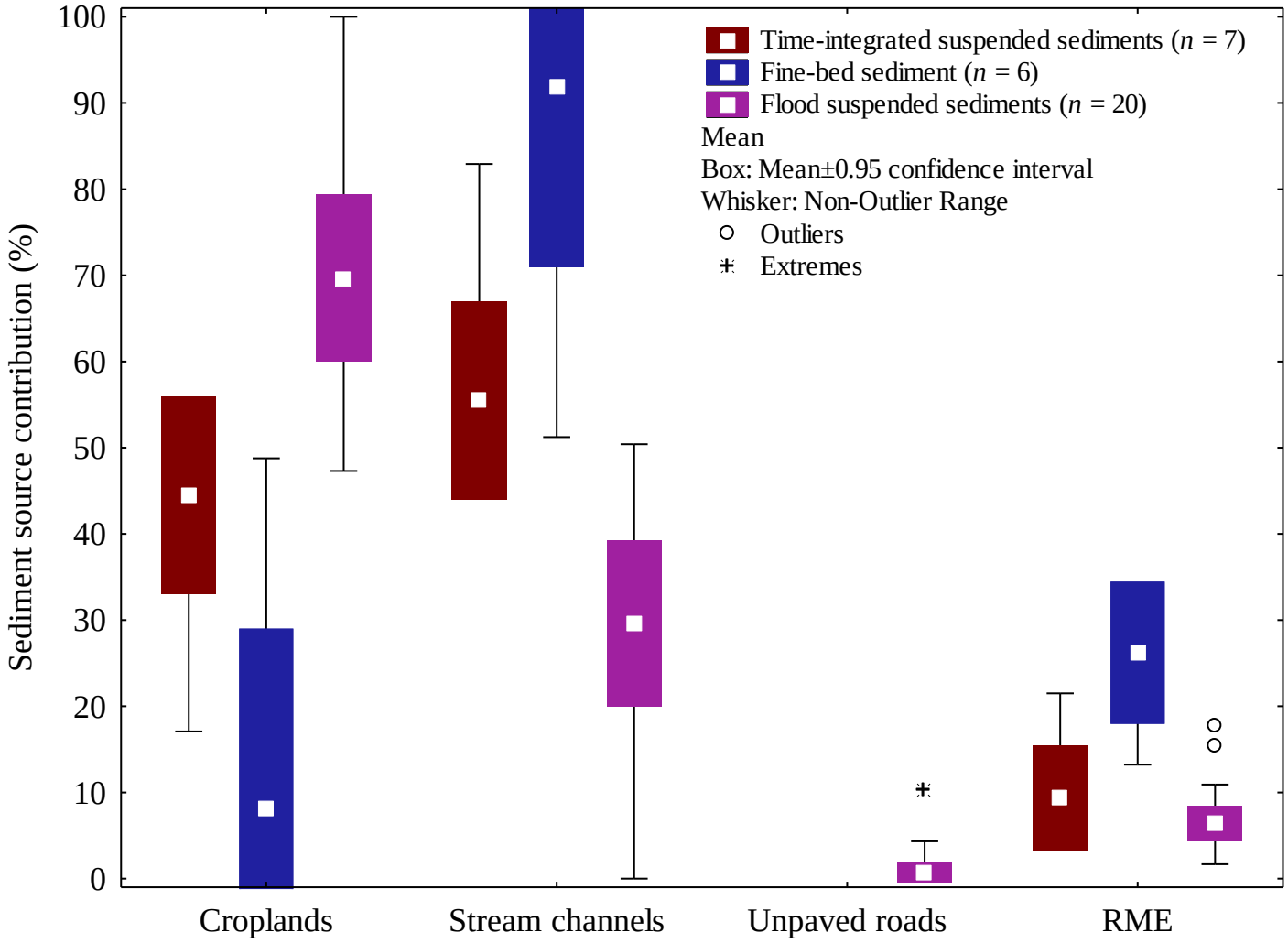
Sediment source contribution (%)
100
90
80
70
60
50
40
30
20
10
0
Time-integrated suspended sediments (n = 7)
Fine-bed sediment (n = 6)
Flood suspended sediments (n = 20)
Mean
Box: Mean±0.95 confidence interval
Whisker: Non-Outlier Range
Outliers
Extremes
Croplands
Stream channels
Unpaved roads
RME

Figure 8

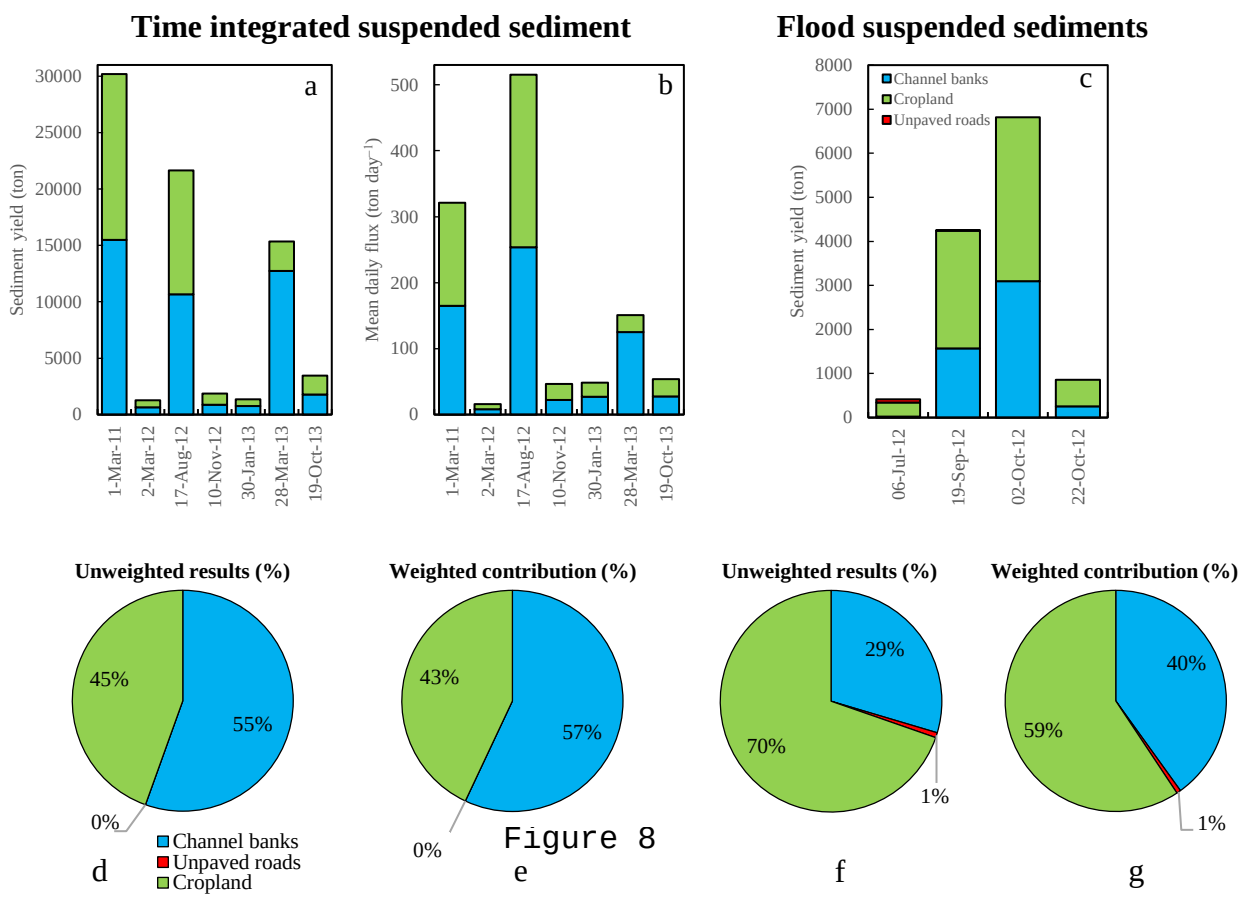

Figure 8

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

Land use (%)	Sub-catchment					Total
	1	2	3	4	5	
Cropland	73.1	73.8	78.6	74.7	73.8	-
Grasslands	18.1	17.7	16.0	17.0	17.0	-
Forest	7.7	7.4	5.2	7.0	7.4	-
Water body	0.4	0.4	0.3	0.4	0.4	-
Urban	0.7	0.7	0.0	0.9	1.4	-
Number of sediment samples collected following each sediment sampling strategy						
TISS	7	6	7	6	7	33
FBS	5	3	8	3	6	25
FSS	-	-	-	-	20	20
Total	12	9	15	9	33	78

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

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

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

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

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

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

Table 4. Discriminant function analysis (DFA) output.

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

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

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