Runoff, soil loss, and sources of particulate organic carbon delivered to streams by sugarcane and riparian areas: an isotopic approach

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Abstract. Soil erosion leads to land degradation and translocation of soil particles together with associated particulate organic carbon (POC) and nutrients, thereby influencing the global carbon cycle. In the present study, we estimated the contribution of POC delivered to a first-order stream from upslope sugarcane fields and a riparian forest in southeast Brazil. The results show that the amount of surface runoff and soil erosion generated in the riparian forest is significantly lower than in the upslope sugarcane field. However, the contribution of the forest to the total stream bed POC was above 70%, even though most sediments delivered to the stream originated from the upland sugarcane fields. The discrepancy between sediment and POC delivery from both land uses is a consequence of the presence of preferential runoff pathways from the agricultural fields, through the buffer strips, to the stream. This disconnection between the main sources of sediment and POC to the first-order stream is a potentially important mechanism influencing the transfer of POC from upslope areas to waterways. This mechanism should be considered in order to more reliably assess fluxes of OC from upslope areas to first-order streams in landscapes where arable land is separated from streams by a semi-natural buffer zone with permanent vegetation.

Keywords: soil erosion, lateral fluxes of particulate organic carbon, sugarcane, riparian forest, preferential runoff pathways

1 Introduction

Soil erosion is both a fundamental phenomenon that governs biogeochemical cycling of essential elements in the Earth system (Berhe at al., 2018; Wang et al., 2017), and one of the main causes of land degradation, causing losses of ecosystem services such as food production (Brady and Weil, 2013; Pimentel, 2006; Pimentel et al., 1995). Moreover, due to expected changes in the Earth's climate, an increase in the total rate of soil erosion is expected (Berc et al., 2003; Yang et al., 2003).

Previous research has shown that soil erosion not only leads to soil degradation but also significantly impacts fresh water quality (Filoso et al., 2015). Carbon and nutrients fixed by land plants or added as inputs to crops are laterally displaced from upland soils to inland waters (Cole et al., 2007; Quinton et al., 2010; Regnier et al., 2013; Van Oost et al., 2007; Wang et al., 2017). However, the impact of soil erosion on water quality and carbon cycling is at present not fully understood, especially in tropical areas (Berhe et al., 2018; Cole et al., 2007; Doetterl et al., 2016; Stallard, 1998; Van Oost et al., 2007).

Watersheds are mostly made up of sloping landscapes (Berhe et al., 2008), where the conversion of forest to arable land inevitably causes an increase in soil loss (Oliveira et al., 2015). This is also occurring in Brazil, where sugarcane fields cover an area of approximately 10 million ha, mostly in southeast Brazil (Filoso et al., 2015). Studies have demonstrated that soils cultivated with sugarcane undergo significant changes in terms of physical characteristics (Sant'anna et al., 2009; Silva et al., 2007). In general, increasing soil erosion is a consequence of soil compaction linked to the use of heavy machinery and the subsequent decrease in infiltration capacity, which facilitates surface runoff and soil erosion (Filoso et al., 2015; Silva et al., 2009; Teixeira et al., 2012).

One measure to counteract the detrimental effects of soil erosion downslope of the areas of sediment production is the maintenance of natural or planted riparian forests acting as buffer strips along rivers and streams. It is expected that these vegetation strips protect against stream bank erosion (Martin and Church, 2000; McKergow et al., 2003; Zaimes et al., 2008; Zaimes and Schultz, 2015) and protect water bodies against pollution, by trapping a large fraction of the soil particles and runoff originating from arable land (Bussi et al., 2016; Dosskey et al., 2010; Zhang et al., 2010). However, recent studies have shown that trapping under field conditions is often considerably lower than anticipated from laboratory or experimental plots results due the formation of preferential pathways within the buffer strips that may reduce their buffering capacity (Knight et al., 2010; Salemi et al., 2016; Stehle et al., 2016; Wallace et al., 2018).

In this paper the surface runoff and associated lateral fluxes of soil organic carbon from arable land were measured to: (1) quantify the lateral flux of soil organic carbon from a sugarcane field passing through a riparian forest buffer into a first-order stream; (2) to track the origin of the soil organic carbon in the stream by means of the use of stable carbon isotopic composition ($\delta^{13}C$); and (3) evaluate the effect of a riparian forest buffer on the transfer of soil organic carbon from a sugarcane field to a first-order stream.

2 Material and Methods

2.1 Study area

Field measurements were taken in a 6.5-ha first-order sub-catchment of the Barrocão catchment, located in the Corumbatai River basin, State of São Paulo, (22º36'S, 47º40'W), Southeast region of Brazil (Figure 1). The Barrocão catchment has an average elevation of 510 m above sea level and a hilly topography with an average slope gradient of 15% (Figure 1 - Supplemental Material).

According to the Köppen classification, the climate is subtropical (Cwa), with a distinct dry season from April to September and a wet season from October to March. Mean annual precipitation between 1970 and 2015 was approximately 1320 mm [http://www.leb.esalq.usp.br/leb/anos.html] and the mean annual temperature for the same period was 23ºC. The total precipitation during the one-year study period was 1530 mm.

Soils in the catchment were classified as Ultisols (Soil Survey Staff, 2014), equivalent to Argissolo Vermelho-Amarelo in the Brazilian Soil Classification (EMBRAPA, 2013; Oliveira, 1999). The riparian forest, which is second-growth forest dating back 60 years, covers about 60% of the total studied catchment area. The forest is composed of more than 20 different tree species and is at least 30 meters wide on both sides of the stream, in compliance with the Brazilian environmental law (Forest Code, law nº 12.651 of 25 of May of 2012). Visual observations clearly showed the presence of intense soil erosion on the sugarcane fields upslope of the riparian forest. A large fraction of the water and sediment leaving the sugarcane fields is concentrated in preferential runoff pathways that start in the sugarcane areas, pass through the riparian forest, and flow straight to the small perennial stream that is draining the catchment (Figure 2 - Supplemental Material).

It is important to describe in detail the sugarcane phenological cycle because each phase provides a distinct soil cover of stalks and leaves. Sugarcane has four growth stages, which in total last 12-18 months (Figure 3 - Supplemental Material). These growth stages are characterized by different groundcover: 1) 10% groundcover - establishment (germination or re-growth emergence); 2) 10% to 70% groundcover - tilling (canopy establishment); 3) 70% to 80% groundcover - culm formation and 4) > 80% plant cover - ripening (plant senescence) (Ellis and Lankford, 1990).

Field measurements were taken in the eastern and the western slopes of the watershed, hereafter called slope A and slope B, respectively, which have been continuously cropped with sugarcane since the 1950s (Figure 1 and Figure 1 - Supplemental Material). Sugarcane plants are replanted every 5 – 6 years, as yields annually decline by about 10% (Cabral et al., 2012). The data reported for slope A (CTC15 cultivar) refer to sugarcane plant cultivars planted in February 2014, with the first harvest in June 2015. Therefore, from June to the end of this study, sugarcane in slope A was the first ratoon (Figure 4 - Supplemental Material). On slope B, sugarcane (RB867515 cultivar) was planted in March 2012, the first harvest was 18 months later, while the first ratoon was harvested in October 2015. Therefore, the data reported here for slope B refer to the second ratoon for the whole study period (Figure 4 - Supplemental Material). The sugarcane cultivars used in our catchment cover more than

35% of the total sugarcane area in Brazil due to their rapid growth, high productivity, tall upright growth characteristic, high-density of culm, good sprouting from stump, and great drought tolerance (Chapola et al., 2016).

Traditionally, until 2012, sugarcane leaves were burned to facilitate harvesting. However, this practice was banned in the State of São Paulo; from 2012 onwards, pruned leaves were left on the ground and used to fuel biomass boilers to provide energy. Due to the steep slopes of the Barrocão catchment (Figure 1 – Supplemental Material), sugarcane harvesting has always been done manually. In contrast, soil tillage and sugarcane transport have always been done mechanically. Soil management and fertilizer application has changed little over time. Annually, about 350 kg ha^{-1} of mineral fertilizer (NPK) is applied to slopes A and B, and a subsequent application of 2 Mg ha^{-1} of Ajifer®, an organic nitrogen compound containing 7.5% nitrogen, 7% sulfur and 10% organic carbon, is applied only to slope A, because each slope is managed by different owners with different fertilizing decisions.

2.2 Infield measurements

Soil saturated hydraulic conductivity (K_{sat}) measurements were done on 25 randomly selected points, comprising 9 from riparian forest, 8 from sugarcane slope A and another 8 from sugarcane slope B, using a compact constant head permeameter (Amoozegar, 1992). These measurements were conducted at 0.15, 0.30, 0.50 and 0.90 m soil depth. For each depth point, K_{sat} rate was measured in triplicate.

2.3 Sampling

Soil samples were collected in triplicate with an Edelman auger in the top, middle and footslopes of the sugarcane slopes and in the riparian forest. Soil samples were collected from the following depths: 0.05, 0.15, 0.30, and 0.50 m.

From November 2014 to November 2015, the amount and intensity of rainfall as well as surface runoff and lateral soil fluxes were measured in sugarcane fields and riparian forest. The amount and intensity of rainfall were measured at 10-min intervals with a tipping-bucket rain gauge with a resolution of 0.254 mm (RainLog, RainWise Inc.). The gauge was installed in a cleared area at about 500 m from the stream (Figure 1). After each field campaign, the rain gauge was cleaned to prevent clogging by debris. To classify rainfall events as an intensive event, therefore erosive event, at least 15 mm of rainfall must have been recorded in one hour or at least 20 mm of rainfall must have been recorded in four hours (Cruciani et al., 1998).

Surface runoff generation and lateral soil fluxes were measured in erosion plots. These had a pentagonal shape to direct runoff to a 20-L plastic reservoir at the end of the plots. The total area of each plot was 1.8 m^2. Triplicate plots were installed 10 m from each other in the middle of the slope in both cropped fields (slopes A and B) and in the riparian forest. The distance from the triplicate plots on slopes A and B to the triplicate plots of the riparian forest was approximately 70 meters. The erosion plots used are small (1.8 m^2) for erosion evaluation (Bagarello et al., 2018). The reason for using these plots was that this was the size accepted by the farmer to prevent a significant loss of sugarcane cropped area. The main caveat in using such small plots is that lateral flux of soil particle by temporary gully formation is neglected, and the type of lateral soil flux measured in these plots was by soil detachment caused by raindrop impact and the interrill erosion. Therefore, soil loss can be underestimated in our study, making extrapolation to other sugarcane areas difficult. On the other hand, as the same plot area was adopted in the whole study area, intercomparisons between slopes A and B, and riparian forest are still valid.

Surface runoff generation, expressed in millimeters, was calculated as:

$$SR = \left(\frac{V}{A}\right)\ 1000 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

where: SR = surface runoff generation (mm), V = volume of water collected in the reservoir (m^3) and A = the area of the erosion plot (m^2).

The water in the 20-L reservoir was collected after intensive rainfall events (Cruciani et al., 1998). From November 3, 2014 until November 5, 2015, samples were collected after 25 rainfall events (Figure 5 - Supplemental Material).

Soil lateral flux was calculated by passing the water collected in the 20-L reservoir through a 63-µm sieve to separate coarse and fine solids. The concentration of coarse solids (expressed as g m^{-2}) was obtained after drying the material that was retained in the sieve at 60°C until the mass remained constant and by dividing by the plot area (1.8 m^2). The concentration of fine solids (expressed as g m^{-2}) was obtained by filtering the water volume that passed through the 63-µm sieve using pre-weighed and calcinated quartz filters of 0.7 µm. After filtration, the filters were weighed after being dried at 60°C until a constant weight was obtained. The concentration of fine solids was subsequently calculated by subtracting the filter weight from the total weight (filter + soil material) and dividing the solid mass by the plot area (1.8 m^2).

To estimate the amount of deposited sediments, a bathymetry survey was carried out every four months (Nov/2014, Mar/2015, Jul/2015, Nov, 2015) during the sampling period by measuring the height of the bed sediment column. This was done in 18 transects across the stream channel, distant one meter from each other, located upstream from a weir installed in the final portion of the catchment (Figure 1 –

Supplemental Material). In each transect three measurements were taken, one in the center, one in the left and one in the right banks of the the stream channel. Besides, stream surface bed sediments were also collected in four random selected points upstream from the weir (Figure 1 – Supplemental Material). The sediments were also collected in triplicate (margins and center of the channel), five times (Nov/2014, Feb/2015, May/2015, Aug/2015, Nov, 2015) evenly distributed throughout the duration of the study, yielding a total of 60 stream bed sediment samples. We tried to collect suspended solids during fast rising water events. For this purpose, single-stage samplers (model US-S-59 -United States Government, 1961) were installed in the stream channel at the catchment outlet (Figure 1 – Supplemental Material) where a weir was installed (Andrade, 2013). On several occasions the sampler was buried by the high load of sediments entering the stream. Consequently, only four samples of suspended solids were collected, where only the fine fraction was present and obtained using the same procedure as described above for eroded soil particles. For statistical purposes, nine additional samples from a previous study conducted in the same catchment, and collected with the same methodology of this study, were included in our analysis (Andrade, 2013).

To quantify the contribution of sugarcane fields and the riparian forest to POC in the stream sediments, we used the MixSIAR model (Moore and Semmens (2008)), a Bayesian mixing model that uses the stable carbon isotopic signatures of the POC sources to estimate their relative contribution. We ran the MixSIAR model using the stable carbon isotopic composition, assuming as sources of particles to streams the lateral soil flux from the erosion experimental sugarcane plots installed on slopes A and B, and the lateral soil flux from the erosion experimental riparian forest plots. We also assumed that there was no isotopic fractionation taking place between the eroded material and stream particles.

The stable carbon isotopic composition of the bulk lateral soil flux used in the MixSIAR was estimated by the weight average of the carbon stable isotopic composition of the fine and coarse fractions according to the following equation:

$$\delta = \frac{[X].\delta_{coarse} + [Y].\delta_{fine}}{[X+Y]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$

Where, δ is the o $\delta^{13}C$ weight average for the bulk lateral soil flux sample; [X] and [Y] are the absolute masses of coarse and fine fractions, respectively; and δ_{coarse} and δ_{fine} is stable carbon isotope composition of the coarse and fine fractions, respectively.

2.4 Laboratory measurements

Before analysis, solids collected from erosion plots in the 20-L reservoir, and solids from the stream were dried at 60º C. Soil and stream bed sediment samples were passed through a 2-mm sieve to remove small rocks, roots, leaves and charcoal fragments. Next, samples were homogenized, hand-ground with a mortar, weighed and packed in tin capsules. Organic carbon was determined by combustion in a Carlo Erba CHN analyzer (Thermoquest, Rodano, Italy). Due to the absence of carbonate rocks in our catchment and the soil acidity ($pH \leq 4.7$) we expected no or minimal presence of inorganic carbon, and therefore the total carbon measured was assimilated to organic carbon. Isotope measurements were performed with a Finnigan Delta-E mass spectrometer (ThermoFinnigan, Bremen, German). The $\delta^{13}C$ and $\delta^{15}N$ values were reported in per mil (‰) relative to Pee Dee Belemnite (PBD) standard and relative to air N_2, respectively. Analytical precision ($\pm 1\sigma$) was ± 0.2 ‰ for $\delta^{13}C$ and ± 0.3 ‰ for $\delta^{15}N$. The average precision of C and N concentration measurements was ± 0.1 %. Data reproducibility was checked by replicate analysis of selected samples and a laboratory standard.

To determine the grain size of the soil and sediments, granulometric analyses were performed to determine the sand (0.05 – 2.0 mm), silt (0.02 – 0.05 mm) and clay (< 0.02 mm) size-fractions for 8 soil profiles: 6 located in the top, middle and footslopes of the sugarcane areas A and B, and 2 in the top and middle of the slope in the riparian forest. These analyses were performed using the Bouyoucos hydrometer method (Bouyoucos, 1926).

2.5 Statistical analysis

We tested for diferences in the carbon, nitrogen and δ^{13}C of soil organic matter between the slopes A and B, and riparian forests by comparing these variables in the 0-5 cm depths from 9 soil pits in each of the slopes and riparian forests. Carbon and nitrogen concentrations were transformed to achieved normality, and a generalized linear model assuming a normal distribution and an identical linking function was applied to test for differences. Soil δ^{13}C could not be transformed to achieve normality, so in this case we used the Kruskall-Wallis non-parametric test.

The measured runoff volumes were not distributed normally, and no transformation was possible due to the large number of rainfall events which did not generate runoff in the riparian forest (Figure 5 - Supplemental Material). Therefore, we used a non-parametric method, the Kruskall-Wallis test, to test significant differences between slopes A, B and riparian forest. The lateral soil flux (expressed as mass of solids per area), as well as the organic carbon concentration of the soil, the lateral soil organic carbon flux (expressed as mass of carbon per area) were also not distributed normally. We used a box-cox transformation to achieve normality, and we tested for differences between slopes and riparian forest applying a generalized linear model, assuming a normal distribution and an identical linking function. The $\delta^{13}C$ of the solids in the lateral flux was not distributed normally; however, no transformation was possible for $\delta^{13}C$ values. In this case we also used the non-parametric test, Kurskall-Wallis. In these statistical models the average value between the triplicate plots was used.

Only differences at the 0.05 of probability level were reported as significant. The central tendency of the values was expressed by the median followed by the first and third quartile between brackets. Tests were done using STATISTICA13 package.

For quantification of the sugarcane and riparian forest contributions to the stream sediments, the Markov Chain Monte Carlo (MCMC) in the MixSIAR was set as follows: chain length: 3,000,000; burn-in: 1,500,000; thin: 5000, and number of chains: 3. The error structure was set as “process”. With these settings the Gelman-Rubin diagnostic was < 1.05 for all cases; and the Geweke diagnostic was < 5% for the three chains of the MCMC.

3 Results

3.1 Characteristics of the agricultural and riparian forest soils

Sand was the predominant grain size fraction in the soil profiles of slopes A and B (Table 1 – Supplemental Material). In the riparian forest, sand represented about 50% of the grain size fraction (Table 1 – Supplemental Material). Soil hydraulic conductivity (K_{sat}) was significantly higher ($p < 0.01$) in the riparian forest than in the sugarcane slopes until 0.5 m depth (Figure 7 - Supplemental Material). Most of the K_{sat} values in the riparian forest were higher than a rainfall intensity of 15 mm h^{-1} above 0.5

m depth (Figure 6 – Supplemental Material). On the other hand, in the sugarcane slopes all K_{sat} values were lower than this threshold (Figure 6 – Supplemental Material).

Soil organic carbon and nitrogen concentrations were higher ($p < 0.01$) in soil profiles of the riparian forest compared to soil profiles of sugarcane plots (Figure 2A-B). Additionally, organic carbon and nitrogen concentrations decreased with depth in the riparian forest, while this decrease was limited or absent on the sugarcane slopes (Figure 2A-B).

The $\delta^{13}C$ of topsoil in the riparian forest was approximately -25‰, increasing to -23‰ at a depth of 0.3 m (Figure 2C). The $\delta^{13}C$ of sugarcane soil in both slopes showed a different pattern. In the topsoil, $\delta^{13}C$ varied from -19‰ (slope A) or from -17.5 ‰ (slope B), decreasing to -21‰ at a depth of 0.3 m, below which the $\delta^{13}C$ became constant in both slopes (Figure 2C). Differences in the $\delta^{13}C$ of soil between sugarcane slopes and the riparian forest were significant ($p < 0.01$) in the first 0.15 m depth. The $\delta^{15}N$ of the soil increased with depth in all profiles (Figure 2D). In general, there was a tendency of higher soil $\delta^{15}N$ in the riparian forest than in the sugarcane plot B. However, this difference was only significant ($p < 0.05$) in the topsoil.

Precipitation, runoff and soil loss

The total precipitation during the one-year sampling period was 1,530 mm, which is somewhat higher than the historical average annual rainfall over the past 45 years in this region (1,320 mm). Despite the predominance of low intensity precipitation (< 15 mm h^{-1}), which comprised almost 90% of the events, high intensity precipitation (> 15 mm h^{-1}) contributed most to the total precipitation (56% of the total rainfall amount).

During two rainfall events (January 1 and March 3, 2015), no runoff was generated in the erosion plots ion slope A, while a lack of runoff generation was observed only once (September 9, 2015) in the plots on slope B. On the other hand, runoff was not generated during eleven out of twenty-five rainfall events on the plots in the riparian forest (Figure 5 - Supplemental Material). The highest runoff was observed at the plots of slope B followed by plots of slope A and the plots at the riparian forests (Figure 3). The total amount of generated runoff was only 2% of the total precipitation in the riparian forest and 6% and 10% on slopes A and B, respectively (Figure 3A).

Most of the cumulative lateral soil flux (expressed as mass of solids per area) on slope B occurred during the first growth stage of sugarcane (November-December 2014). Afterwards, with growth of the sugarcane, the lateral soil flux decreased (Figure 3B).

As we grouped the solids from the lateral soil flux in two fractions (fine and coarse), we tested for differences in these two fractions separately. At the end of the experiment, the cumulative lateral coarse and fine solid fluxes on slopes A and B were significantly higher ($p < 0.01$) than in the riparian forest (Figure 4). The proportion of coarse particles in the lateral soil flux was more than 80% in slopes A and B and decreased to approximately 50% in riparian forest.

The POC concentration of the lateral soil flux was significantly lower ($p < 0.01$) on slopes A and B than in the riparian forest for the coarse as well as for the fine fraction (Figure 5).

Consequentely, the cumulative lateral POC flux was not significantly different between slope B and riparian forest for the coarse and fine fractions, while both were higher than this flux on slope A (Figure 6). Approximately 40% of the POC in the lateral flux was carried as coarse carbon, and the remainder as fine carbon for the forest and slope A plots, while in the slope B such proportion decreased to 30% and 70%, respectively.

As expected, for both fractions, the δ^{13}C of lateral POC flux from slopes A and B were significantly higher ($p < 0.01$) than δ^{13}C of the riparian forest (Figure 7).

3.2 Riverine bed sediments and suspended particulate organic matter

During the sampling period, a sediment deposition of approximately 860 g m^{-2} was estimated by bathymetry in the stream channel.

The particulate organic carbon and nitrogen concentration of the suspended solids in the stream were an order of magnitude higher ($p < 0.01$) than concentrations observed in the bed sediments of the stream (Table 1). On the other hand, there was no significant difference between the δ^{13}C and δ^{15}N values of suspended solids and bed sediment (Table 1). Granulometric analysis of the stream bed sediments revealed a sand concentration higher than 80 %. This concentration is similar to the one observed in the sugarcane soil and in the particles generated by sugarcane runoff (Table 1 – Supplemental Material). POC concentration of the stream suspended solids was intermediate between the carbon concentration of the coarse and fine lateral soil flux. On the other hand, the POC concentration of the stream bed sediment was closer to the coarse fraction of the lateral soil flux.

Using the MixSIAR model, we estimated that the POC median contribution from the forest soil lateral flux to the stream suspended solids was 73% (1st quartile = 68%, 3rd quartile = 78%), and from the sugarcane soil lateral flux was 27% (1st quartile = 22%, 3rd quartile = 32%). Most of the POC in the stream bottom sediment also mainly originated from the forest soil (75%, 1st quartile = 69%, 3rd quartile = 80%), while sugarcane soil contributed to the remainder 25% (1st quartile = 20%, 3rd quartile = 31%).

4 Discussion

The total volume of runoff generated in the erosion plots was about three times higher on the sugarcane slopes compared to the riparian forest (Figure 3). While in the riparian forest plots, approximately 30 mm of cumulative runoff was generated over the study period, in sugarcane plots A and B, approximately 90 and 150 mm of cumulative runoff was generated, respectively (Figure 3). We found only one study on runoff generation in sugarcane fields in Brazil. Therefore, it was not possible to make broad generalizations. The cumulative sugarcane runoff of 60 mm year^{-1} found by Youlton et al. (2016) in the municipality of Itirapina, approximately 80 km from our study site, was lower than the cumulative runoff found here. Moreover, the runoff:rainfall ratio obtained by these authors was 4%, which is lower than the ratio found in the slope A (6%) and in the slope B (10%). A potential explanation for this difference is the steeper slopes of this study (15%) compared with the Youlton et al. (2016) (9%).

The lateral soil flux on the sugarcane slopes was significantly higher compared to the riparian forest (Figure 3-4). This was especially true on slope B, where soil cover was low during most of the rainy study period (Figure 4 – Supplemental material). The higher soil loss in sugarcane fields was probably related to the lower water infiltration rate (lower K_{sat}) found in sugarcane plots compared to the riparian forest (Figure 7 - Supplemental Material), probably a consequence of the use of heavy machinery in the sugarcane fields (Andrade, 2013; Sant’anna et al., 2009; Silva et al., 2007; Silva, 2014). This leads to topsoil compaction and surface crust formation, reducing the water infiltration capacity and increasing the generation of surface runoff (Fernandes et al., 2013; Meyer et al., 2011; Silva, 2014). On the contrary, forested areas generally have higher soil porosity because of the higher concentration of organic matter and the existence of a large number of roots, which contribute to higher infiltration capacity and water percolation (Bonell and Bruijnzeel, 2005; Wine and Zou, 2012).

It was also observed that runoff generation heavily depends on the crop cycle, a conclusion also reached by Youlton et al. (2016). Higher runoff volumes were observed on slope B (Figure 3), where the first growth stages of sugarcane coincided with the rainy season (Figure 4 – Supplemental material). According to Silva et al. (2016), during these initial growth stages, the leaf area index (LAI) is still low (< 1 m^2 m^{-2}), increasing to 3 m^2 m^{-2} in the third growth stage. On the other hand, the LAI of the riparian forest (4 to 5 m^2 m^{-2}) was constant during the entire year (Silva et al., 2016). The higher the LAI, the greater the interception of water by leaves, preventing further increases in runoff generation (Fernandes et al., 2013). Therefore, to prevent severe soil loss, it is highly recommended that farmers avoid having the first stages of sugarcane development coincide with the rainiest months of the year, which in southeast Brazil takes place between October and March.

In line with runoff, soil loss was also inversely related to soil cover (Figure 3), as most of the lateral soil flux occurred during the establishment of the sugarcane crop on slope B, when the soil cover was minimal (November 2014 to December 2015). This allowed soil detachment by the raindrop impact. Coarse soil particles are often detached by raindrop impact and by turbulent flow generated on the compacted sugarcane soils (Strudley et al., 2008), rather than by the overland flow (Parsons, 1991). In addition, the removal of the carbon-rich topsoil in sugarcane fields by erosion (Figure 2) contributes to the decrease of soil aggregate stability (Silva et al., 2007), potentially contributing to lower carbon concentration, as suggested by Wynn et al. (2006). These facts probably explain the high lateral soil flux mainly as coarse fraction (Figure 4), and the lower carbon concentration of lateral soil flux on the sugarcane slopes than in the riparian forest (Figure 5).

The lower soil organic carbon concentration in the sugarcane fields, compared to the riparian forest, is caused by multiple factors. Firstly, input of carbon via litterfall is generally lower in cultivated fields compared to forests. For the type of forest present in the study site (Semidecidual Atlantic Forest), Martinelli et al. (2017) estimated an annual carbon input of 5 Mg ha^{-1} via litterfall. Sugarcane produces large amounts of straw varying from 7 to 9 Mg ha^{-1} of carbon (Lisboa et al., 2018). However, in our study area, only about 20% of straw was retained in the field, which would be equivalent to a potential carbon input of approximately 1.4 to 1.8 Mg ha^{-1}. Secondly, the higher sand content in the sugarcane soils compared to the riparian forest soil (Table 1 - Supplemental Material), could play a role, since the organic carbon storage is known to be lower in sandy soil than in clay soil (Assad et al., 2013; Saiz et al., 2012). Finally, several studies have shown a decrease in soil organic carbon due to soil cultivation (e.g. Assad et al., 2013; Don et al., 2011; Eclesia et al., 2012; Guillaume et al., 2015).

The higher topsoil organic carbon concentration of the riparian forest compared to the sugarcane topsoil is reflected in the larger relative contribution of organic matter from this area (70 %) to the stream. However, despite the presence of a 30 m wide riparian forest, approximately 30 % of the POC found in the streams originates from sugarcane soils.

Although a rigorous survey on the formation of gullies was not conducted, we noticed the presence of ephemeral gullies and preferential pathways efficiently connecting the sugarcane fields to the stream, bypassing the buffering effect of the riparian forest. This suggests that sediments and the attached carbon can be efficiently transported from the sugarcane fields to the stream channel through these preferential runoff pathways (Wallace et al., 2018; Pankau et al., 2012; Stehle et al., 2016). These results thus strongly suggest that these preferential pathways substantially decrease the efficiency of riparian forest to trap eroded sediments since the bathymetry estimated that 860 g m^{-2} was carried to the stream channel, while the total soil loss in the riparian forest was only 45 g m^{-2} (Figure 3). Zhang et al., 2010 performed a meta-analysis compiling 73 studies that provided quantitative results on sediment trapping by vegetated buffers. The authors predicted a sediment removal efficiency of at least 80% for slope degree, soil type and vegetation types similar to our study. In contrast, Wallace et al., 2018 found that the presence of preferential pathways could reduce the vegetated buffering potential by as much as 78%. Therefore, adequate management of riparian buffer strips is necessary to ensure their optimal functioning.

5 Conclusion

The results of this study indicate that runoff generation is greater on slopes under sugarcane cultivation compared to a riparian forest. The higher runoff generation resulted in larger lateral soil flux in the sugarcane fields. Most of the runoff and lateral soil flux was generated when sugarcane was in the first growth stages, when soil cover was low. Therefore, we strongly recommend that farmers try to avoid harvesting sugarcane during periods of the year characterized by the highest rainfall intensities (October to March). The riparian forest was not able to buffer the majority of the soil particles coming from eroding sugarcane fields and transported to the stream. This was because poor soil conservation in the sugarcane fields allowed the formation of gullies and preferential pathways that cut through the riparian forest, transporting sediments from upslope agricultural fields into the stream. Therefore, an effective soil conservation strategy which prevents the formation of preferential pathways through the riparian forest would be highly desirable. Finally, although most of the sediments in the stream were generated in the sugarcane fields, the riparian forest was still an important source of carbon to the stream.

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