ABSTRACT

Title of dissertation: SUGARCANE AGRICULTURE AS AN AGENT OF GEOMORPHIC CHANGE AND STREAM DEGRADATION IN BRAZIL

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Intensive agriculture profoundly alters the geomorphology, hydrology and nutrient balances of catchments. The result is the degradation of headwater stream ecosystems via inputs of excess sediments, surface runoff, and nutrients. To mitigate the negative effects on streams, watershed managers can implement riparian buffers, which are designed to intercept, process, store, and remove excess material from upslope agricultural source areas. While extensive research on those topics exists for temperate regions of developed countries, little is known in tropical regions of developing countries. To address this knowledge gap, I investigated the effects of sugarcane agriculture on catchment geomorphology and headwater stream ecosystems in Brazil. I studied 11 first and second order catchments spanning a sugarcane-forest gradient near Piracicaba, SP, to answer three main questions. (1) Is sugarcane agriculture an important agent of geomorphological change via gully formation? (2) Does gully formation influence the effectiveness of riparian buffers while increasing the stream response to storm events, and the amount of sediment in high flows? (3) Can land cover history in terms of sugarcane, and forest cover explain the variability in stream nutrient (nitrogen and phosphorus) concentrations? The overall results suggest that sugarcane agriculture is a driver of geomorphic alteration via gully formation in small order catchments in Brazil. Gullies act as effective conduits of surface runoff from upslope source areas to streams, increasing the magnitude of the stream's response to storms and the amount of sediment transported in high flows. Consequently, gully formation may overwhelm any protective role played by riparian buffers. Sugarcane agriculture also increases stream nutrient concentrations to a point rarely recorded for streams draining intensive cropping in Brazil. However, there is little evidence that forested riparian buffers significantly mitigates the extent to which sugarcane agriculture affects stream nutrient concentrations. Additional policies to the restoration of riparian forests are needed to effectively protect headwater streams in Brazil.

SUGARCANE AGRICULTURE AS AN AGENT OF GEOMORPHIC CHANGE AND STREAM DEGRADATION IN BRAZIL

By

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Preface

This dissertation consists of an introduction, three research chapters, and a summary section. All research chapters are presented in manuscript form with: an introduction; sections on the study area, methods, and results; a discussion including the implications; references; and any supplemental information. Some repetition of the description of the study area occurs throughout the chapters. Figures, figures, and captions are at the conclusion of each chapter.

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Chapter 1: Geomorphic change in tropical catchments under intensive sugarcane agriculture in Brazil

Introduction

Headwater streams influence the supply, transport, and fate of water and solutes in watersheds (Vannote et al. 1980). Despite their relatively small dimensions, they account for a large percentage of river drainage networks (Leopold et al. 1964), playing a disproportional role in contributing to the overall ecological integrity of the downstream fluvial network (Freeman et al. 2007). Low-order streams process nutrients and organic matter, influencing the stream water quality (Vannote et al. 1980, Alexander et al. 2000, Peterson et al. 2001), as well as providing diverse aquatic habitat that sustains a rich biodiversity throughout the stream network (Meyer et al. 2007). Consequently, these streams are essential for the provision of important ecosystem services such as water quality and quantity (Alexander et al. 2007, Winter 2007). For these reasons, many countries have created specific regulations or promoted management practices to protect headwater streams, especially given increasing pressure from human activities (Nadeau and Rains 2007).

Intensive agriculture in which production per unit of land is increased dramatically through industrial mechanization, agrochemicals and high-yielding crop varieties (Matson et al. 1997) is one activity that can degrade headwater streams profoundly; particularly by changing the stream's flow regime, and being a source of diffuse pollution. Based largely on studies in developed countries, we know that agriculture favors the development of excess surface and subsurface flows by altering the partitioning of precipitation into infiltration and overland flow, and subsequently, the partitioning of infiltrated water into evapotranspiration, soil storage, and deep percolation (Bruijnzeel 1990). When surface and subsurface flows predominate over groundwater, greater amounts of water can be discharged to streams within a short period of time (Poff et al. 2006). As a result, streams respond more readily to storm events, which increase the frequency of erosive flows and cause channel incision, bank erosion and sedimentation (Jacobson et al. 2001). Moreover, excess surface runoff enhances soil erosion in the uplands that also contributes to stream sedimentation (Jacobson et al. 2001). These collective changes reduce the stream's natural diversity of habitats, and substrate patterns, causing severe losses of biodiversity (Poff et al. 1997, Poff and Zimmerman 2010). In addition to excess inputs of sediments, non-point source pollution arises from inputs of nitrogen and phosphorus added as crop fertilizer that is not completely taken up by plants. This increases instream nutrient concentrations, reducing the water quality of riverine ecosystems (Carpenter et al. 1998, OECD 2001, Scanlon et al. 2007), and increasing export to coastal waters (Rabalais et al. 2009). Stream degradation from such alterations has prompted practitioners to implement strategies to mitigate the negative consequences of agriculture on streams.

Riparian buffers have been used as a management tool for decades in developed countries such as the U.S. (Caruso 2000, Dosskey et al. 2010, Stutter et al. 2012, Stubbs 2014). Riparian systems are positioned in the transitional area between aquatic and terrestrial ecosystems; hence, buffers can intercept and potentially reduce material and energy moving between the upland source areas to streams (Lowrance et al. 1984, Cooper et al. 1987, Dosskey et al. 2010, Roberts et al. 2012). Despite promising results from transect scale studies showing the reductive capacity of buffers, responses by stream ecosystems to this type of intervention have been variable and some would say anemic (Dosskey et al. 2010). Reasons for its failure can include a reduced capacity to trap and process excess material from uplands being transported in concentrated flows (Dosskey et al. 2002, Helmers et al. 2005).

Ideal performance of vegetated riparian buffers in reducing diffuse pollution requires that flows carrying most material from agricultural source areas be distributed across as much riparian buffer area as possible. This may not necessarily happen when there are concentrated flows (Dillaha et al. 1989, Weller et al. 1998, Dosskey et al. 2002) such as those common in agricultural systems. Plowing, furrowing, and construction of unpaved and paved roads enhance the formation of surface-concentrated runoff that move through only parts of the buffer strip, thereby reducing the removal efficiency of riparian buffers; portions of these buffers become inundated during large runoff events that impair the material trapping capacity (Dillaha et al. 1986, Dillaha et al. 1989). In sum, in agricultural fields where concentrated flow is common, the buffer capacity to mitigate the agricultural impacts on streams is compromised (Dillaha et al. 1989, Daniels and Gilliam 1996, Dosskey et al. 2002, Knight et al. 2010).

Gully erosion is the most profound consequence of excess concentrated flow on the land (Poesen et al. 2003, Valentin et al. 2005); however it is not generally acknowledged as a relevant factor affecting riparian buffer effectiveness. Even the extent to which gully erosion contributes to the problem is not fully understood; rather, pathways and the importance of gullying have been inferred from changes in instream storm flow and sediment dynamics (Costa and Prado Bacellar 2007, Zaimes et al. 2009, Duvert et al. 2010). However, gullying is probably a major factor of stream degradation because gullies can be major sources of sediment production in a catchment (Poesen and van Wesemael 1996) and are often direct conduits of excess runoff from agricultural fields, enhancing the transport of water (Elsenbeer et al. 1994) and associated materials (Duvert et al. 2010) to stream channels. Furthermore, as the drainage network expands with gully formation the effectiveness of riparian buffers to protect streams is expected to decrease. Yet, understating of the full extent of the detrimental contribution of gully erosion on streams is still limited given that most research has not explicitly coupled changes in stream variables with gully development.

In contrast to the extensive research in developed countries, information about the impacts of agricultural intensification and expansion on small headwater streams in tropical developing countries is limited (Gucker et al. 2016). Knowledge is also lacking on the effectiveness of programs and policies to mitigate the agricultural impacts on streams via riparian buffers. This is not only due to economic limitations but because the diversity of biomes, geomorphic characteristics, and land use histories make the study of agricultural impacts in these regions difficult. Moreover, while developing countries have been called upon to intensify and expand agricultural production to meet the extraordinary increase in consumption of agricultural products in the most sustainable way (Alexandratos and Bruinsma 2012, OECD-FAO 2015), what has not been generally considered is that several of these countries have long been plagued by severe gully erosion from poor agricultural management (Lal 1983, 1992). This, in turn, may have caused severe stream degradation and may have reduced the effectiveness of environmental policies. Limited knowledge on the impacts of agriculture on headwater streams, perhaps highly associated with excessive gully formation, imposes great socio-economic challenges for developing countries to manage scarce water resources.

Brazil and sugarcane agriculture

The focus of this dissertation is Brazil. This is a country that will likely experience the largest increase in agricultural production over the next 40 years, is rich in valued natural resources (Strassburg et al. 2014), and has one of the most advanced set of environmental laws in the world. However, scientific knowledge on impacts of intensive agriculture on small headwater streams, and on policy effectiveness to protect streams remains scant.

Sugarcane agriculture has been one of the most important intensive agricultural crops in Brazil since colonial times. In more recent decades, sugarcane production in Brazil has played a central role in the supply of renewable energy; Brazil is the leading ethanol producer from sugarcane (EIA 2012). The increasing demand for renewable energy in Brazil and worldwide has fueled an unprecedented expansion and intensification of the crop (Goldenberg 2008, Rudorff et al. 2010). Productivity has increased 70% since the 1970's (IBGE 2006), and stems from agricultural intensification in the form of technological improvements including intensive high-yielding crop varieties, use of fertilizers, increased mechanization, and crop expansion onto degraded and marginal lands (Graziano da Silva and Kohl 1984, Sparovek et al. 2007, Rudorff et al. 2010, Vitti et al. 2016). While sugarcane production generally occurs assuming that its cultivation is a form of 'green' agriculture (Macedo 2005, CGEE 2012), studies suggest otherwise (Martinelli and Filoso 2008, Filoso et al. 2015). Currently, we know that sugarcane can adversely affect a stream's biology (Ferreira et al. 2012, Schiesari and Correa 2016). However, studies documenting the impact on other stream's variables (e.g., nutrient concentration, sediment dynamics and flow regime) are virtually nonexistent.

This lack of knowledge has implications for regulations on riparian buffers. Recently, one of the most important environmental laws protecting water resources in Brazil— the Forest Code—was being revised (Tollefson 2011, Soares-Filho et al. 2014). The Code requires conservation and restoration of forests on farmlands, especially along waterways that are established as "areas of permanent protection" (APPs) (Brasil 2012). Because riparian buffers were officially designated as APPs, the Code provides a clear means for protecting Brazilian water resources (Ahrens 2005) from any kind of pollution, including non-point source pollution from agricultural fields. Given these provisions, farms and practitioners tend to assume that water resources will be protected if the requirements of the Forest Code are respected. Yet resources to invest in science to support this assumption are scarce as are resources to invest in efforts to ensure policy compliance (Soares-Filho et al. 2014). While policies such as Brazil's Forest Code potentially provide strong environmental protections to streams, unless the science that supports such policies are adequately tested, they may be ineffective even if implemented (Palmer 2009). Studying the impacts of sugarcane agriculture on small headwater streams in Brazil is, therefore, essential for filling some of the knowledge gaps related to the contribution of gully formation to stream degradation and the effectiveness of riparian buffers. This research will also expand our understanding of the impacts of intensive agriculture in understudied developing countries.

Research goals and chapter findings

In this dissertation, I examined the effects of sugarcane agriculture on catchment geomorphology and headwater stream ecosystems. Specifically, the objectives of this research were to: 1) investigate whether sugarcane agriculture has been an important agent of geomorphological change via gully formation; 2) assess the extent that gully formation directs concentrated flow to streams while influencing the effectiveness of riparian buffers, the stream response to storm events, and the amount of sediment being transported in high flows; and 3) determine whether land cover history, in terms of sugarcane and forest cover, explains the variability in nutrient concentrations, while assessing how the nutrient levels found by this research compare to levels found throughout Brazil. For all three objectives, I used data collected for 11 first to second order catchments in which sugarcane agriculture and forest were the only two land covers. The catchments were located in the State of Sao Paulo, Brazil, that accounts for at least 60% of all sugarcane production in the country (IBGE 2015). The results from this research may be applied to a large extent of areas where sugarcane is produced within Brazil.

For chapter 1, I used methods of geographic information systems (GIS) to determine the geomorphic process domains for the study area in the period prior to recent sugarcane intensification, and compared the location of channel heads from two time periods within the process domains. Information on channel heads were from (1) heads associated with streams mapped in official records prior to sugarcane intensification (1970's); and (2) heads mapped during recent field surveys. The process domains were derived from the slope-specific contribution area relationships. The results indicated that gully formation was a common erosion process in the study catchments, and that there has been change in the position of channel heads within the geomorphic process domains. The channel initiation threshold post-sugarcane intensification has decreased relative to that observed during the onset of intensification, and appeared less and less dependent on slope for a given contributing area through time.

For chapter 2, I also used GIS-methods to describe the flow accumulation pattern within the study catchments under current condition to quantify (1) the potential extent to which gullies may direct concentrated surface runoff from upslope source areas including sugarcane fields, and dirt roads to streams, and (2) the potential extent to which concentrated flow in gullies may affect the interception of surface runoff from upslope source areas by riparian buffers. I also monitored stream flow, precipitation, and, during storm flows, suspended sediment to understand whether gully formation might be a significant factor controlling the stream's response to storm events, and the amount of sediment being transported in high flows. The results showed that gully formation significantly reduced the riparian buffer effectiveness because a high amount of flow accumulation from source areas that should be intercepted by the riparian buffers were directed straight to existing stream channels via gullies. The results also indicated that gully formation was one of the major factors regulating the magnitude of the streams' response to storms. Additionally, there was a high probability that gullies, as conveyors of surface runoff to streams, are important controls of the amounts of sediment being transported during high flows.

Finally, for chapter 3, I conducted bimonthly baseflow water quality sampling, and quantified the land cover patterns in terms of sugarcane and forest cover within each study catchment over a 51-year period to understand how these two datasets relate. I also conducted a literature survey to place the results of this research into context. While concentrations of nitrogen (N) and phosphorus (P) were higher than previously reported for headwater streams in Brazil draining agricultural catchments, the amount or age of land cover in sugarcane was not a good predictor of N; however, it was a statistically significant predictor for P but in a way that was not expected.

The overall results suggest that sugarcane agriculture is a driver of geomorphic alteration via gully formation in small order catchments in Brazil, increasing the hydrologic connectivity between upland source areas and streams. Increased hydrologic connectivity via gullies has contributed to stream degradation, particularly via altered stream hydrology and enhanced sediment transport. Under such conditions, the detrimental effects of gully formation on streams likely overwhelm any protective role played by riparian buffers. Sugarcane agriculture can also increase stream nutrient concentrations to a point rarely recorded for streams draining intensive cropping in Brazil. There was also little evidence that forest cover within the catchments controlled the extent to which sugarcane agriculture affected stream nutrient concentrations. These findings imply that additional policies, informed by science, are needed to protect headwater streams effectively in Brazil. Finally, the outcomes of this research expand our limited knowledge of the impacts of intensive agriculture on tropical streams.

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Chapter 1: Geomorphic change in tropical catchments under intensive sugarcane agriculture in Brazil

Introduction

Intensification and extensification of agriculture in response to growing food demand has been a fundamental agent of geomorphological change (Dotterweich 2013, Ellis et al. 2013). Since the Neolithic, removal of natural vegetation and subsequent crop cultivation has created areas of bare or sparsely vegetated earth vulnerable to soil erosion (Lowdermilk 1953, Mei-e and Zhu 1994). As regular tillage on larger fields smooths and compacts soil surfaces, surface runoff and soil erosion on hillslopes increase (Blanco-Canqui and Lal 2010). More recently, unparalleled population growth has driven the creation of industrial agriculture, which, with the use of heavy machinery, puts further pressure on soil resources (Pimentel et al. 1987, Lal and Stewart 1990, Messerli et al. 2000, Pimentel 2006). Currently, it may take only 40 years to strip 2.5 cm of soil off agricultural fields —more than 20 times typical geologic rates (Wilkinson 2005). As a result, degraded landscapes caused by interril, rill erosion and piping processes (Poesen et al. 2003) manifest in many regions under different climate conditions despite diverse land use histories; being drainage network expansion via gully erosion possibly the most profound consequences of agricultural intervention on the land (Castillo and Gomez 2016). Eroded material forms new sedimentary structures, including colluvial deposits on footslopes and in depressions, as well as alluvial deposits, fans, and floodplains that later become fluvial terraces (Dotterweich 2008). Today, 40% of the Earth's landscapes result from long-term agriculturally induced soil erosion (Hooke 2012).

Tropical developing countries have been called on to meet recent global demand for agricultural products (Alexandratos and Bruinsma 2012). Brazil in particular plays a central role in the supply of renewable energy as the leading ethanol producer from sugarcane (EIA 2012). Consequently, the total area cultivated for sugarcane has increased more than 200%, and crop productivity has also increased by about 70% since 1975 (IBGE 2006a), when the Brazilian government incentivized cane production in response to the first crude oil crisis (OECD-FAO 2015). The notable increase in production capacity stems from agricultural intensification in the form of technological improvements that include increased mechanization since 1960 (Graziano da Silva and Kohl 1984), particularly after 1990 (Vitti et al. 2016), and crop expansion onto degraded and marginal lands, such as steep and easily eroded hillsides (Sparovek et al. 2007, Rudorff et al. 2010, Vitti et al. 2016). Although significant economic gains have accompanied the growing ethanol energy sector that are essential for the Brazilian balance of trade—1.7% of the 2014 Brazil's GDP come from the sucro-energy industry (Neves et al. 2014)—geomorphic changes may also follow this intense sugarcane production. However, the extent of geomorphic alterations via gully erosion from sugarcane intensification has remained largely unexplored (Castillo and Gomez 2016).

Geomorphic alterations associated with sugarcane intensification are of particular interest given growing concerns regarding Brazil's available water resources and energy production capacity; particularly in the State of São Paulo (Coutinho et al. 2015, Loyola and Bini 2015, Meganck et al. 2015), where more than 50% of the country's total area in sugarcane is found (IBGE 2015). Excess sediment inputs from soil erosion in sugarcane-dominated catchments in Sao Paulo has reduced energy generation capacity of hydropower plants (Chaves 2002); in some cases, dams have been shut down entirely (Fiorio et al. 2000), and treatment costs for potable water have increased with excessive sedimentation (Toledo 2014). Should sugarcane intensification be a significant agent of channel network expansion, soil conservation policies must address this problem to guarantee sustainable provision of water resources.

Geomorphic process domains and sugarcane intensification

Geomorphic alterations caused by agriculture may be assessed through analysis of process domains (McNamara et al. 2006). Process domains are “spatially identifiable areas characterized by distinct suites of geomorphic processes” (Montgomery 1999)—watershed areas dominated by comparable geomorphic processes. Process domains are often used to classify landforms and include for example convex hillslopes, concave valley forms and fluvial bottoms within which one or more surface processes prevail for the detachment and transport of sediment (Montgomery and Dietrich 1994). In humid soil-mantled landscapes, geomorphic thresholds usually delimit these domains. A geomorphic threshold represents a limit of equilibrium—a critical point that if exceeded a response occurs. It represents the balance between driving (e.g., water accumulation, slope) and resisting (e.g., vegetation cover and soil erosivity) forces (Schumm 1979). Hence, it separates different erosion mechanisms, such as areas dominated by diffusive erosion (e.g., rain splash erosion that form convex topography) and incisive erosion (geomorphic response from excess amount of flow energy relative to sediment load) that leads to channelization (Montgomery and Foufoula-Georgiou 1993, Montgomery and Dietrich 1994). When limits are exceeded due to modifications of those forces, a new equilibrium arises along with a corresponding change in form (Schumm, 1979). Channel heads in particular are a landscape feature that resides near or at geomorphic thresholds. They represent the transition between channeled and unchanneled valleys, demarcating a region initiated and maintained when concentrated runoff produces flow shear stress in excess of a critical value to erode a channel (Patton and Schumm 1975, Begin and Schumm 1979). Channel heads therefore describe a very specific balance of forces determining slope stability.

Given that sugarcane intensification alters water availability to the soil, its spatial distribution (Fernandes et al. 2013), and soil erosivity (Cerri et al. 1991, Oliveira et al. 1995), I asked whether sugarcane intensification has become an agent of geomorphic disequilibrium. Specifically, I evaluated whether the intensification process has influenced patterns of channel heads via gully formation within geomorphic process domains. Information about channel heads was compared between two time periods: (1) prior to sugarcane intensification when streams were mapped for official records; and (2) during recent field surveys in which channel heads were mapped. The distribution of gullies within sugarcane fields as well as channel initiation thresholds were expected to have changed between periods relative to geomorphic process domains.

Study area

The study was focused on 11 first to second order catchments draining to the Barro Frio stream (quadrant delimited by the following coordinates 22º36’55.9”S—22º37’14.8” S and 47º40’2.5”W—47º40’38.3”W, Figure 1.1, Table 1.1), located ~15 km from Piracicaba city, São Paulo. This region was traditionally and is currently part of the most important sugarcane production region in Brazil (IBGE 2006b). Before sugarcane was introduced to the region in the 18th century (Dean 1976, Victor et al. 2005), the study catchments’ land cover was deciduous and semi-deciduous forests, savanna, and swamps (Rodrigues 1999). During the study of data collection (2013), the only two land cover types in the catchments were sugarcane and secondary native forest [Bezerra, chapter 3]. The study area is marked by excessive magnitudes of soil erosion associated with sugarcane agriculture (Fiorio et al. 2000, Sparovek and Schnug 2001, Weill and Sparovek 2008).

The catchments lie at 500–600 m elevation (Figure 1.1), and are representative of the sugarcane cultivation region of Sao Paulo state with regard to soil type and topography. The underlying geology has sedimentary sequences composed of arenitic, silty, argilitic and conglomeratic materials of meso-palaeozoic age that were deposited in large syneclise-type sedimentary basins (CPRM 2004). More specifically, the catchments on the North side of the mainstem (CA, CF, CM, P5, P6 and P7) are characterized by silic-pelito-shale material with low dissected hills, and those on the South side (CC, P1, P2, P3 and P4) by silico-argillo sediments irregularly intercalated with fine sandy-calcareous layers with broad smooth hills (CPRM 2010).

The dominant soil type is ultisol (Figure 1.1) with low cation exchange capacity and textural B horizon immediately below the horizon A or E (official soil map-1:500,000, Oliveira 1989). Ultisols are naturally susceptible to erosion because their coarse-textured topsoils have poor aggregation capacity and low resistance to the shear force of rain splash (Brady and Weil 2014). Soil depth to bedrock is variable, and impediment clay layers at shallow depths (~ 50 cm) are common. Water percolation in Brazilian ultisol soils varies from good to poor (EMBRAPA 2013).

Climate in the study region is classified as equatorial winter dry (Aw) (Köppen-Geiger classification, Rubel and Kottek 2010), with average temperatures varying from 20°C during the coolest dry months (April – September) and 24°C during the warmest wet months (October – March). Average annual rainfall in the dry season is 230 mm, and in the wet season it is 1000 mm.

While management in sugarcane agriculture can vary significantly in Brazil, depending on the region, property size, and other aspects, management was quite similar in the study catchments in recent years (personal communications with farmers). It includes first leveling the terrain and forming contour terraces usually in the dry season (land preparation) and then planting sugarcane using stalks. The contour terraces are composed of a trench followed by a ridge; they run perpendicular to the slope and follow the topographic contour lines in order to reduce the volume and velocity of excess runoff water generated within sugarcane fields. Land preparation and planting using stalks is usually repeated every 3 to 5 years in the study region. When the current study begin in June 2013, this typical land preparation process had not occurred because farmers were in a ratoon cane crop period when they grow crop from stubbles of the previous crop.

Between June and September of 2013, sugarcane was harvested manually in all catchments and transported to mills via trucks and using dirt roads. Plowing occurred subsequent to harvesting.

Methods

The study required definition of the periods pre and post sugarcane intensification. For the purpose of this research, pre sugarcane intensification period was defined based on two sources of information: (i) historical records indicating that agricultural intensification started sometime in the 1960's in Brazil (Graziano da Silva and Kohl 1984), and (ii) tangible field evidence of agricultural activities associated with intensification specific for the study area. The field evidence describes when implementation of contour terraces started to occur in the study catchments, i.e., sometime between 1962 and 1978 (Figure 1.2). Therefore, the pre sugarcane intensification period was defined for this study as anytime before 1978, and post intensification anytime after 1978.

Geomorphic process domains

I used plots of the logarithms of local slope gradient (S, m m^{-1}) and specific contributing area (SCA), herein S-SCA plot, to delineate geomorphic process-specific domains (e.g., Montgomery and Foufoula-Georgiou, 1993; Ijjasz-Vasquez and Bras, 1995; Tucker and Bras, 1998). Slope and SCA represent first-order approximations of physical conditions, and indicate which processes are most likely active (Schumm 1977, Begin and Schumm 1979). The boundaries of domains in S-SCA plots are usually marked by nonlinearities (structural breaks in the relationship) that represent transitional geomorphic features in the field, including the channel heads (Montgomery and Foufoula-Georgiou 1993, Stock and Dietrich 2003, McNamara et al. 2006).

The variables S and SCA were derived from a digital elevation model (DEM) using a contour map from 1979 with a horizontal resolution of 1:10,000 (IGC 1979) to obtain the DEM. This 1979 contour map was the oldest official source of elevation data available for the study region and matched the period when the agricultural intensification began in the country as mentioned before. Hence, I assumed that the DEM derived from the 1979 contour maps represent a terrain less influenced by sugarcane agricultural intensification.

I used geographical information system (GIS) toolkits implemented in ArcMap 10.3 (ESRI 2011) to extract S and SCA from the DEM. First, contours and the drainage network from the 1979 map were digitalized manually and georeferenced to the datum UTM Córrego Alegre. The georeferencing process was based on the geographic coordinates of the contour maps and coordinates recorded in the field with a GPS TRIMBLE PRO XT (accuracy <1m). Then I applied the interpolation method TOPO to RASTER (Hutchinson 1989) to model the DEM with a 2.5 pixel size given the 5-m distance between contours. I checked the accuracy of the DEM by comparing modeled contours generated using the *contour tool* with those of the input contour map. Finally, S and SCA were obtained for each 2.5-m pixel within the area delimited by the study catchments' boundary using TauDem and the D-infinity flow direction model (Tarboton

1997). The catchments' boundaries were determined by manual interpretation (arguably the most accurate method) of the contour map.

Channel heads prior to sugarcane intensification

I used a 1962-aerial orthophotograph amended with the 1979-streamline map (hereafter 1962-channel heads) as the data source of channel heads to represent the location of heads less influenced by sugarcane agricultural intensification (i.e., pre intensification). The 1962 photo characterized the study landscape during a time historically known to include the outset of agricultural intensification in Brazil but it may be prior to its arrival in the study catchments (as described before). The 1962 photos were adequate for this study because most of the study area lacked forest canopy along streams so that channel heads would be identified.

To determine the channel head location, I used the definition proposed by Morgan and Mngomezulu (2003). This definition describes gully stretches and their headcuts as linear features with a clearly defined depth and a marked tonal contrast, usually light to dark gray, between the sidewalls and the surrounding land. Therefore, channel heads were located at the most upslope end of defined channels. Canopy cover prevented precise location of channel heads within two catchments (CA and P5). In these cases, I assumed that the heads were located at the upslope end of 1979 streamlines. I mapped the headward extent of each channel in a point shapefile, and extracted the S and SCA data from the slope and SCA grid maps obtained for the study region.

The final 1962-channel heads maps I used resulted from resolving stream-related discrepancies between the 1962-photo and the 1979-streamline map. Differences were threefold. First, the 1979-streamline map showed channel head positions upstream from those found within the 1962-photo (true for catchments P4, P5 and P7); for other catchments (CC, CF, P2, P3, P6), the inverse pattern occurred. Second, one of the streams of catchment P3 in the 1979-streamline map was shifted in relation to that in the 1962-photo. Third, streamlines were absent in the 1979-map to describe the stream channel of catchment P6 and some tributaries of the mainstem of other catchments (CF, P2, P3 and P4). Given these differences, I used the channel head positions consistent with those observed in the 1962-photo only.

Channel heads following sugarcane intensification

I obtained the source of channel head data for the period after sugarcane intensification from field surveys conducted during the period from July 2nd and August 8th, 2013 (hereafter 2013-erosional features). The field survey consisted of walking along dirt roads and paths built within sugarcane fields and adjacent to streamside vegetation to generate an inventory of erosional features associated with channel initiation within the study catchments. I mapped (GPS TRIMBLE PRO XT with accuracy < 1m), measured dimensions, and photographed all erosional features observed within the study catchments. The dimensions (width, depth, and length) of the head of each feature were collected using a measuring tape, and the feature head was photographed with a digital camera (Sony Cyber-shot DSC-W-120). The specific location of each erosional feature was determined as the most upstream point of the feature. During the field survey, I also noted whether an erosive feature cut through the existing riparian buffer. For some gullies, however, it was not possible to fully verify whether the gully traversed the entire riparian extension given hazardous conditions, e.g., significant drop in elevation (sometimes more than 10 m) along the gully. For those cases, the gully was assumed to have cut through the riparian vegetation if the gully was located within a 10 m perpendicular distance from the existing stream. The final number of gullies that cut through the riparian vegetation was a subset of the total number of mapped gullies. In the laboratory, I corrected the accuracy of the geographic location information of the 2013-mapped erosional features using the Pathfinder software (Trimble 2003) and based on the Campinas reference station established by the Brazilian Institute of Geography and Statistics (IBGE). After correction, the accuracy of approximately 95% of the data points was less than 1 m and no point had positional error greater than 5 m.

Gully formation can be considered along a continuum from rill erosion to gully and river channel erosion (Nachtergaele and Poesen 2002) and this differentiation is key when assessing channel expansion over time. As gullies are commonly defined as a channel with a cross-sectional area larger than 0.09 m^2 (Hauge 1977, Poesen et al. 2003), I used that critical, cross-sectional size to distinguish a rill from both ephemeral and permanent gullies. Criteria distinguishing an ephemeral and permanent gully are rather vague (Poesen et al. 2003), and thus the classification was based on definitions from the Soil Society of America (SSSA) that defines a gully to be a channel "deep enough (usually > 0.5 m) to interfere with, and to not be obliterated by, normal tillage operations". Accordingly, I assumed that ephemeral gullies were those with a cross-sectional area of $\geq$ 0.09 m^2 and a depth < 0.5 m. Permanent gullies were then those erosional features with a cross-sectional area of at least 0.09 m^2 and a depth $\geq$ 0.5 m (Figure 1.3). To be classified as a gully, the mapped erosional feature also had to have a nick point indicative of channel initiation by concentrated runoff (SSSA, 2008). I mapped the headward extent of each erosive feature in a point shape file and extracted the S and SCA from the slope and SCA grid maps obtained for the study region.

To ensure that the 2013- mapped erosional features did not exist in 1962, I overlaid them on the 1962-orthophoto to look for any textural evidence that the 2013-features were there in 1962. The overlay procedure was impractical for those features located in areas that had canopy cover in 1962 (parts of three catchments, CA, CM, part of CF and part of P5).

Data analysis

I evaluated the structural breakpoints on the slope versus specific contributing area relationship (herein S-SCA relationship) using the data for the entire study area to determine the geomorphic process domains (Montgomery and Dietrich 1994, Ijjasz-vasquez and Bras 1995, Tucker and Bras 1998, McNamara et al. 2006). The latter studies typically locate the breakpoints visually within the S-SCA distribution. Instead, I used multivariate adaptive regression splines, MARS (Friedman 1991, 1993), to identify nonlinearities (i.e., breakpoints) in the predicted *y* by using hinge functions. I implemented MARS using the *earth* command of the Earth package (Milborrow 2016) performed in R software (R Core Team 2016). I allowed the *earth* algorithm to find multiple breaks by applying a penalty and no pruning method, given that more than two geomorphic process domains are usually identified within S-SCA relationships (Montgomery and Dietrich 1994). Nevertheless, *earth* identified a single breakpoint. Therefore, I fitted MARS to the S-SCA dataset and then fitted MARS to the left side of the first significant partition. I then fitted MARS one more time to the left side of the second significant partition. I also identified structural breakpoints using the *piecewise.linear* function from the SiZer package (Sonderegger 2012) in a similar manner. The resulting breakpoints from SiZer were nearly identical to those found with the MARS approach and, thus, only MARS results are reported.

To understand the spatial distribution of geomorphic process domains identified by MARS and to ensure that identified breakpoints matched my interpretation, I mapped each S-SCA region depicted by the breakpoints for the study landscape. I then used a three step analysis to examine how the location of the 2013-erosional features related to the geomorphic process domains and to the 1962-channel heads to assess the importance of the intensification of sugarcane agriculture on drainage network expansion. First, I plotted the S-SCA values of 1962-channel heads and 2013-erosional features within the process domain diagram. Second, I analyzed the statistical significance of regression lines associated with each group of heads (i.e., 1962 and 2013 datasets) and tested whether the slopes of each regression were different with analysis of covariance (ANCOVA). Finally, I used multivariate analysis of variance (MANOVA) to assess the differences in the combined S-SCA dispersion between each group of heads.

Results

Geomorphic process domains

The analysis with MARS revealed three structural breakpoints in the S-SCA relationship (Table 1.2). Presented in the order found, there was a break at SCA of 2686.5

(or 6716 m^2), another at 76.8 (or 192 m^2), and the final break at 17.6 (or 44 m^2). A positive relationship characterized the region including data smaller than SCA of 17.6. This implies a convex topography on hilltops at region I (Figure 1.4a), where diffusive sediment transport processes predominate and thus channel incision is not supported (Montgomery and Foufoula-Georgiou 1993). A convex topography at the hilltops was evidenced by the spatial distribution of the areas with SCA smaller than 17.6 at or near the watersheds' boundary of seven catchments (sites CA, CF, CM, P1, P2, P6, and P7, Figure 1.4e). The remaining catchments had much less (sites P4 and P5) or virtually nonexistent (sites CC and P3) area at SCA < 17.6.

For the dataset with SCA greater than 17.6, MARS indicated that slope scaled negatively with SCA (Table 1.2). This inverse association indicates concavity, i.e., decreasing rate of change in slope for each unit of SCA above 17.6 (Figure 1.4b,c,d). Therefore, the breakpoint at SCA 17.6 delimited the turning point from convex to concave topography.

In increasing order of SCA, region II was delimited by the breakpoints at 17.6 and 76.8, and its associated S-SCA relationship had the highest negative rate of change in slope. In region III (from SCA of 76.8 to 2686.5), the S-SCA relationship, though still negative, had much smaller declivity than in region II (Table 1.2). The concave pattern of the S-SCA dataset within 17.6 and 2686.5 suggests that the breakpoint at 76.8 delimited two process domains: flows/landslides on the higher slopes where channel heads may start to form (Domain II) and unchanneled valleys on lower slopes (Domain III, Montgomery and Foufoula-Georgiou, 1993).

The spatial distribution of data associated with regions II and III identified with MARS, however, did not always support a clear process interpretation of the structural breakpoint at SCA 76.8 (Figure 1.4). Different spatial patterns emerged for distinct groups of study sites. For five catchments CA, CF, P6, P5, and P7, mapped regions II and III were located as expected, with region II away from the most upslope hilltops and distributed in broad swaths of hillslopes. However, mapped datasets for three catchments (CC, P3, and P4) showed region II occurring at and closer to hilltops (Figure 1.4f). The dataset associated with region III mapped as predicted at unchanneled valleys for six catchments (CA, CF, CM, P5, P6, and P7), whereas mapped region III included unchanneled valleys and some hillslopes for the remaining sites (CC, P1, P2, P3, P4) (Figure 1.4g). Thus the distinction of geomorphic process domains (II and III) within 17.6 and 2686.5 may not apply for all catchments.

The abrupt break found at the SCA of 2686.5 (i.e., after which the rate of change in slope per unit of SCA was much smaller than in previous regions) can be interpreted as channelized valleys or Domain IV, where runoff erosion predominates and gives rise to fluvial channels (Ijjasz-vasquez and Bras 1995). Indeed, S-SCA values greater than 2686.5 (region IV) mapped narrow linear bottoms in dendritic patterns (Figure 1.4h), consistent with a persistent channel network.

Despite differences of interpretation arising from MARS breakpoints and mapped regions, I considered the four domains identified with the MARS’ results to adequately describe of the location of channel heads within geomorphic process domains. Nevertheless, I discuss implications of the discrepancy in detail below.

Channel heads prior to sugarcane intensification

The analysis of the 1962-photo amended with the 1979-streamline map revealed 24 heads associated with well-developed channels for the period representing a landscape less influenced by the sugarcane intensification process in the study area (Figure 1.5a). Nearly all 1962-channel heads fell well within the transition zone from unchanneled to channeled valleys (Domain III). However, some 1962-heads were also present in domains less prone to incision (i.e., in Domain I and the lower portions of Domain II) where sugarcane was already present in 1962. Overall, the 1962-channel heads were characterized by a negative S-SCA relationship ($R^2 = 0.17$, $p = 0.05$). Any region at and above the regression line mapped channel bottoms and potential channel head locations (Figure 1.5b).

Channel heads following sugarcane intensification

I inventoried 126 erosional heads (Figure 1.7a) in 2013, of which 60% led to permanent gullying and 36% were at the ephemeral stage (Table 1.3). Out of the 76 2013-mapped permanent gullies, 63 were not detected in the 1962-photo, implying that 83% of the mapped gullies were features that have possibly developed after 1962. Twenty three of those 63 permanent gullies cut through the existing riparian buffer, and 8 of those 23 were in advanced channel forms, indicating intense network expansion since 1962. The remaining 55 permanent gullies were in an earlier developmental stage, suggesting more recent formation. The mapped ephemeral gullies and rills (50 features) were in an earlier developmental stage, as they are, by definition, new erosional features (Poesen et al, 2003). The majority of these erosional features were mapped along dirt roads bordering existing riparian vegetation. My inventory also revealed that 46 surveyed erosional features (38%) occurred along the downslope margin of contour terrace risers (Figure 1.8).

Most erosional features mapped in 2013 occurred in process domains I-III (Figure 1.6a) and the majority of them mapped at or below the S-SCA regression line associated with the 1962 channel heads (Figure 1.6b). Including only those features that were not identified in the 1962 photo, the S-SCA relationship associated with the 2013 data was negative ($R^2 = 0.04$, $p = 0.03$) and its slope was smaller than that observed in 1962 ($p < 0.001$).

The MANOVA indicated a smaller S-SCA combination for the 2013 features than for the 1962 channel heads (Pillai's trace = 0.18, $F_{1,134} = 15.05$, $p < 0.001$); both SCA and S discriminated between groups of heads in each time period ($F_{1,134} = 5.49$, $p = 0.02$ and $F_{1,134} = 16.87$, $p < 0.001$, respectively, Figure 1.6c). With such a reduced channel initiation threshold, the apparent area prone to incision (i.e., above the S-SCA regression line) in 2013 was 2.4 times greater than in 1962 (Figure 1.7b). In addition to a reduced S-SCA threshold, I observed greater scatter of the 2013-erosional features S-SCA data compared to that of 1962 (Figure 1.6b).

Discussion

The impact of agricultural management on landscape evolution via gully formation has been well documented in many parts of the world for over a century (Castillo and Gomez 2016). However, scientific studies examining the relationship between agricultural intensification and geomorphic changes associated with drainage network expansion are however still scant for several areas highly prone to such alterations (Torri and Poesen 2014). These areas include cultivated fields with sugarcane agriculture in Brazil where a combination of frequent intense precipitation events and highly weathered erodible soils makes landscape particularly vulnerable to geomorphic imbalances; especially after protection from forest cover is removed, and poorly aggregated soils become compacted by the use of heavy machinery during agricultural management. This study is possibly the first empirical evaluation on geomorphic changes associated with sugarcane intensification in Brazil. The results indicate that though channel heads in the period characterized by a less intensive agriculture follow expected slope-dependent threshold for channel initiation, the spatial distribution of the geomorphic process domains suggests a long-term agriculturally induced landscape. Therefore, substantial geomorphic disequilibrium has likely started much before the onset of the sugarcane intensification process in the study area.

The comparative analysis of S-SCA distributions of channel heads before and after sugarcane intensification reveals channel initiation thresholds that appear less and less dependent on slope for a given contributing area through time. Such patterns may result from management practices associated with modern sugarcane agriculture including dirt pathways and terraces (see below) that have the potential to alter water routing, soil erosivity and terrain to such an extent to change the entire catchment’s geomorphic configuration. This dynamic view of landscape evolution is consistent with perspectives of channel heads as anything but static; this is apparent in the variability of S-SCA relations, which integrate both spatial and temporal variation in physical proprieties of the soil (e.g., shear stress and slope).

These findings not only expand the theory of landscape evolution associated with land use change to agriculture in understudied tropical regions, but also highlight the high degree of complexity associated with soil conservation practices that are required after agriculture intensification.

Landscape prior to the sugarcane intensification

The discrepancies found between the statistically derived geomorphic process domains and the spatial distributions of these domains suggest that certain catchments were at different stages of landscape evolution in 1979. Those catchments at the North side of the mainstem (CA, CM, P6, and P7) having wider convex hillslopes (Domain I), and broad swaths of hillslopes (Domain II), and unchanneled valleys restricted to areas around the stream channels (Domain III) follow previous descriptions of process domains found for other humid soil-mantled landscapes (Montgomery and Foufoula-Georgiou, 1993, Ijjasz-vasquez and Bras, 1995). This geomorphic pattern characterizes single-convexity landform. However, the landform of those catchments having much smaller or non-existent Domain I, and Domain II located close to hilltops, and Domain III including broad extent of hillslopes is more consistent with double-convexity morphology.

Closer interpretation of the 1962-photo corroborates an argument for double-convexity profile in some catchments. Taking catchment P4 as an example, there is a pronounced drop in elevation close to the drainage divides that contain unchanneled valleys and where channel incision initiates (Figure 1.5a). Given such morphology, the first convex domain in P4 likely occurs at SCA much smaller than 17.6. The breakpoint at 76.8 may distinguish the second convex-concave transition, as it matches the drop in elevation observed in the 1962-photo. It is evident from the photo that catchments CF, P3, and to some extent P5 (despite forest cover) have similar morphological patterns (i.e., pronounced drop in elevation close to hilltops) to that of P4. It is therefore reasonable to believe that the breakpoints identified with the MARS analysis may not represent geomorphic process domains homogeneously across all study catchments.

Different stages of landscape evolution possibly have occurred in the study area due to varying land use histories prior to the intensification process initiated in the 1960-70's. Within the broader Piracicaba region including the study area, forest conversion to agriculture began in the eighteenth century and sugarcane plantation systems started in the early-to mid-nineteenth century (Dean 1976). The catchments located to the South side of the mainstem, (that did not fit well within the classical model of process domains), may well have been cleared and occupied first or preferentially given their smoother landform (see study area for details). Earlier settlement, and a longer use of the land, may explain why catchments P4 and P3 exhibit an erosional scarp resembling a landslide scar consistent with human induced erosion (Ross 1992). Such features often generate morphodynamically unstable landscapes with multiple-step slope profiles, corroborating my interpretation of a double-convexity profile. Moreover, multi-step degradation conforms with landscape evolution models for modern drainage basins in which formation of multiple terraces occur as a result of rapid but episodic erosion generated by land use change and other factors (Schumm 1979).

Landscape following sugarcane intensification

The large number of erosional features mapped in 2013 suggests that the study landscape has undergone rather extreme geomorphic changes since the advent of sugarcane intensification. The systematic migration of the S-SCA threshold values from Domain III towards Domain I underscores a state of dis-equilibrium, with erosional features migrating to areas that would not normally support channelization (Figure 1.9). Over time, less and less slope has been necessary to initiate incision for any given upslope contributing area, and vice-versa.

The disproportionate number of gullies along dirt roads surrounding forest patches suggests that these surfaces are hotspots of incision relative to sugarcane fields. Road surfaces in croplands usually become compacted from high rates of heavy machinery traffic (Ziegler and Giambelluca 1997, Ziegler et al. 2004), and typically redirect and concentrate flow from distant parts of a catchment to specific locations (Montgomery 1994); hence roads must manage large portions of excess overland flow (Ramos-Scharron and LaFevor 2016).

Contour terracing, another management practice applied since sugarcane intensification, may have further exacerbated gully formation. The fact that almost half of terrace margins (42%) were associated with gullying implies that, during rainfall events, terraces may act as effective routing structures of high volumes of surface runoff. A positive association between terracing and gully formation was unexpected because contour terracing has been the most common soil conservation practice applied to sugarcane fields since the 1960’s (Vitti et al. 2016). However, the low incidence of gullying within cane fields suggests that the detrimental effects of terracing are restricted to the road-terrace junctions on their perimeter.

The higher uncertainty in the specific locations prone to incision after intensification (represented by the greater scatter of the 2013-data) suggests high spatial variability of erosional or hydrological processes controlling gully formation (Prosser and Dietrich 1995, Prosser and Abernethy 1996). In a system where dirt roads and terraces exacerbate incision, increased spatial variability of those processes are expected, because neither the location nor the structure of paths and terraces are necessarily fixed through time. For instance, dirt roads are repaired (i.e., smoothed, narrowed, or widened) as needed, and terraces are redone on average every five years during land preparation to cultivate new sugarcane plants. Under such periodic terrain manipulation, flowpath patterns within the catchments likely varied spatially and temporally, and so should the associated erosive capacity to carve a channel. Therefore, the likelihood of gully formation at any point within a catchment has increased as indicated by the uncertainty I found in the S-SCA.

Model for recent landscape evolution in the study area

I propose the following model of landscape evolution for the study area in recent centuries: massive erosion likely occurred in response to forest conversion to agriculture. Throughout the following years, increased erosion likely drove agriculture away from existing stream channels, leading to increased forest cover in abandoned areas, particularly riparian zones (Figure 1.2, Bezerra, chapter 3). This increase in forest cover has likely slowed down erosion (Gyssels et al. 2005) in previously erosion-degraded areas. However, with agricultural intensification, a new pattern of accelerated erosion has begun via the increased erosive capacity of concentrated water flows on highly compacted roads. In general, there has been a relocation of erosional processes, where agricultural fields may be less prone to erosion given soil conservation practices compared to landscapes such as road that dramatically enhance surface runoff and incision.

Implications

The State of São Paulo has some of the most progressive regulations for soil conservation in Brazil (São Paulo 1988, 1993, 1997a, b, c, 2000a, b, 2015). However, the regulations require conservation practices on all arable lands (i.e., "the land area used or capable of use for agrosilvopastoral exploitation"; São Paulo 1997a), but they do not apply to unpaved roads (Vitti et al. 2016). Given my results and substantial knowledge on the detrimental impacts of unpaved roads on catchments' hydro-geomorphological processes (Wemple et al. 2017), policies to prevent and detain gully erosion on unpaved roads of sugarcane dominated areas are critical to reduce significant depletion of ecosystems services.

For instance, a rough extrapolation of the present results to other sugarcane areas in the State of Sao Paulo with analogous systems of mechanization, unpaved roads, contour terraces, and soil type indicates that the mass loss from gully erosion could fill the largest water treatment plant complex in Latin America (Cantareira Reservoir System (1.3 billion m^3) completely 3.8 times (appendix for calculations). The Cantareira system is designed to supply water for 6.5 million people in the São Paulo's metropolitan area.

Should channel network expansion via gully formation continue to progress with agriculture intensification, excess sediment from such geomorphic alterations may dramatically exacerbate water-related problems in SP. Yet, gully erosion is largely ignored in Brazil, particularly in areas cultivated with sugarcane, as indicated by soil loss assessments that do not account for anthropogenically-induced channel network expansion (Sparovek and Schnug 2001, van Lier et al. 2005, Weill and Sparovek 2008). This corroborates global reports on soil erosion which not frequently evaluate gully erosion, making soil erosion rates likely to be underestimated, especially on highly degraded areas (Castillo and Gomez 2016).

Appendix

Data for the estimation included: areal road extents of 0.01 km/m^2, gully density of 14 gullies/km, and average gully head volume of 0.49 m^3. I considered an area of sugarcane on ultisols in the State of Sao Paulo of 68,416 km^2 that equals 66% of the total area with ultisols in SP cultivated with sugarcane in 2015 (IBGE 2015). With that, a total of 4.8 km^3 of sediment may have been lost from gullying on unpaved surfaces in SP. Assuming a bulk density of 1.3 ton/m^3 for cultivated soils with similar texture to our sites (Brady and Weil 2014), the 4.8 km^3 volume represents $6.2*10^9$ tonnes (10^3 kg) of sediment. This amount is sufficient to fill the Cantareira Reservoir System with a volume of 1.3 billion m^3) completely 3.8 times (assuming the same bulk density). Note that this extrapolation underestimates the potential soil loss from gullying because it takes into account only the volume of soil lost from the head of the gully, not from its full length.

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Tables and Figures

Table 1.1 Characteristics of the study catchments

Site	Geographic coordinates		Area *ha*	Slope (mean) *m m^{-1}*
CA	22º36’55.92”S	47º40’25.57”W	5.9	0.17
CC	22º36’55.26”S	47º40’10.15”W	7.2	0.07
CF	22º36’47.53”S	47º40’16.07”W	6.3	0.25
CM	22º36’51.60”S	47º40’21.22”W	5.0	0.21
P1	22º37’14.81”S	47º40’25.54”W	5.6	0.15
P2	22º37’06.27”S	47º40’20.50”W	7.6	0.10
P3	22º36’53.02”S	47º40’07.57”W	12.0	0.14
P4	22º36’45.10”S	47º40’02.50”W	16.5	0.19
P5	22º36’35.72”S	47º40’07.70”W	7.4	0.23
P6	22º36’42.33”S	47º40’08.49”W	2.9	0.19
P7	22º36’41.14”S	47º40’38.30”W	6.1	0.14

Table 1.2 Resulted structural breakpoints from the multivariate adaptive regression splines (MARS) analysis and respective linear model determined. S is slope and SCA specific contributing area

SCA data range	Linear model	R^2	*p*
< 17.6 *(region I)*	S = 119 + 0.45 * SCA	0.02	< 0.001
≥ 17.6 < 76.8 *(region II)*	S = 203 – 0.04 * SCA	0.01	< 0.001
≥ 76.8 < 2686.5 *(region III)*	S = 176 – 0.002 * SCA	0.01	< 0.001
≥ 2686.5 *(region IV)*	S = 112 – 0.001 * SCA	0.15	< 0.001

Table 1.3 Summary of the characteristics of surveyed erosional features within the study catchments in 2013

Erosional feature	n	Depth at feature head (m)				Cross sectional area at feature head (m^2)				Cut through riparian buffers	Evidence of presence in 1962
		Mean	SD	Min.	Max.	Mean	Sd.	Min.	Max.		
Rill	5	0.18	0.14	0.05	0.40	0.05	0.04	0.01	0.08	-	-
Ephemeral gullies	45	0.28	0.15	0.25	0.48	0.22	0.19	0.09	0.86	-	-
Permanent gullies	76	1.04	0.66	0.50	4.00	1.74	2.04	0.09	12.00	23	13

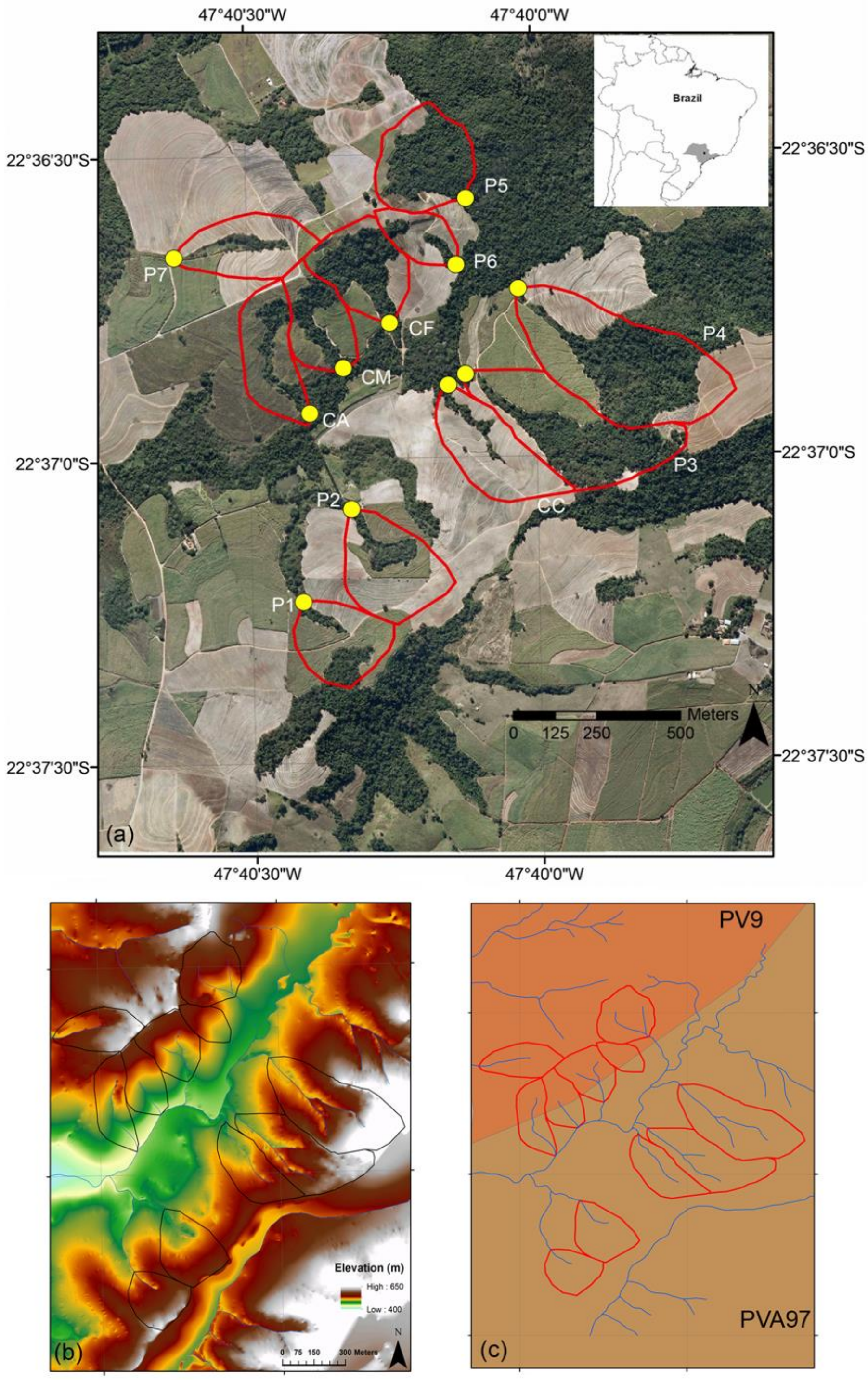

Figure 1.1 (a) Location of the study area in the State of Sao Paulo, Brazil (black dot in the top map) and detailed aerial imagine of the study catchments (orthophoto, EMPLASA 2010/2011). Redlines show watershed delineations. Yellow dot is downstream sampling point. (b) Elevation of the study area. (c) Ultisol types in the study area according to the Brazilian Soil Classification: PV9 ('argissolo vermelho' 9) and PV97 ('argissolo vermelho amarelo' 97)

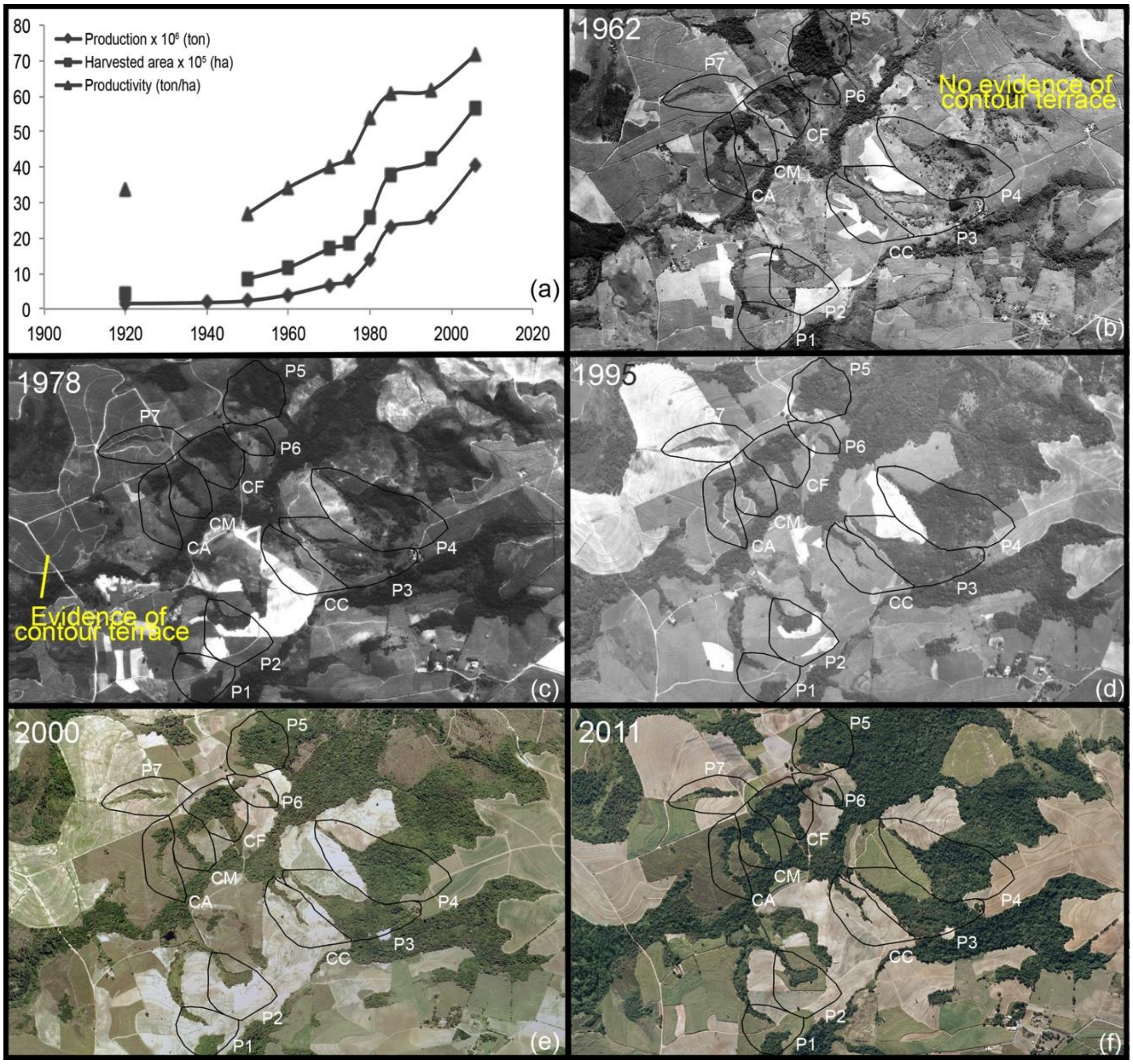

Figure 1.2 Sugarcane production, harvested area and productivity in the State of Sao Paulo (a). Aerial orthophotographs of the study catchments in 1962 (b), 1978 (c), 1995 (d), 2000 (e), and 2011 (f)

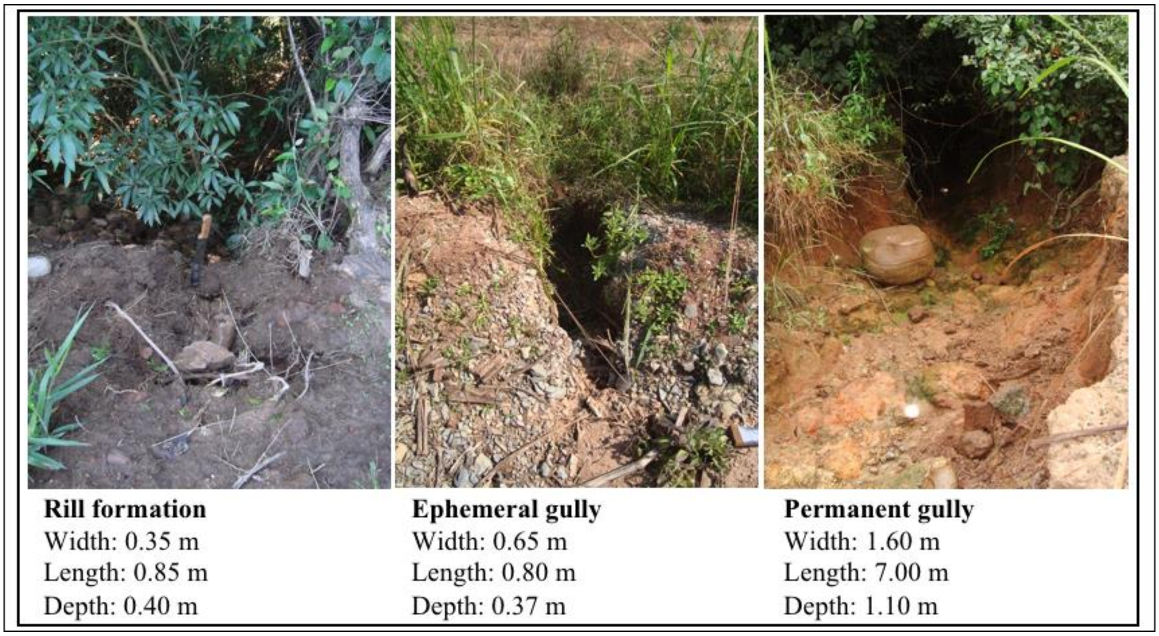

Figure 1.3 Examples of surveyed erosional features and the dimensions of their heads

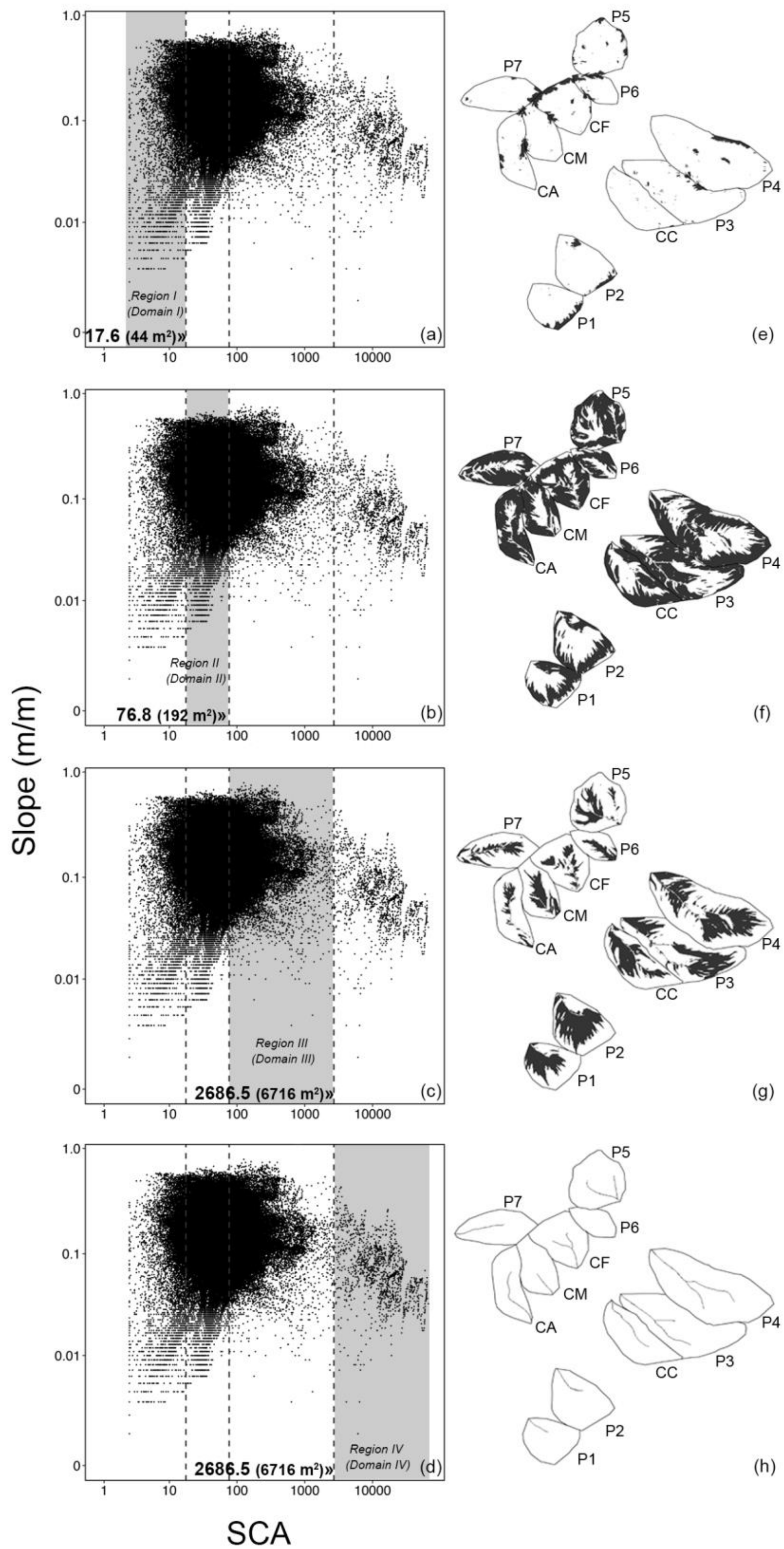

Figure 1.4 Slope and SCA distribution highlighting different geomorphic process domains determined based on the structural breakpoints found with multivariate adaptive regression splines (panels on the left) and mapped regions (panels on the right). The *x* axis is specific contributing area (contributing area per unit contour length using the multiple flow direction D-infinity approach) and *y* axis is local slope in m/m

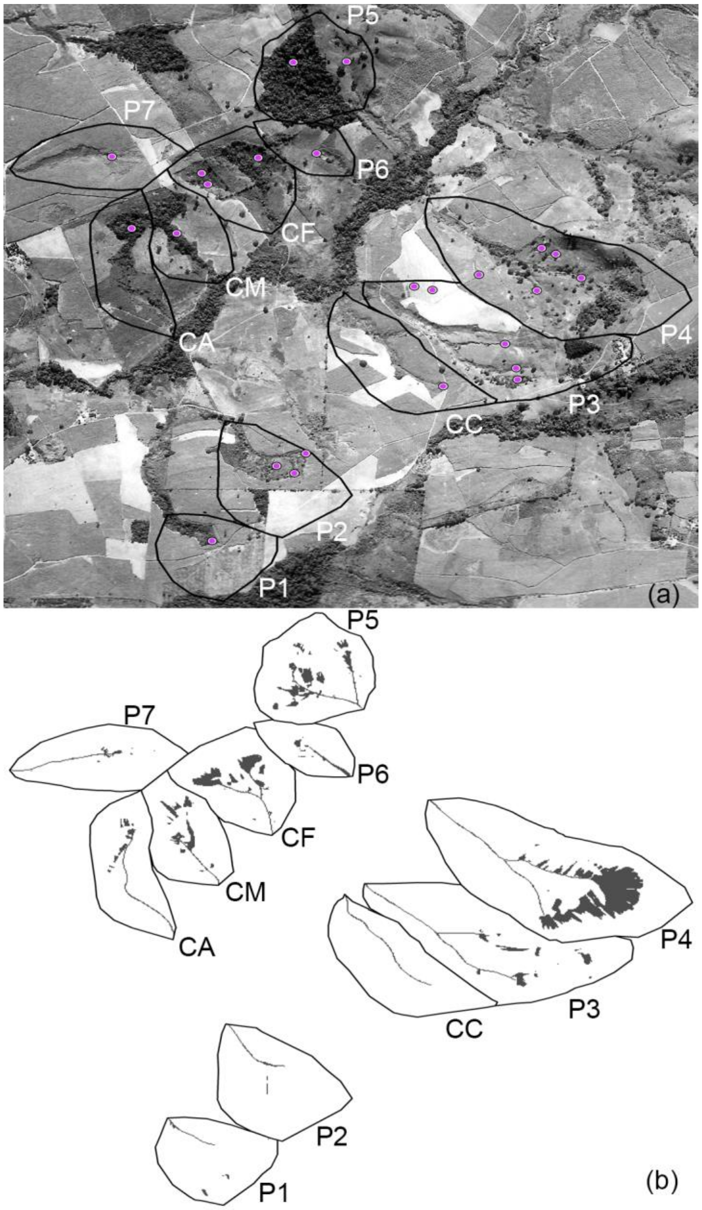

Figure 1.5 (a) Aerial imagine of the study catchments (orthophoto 1962). Channel heads in 1962 (pink dots). (b) Mapped area above the regression line determined with the 1962-channel head data

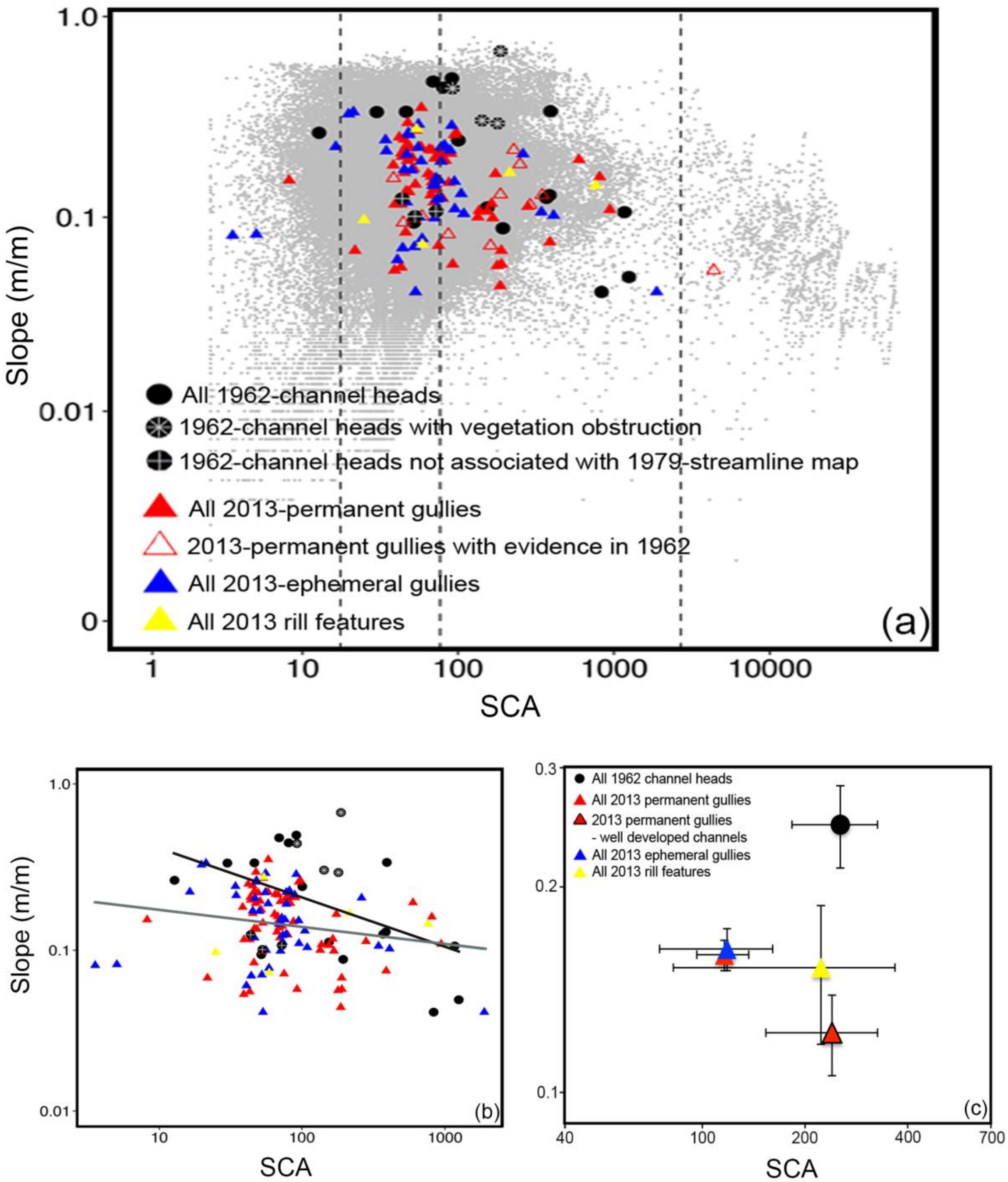

Figure 1.6 (a) Overlap of the S-SCA data of the 1962-channel heads and 2013-erosional features on the S-SCA distribution for the study area. Dashed lines demark different geomorphic process domains based on the structural breakpoints. (b) Linear regression lines for the 1962-channel heads the 2013-erosional features mapped. (c) Relationship between the centroid of SCA and S for the 1962-channels and 2013-erosional feature. Standard error of mean for each axis is shown for each group of data. The *x* axis is

specific contributing area (contributing area per unit contour length using the multiple flow direction D-infinity approach) and *y* axis is local slope in m/m. Legend for panel symbols: all 1962-channel heads (●), 1962-channel heads with vegetation obstruction (⊛), 1962-channel heads in sugarcane fields and not associated with any streamline in the 1979 contour map (⊕), all 2013-permanent gully heads (▲), 2013-permanent gully heads with evidence in 1962 (△), all 2013-ephemenral gully heads (▲), all 2013-rill heads (▲)

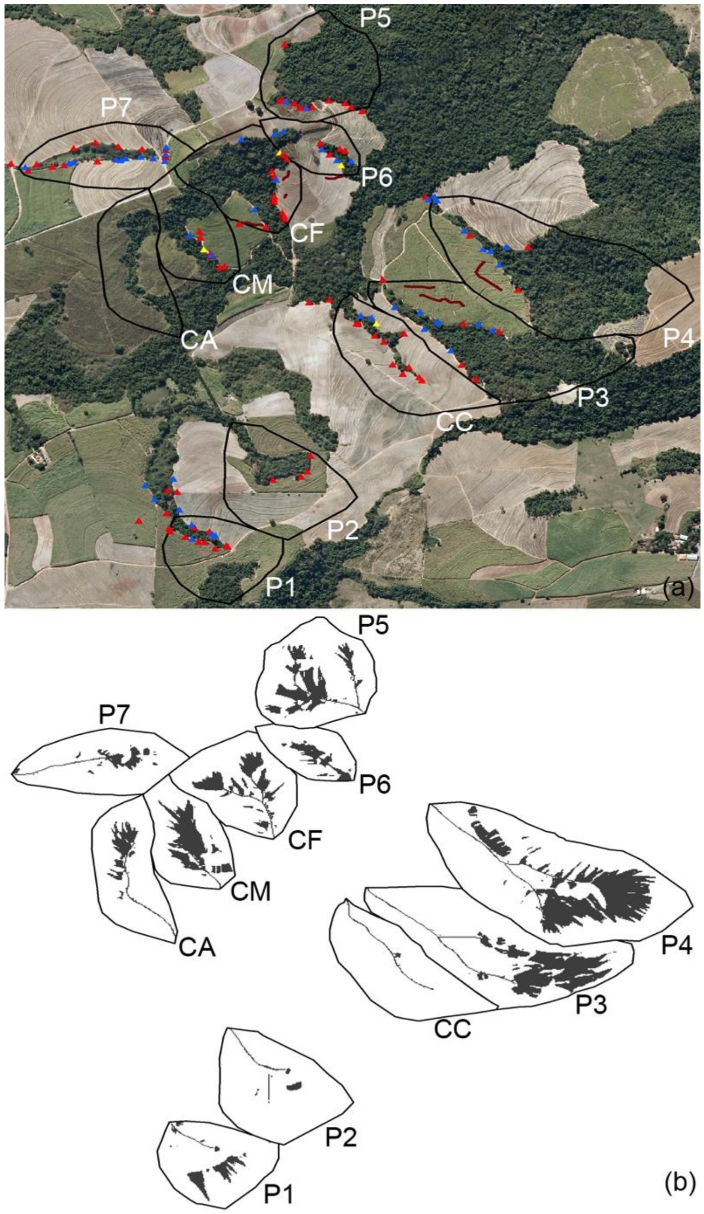

Figure 1.7 (a) Aerial imagine of the study catchments (orthophoto, EMPLASA 2010/2011). Erosional features surveyed in 2013 (dots): permanent gullies (red), ephemeral gullies (yellow), and rills (green). Pink lines are continuous erosional features within sugarcane fields in 2013. Only those erosional features within the catchment boundaries were included in the analyses of this study. (b) Mapped area above the regression line determined with the 2013-erosional features data

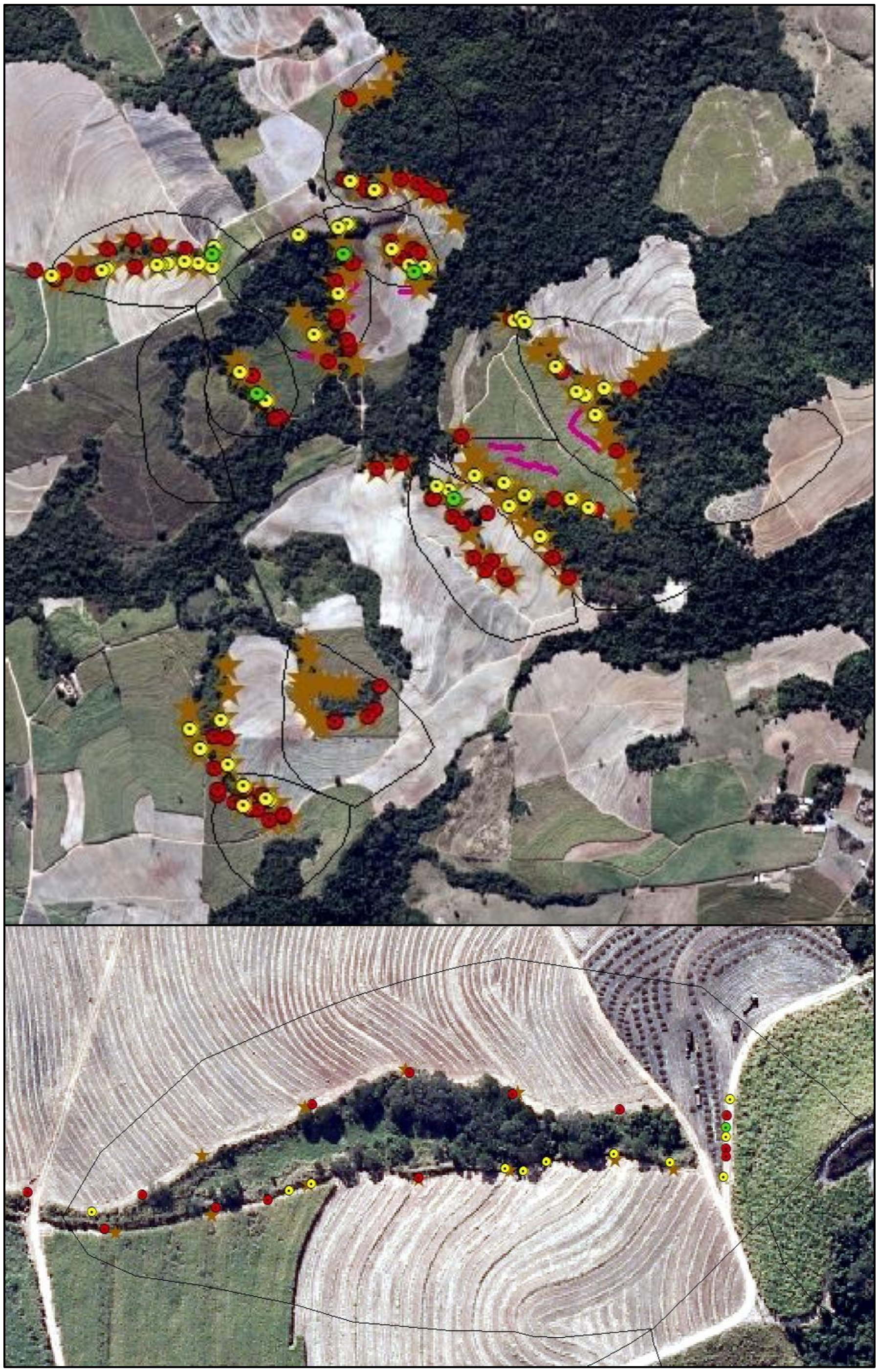

Figure 1.8 (a) Berms extremities (stars) and erosional features (dots: permanent gullies-red, ephemeral gullies-yellow, and rills-green) within study catchments. Pink lines are continuous erosional features within sugarcane fields (top). (b) Detail of one of the study catchments (P7) to show that gullies were occurring at berms extremities (bottom)

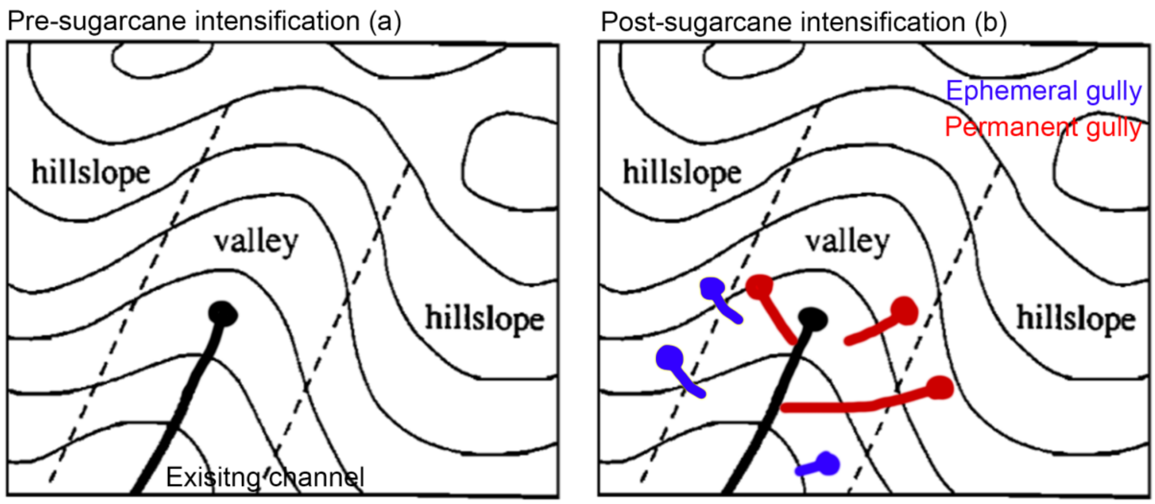

Figure 1.9 Schematic topographic maps illustrating distinction hillslopes, valleys and channels pre (a) and post (b) sugarcane intensification process. Hillslopes are areas of flow divergence, and valleys areas of flow convergence. Dashed lines indicate transition from hillslopes to valleys. The data pre-intensification showed channels (thick black line) typically beginning some distance down valley axes from drainage divide, whereas data post-intensification showed channels (ephemeral and permanent gullies) beginning in areas that would not support channel initiation based on the pre-intensification geomorphic configuration, i.e., in unchanneled valleys and hillslopes, that either were expanding the existing channel network or not. Schematics are adaptations from Montgomery and Foufoula-Georgiou (1993)

Chapter 2: Gully formation in traditional region of sugarcane agriculture in Brazil affects riparian buffer effectiveness and impacts headwater streams

Introduction

Intensive agriculture impacts, driven by changes in the hydrology and geomorphology of watersheds (Montgomery 2007, Gordon et al. 2010), can strongly affect the ecological integrity of stream ecosystems by changing two key governing processes: flow regime (Poff et al. 2006) and sediment transport (Leopold 1956, Syvitski and Kettner 2011, Wilson et al. 2012). In many regions of the humid tropics, a combination of frequent intense precipitation events and highly weathered erodible soils makes watersheds particularly vulnerable to the impacts of intensive agriculture (McDowell and Asbury 1994), especially after protection from forest cover is removed, and poorly aggregated soils become compacted by the use of heavy machinery during agricultural management (Lal 2000).

Landscape features such as dirt roads aggravate the situation by generating large quantities of excess runoff (Ramos-Scharron and LaFevor 2016) and, in extreme cases, by promoting gully erosion (Wemple et al. 2017, Bezerra, chapter 1). Gullies can contribute up to 90% of sediment yields in a catchment (Poesen and van Wesemael 1996, Duvert et al. 2010, Tebebu et al. 2010) and significantly increase surface runoff and the hydrologic connectivity between uphill and downhill areas (Elsenbeer et al. 1994, De Santisteban et al. 2005, Torri et al. 2006). Therefore, tropical catchments with intensive agriculture, and dirt roads and gullies as ubiquitous landscape features are likely to transport high amounts of water and sediment from the watershed to freshwater ecosystems, especially during storm events.

Riparian buffers are often used as a conservation management tool to control the transport of excess runoff and sediment from agricultural catchments to freshwater ecosystems (Caruso 2000, Stutter et al. 2012, Stubbs 2014). However, while the importance of riparian buffers to the structure and function of stream ecosystems is irrefutable (Naiman et al. 2005), their effectiveness at controlling the transport of water and materials to waterways and mitigating the impacts of intensive agriculture is uncertain; effectiveness is supposedly dependent on the riparian buffer’s capacity to intercept surface and sub-surface flows from upland source areas.

Empirical studies have shown that optimal performance of vegetated riparian buffers to retain excess runoff and associated sediment is linked to the uniform distribution of runoff as sheet flow across the riparian buffer length (Dillaha et al. 1989, Dosskey et al. 2002, Knight et al. 2010). Therefore, when surface runoff reaches the riparian buffers as concentrated flow through rills and gullies, the efficiency of riparian buffers typically declines (Daniels and Gilliam 1996, Dosskey et al. 2002, Knight et al. 2010, Hancock et al. 2015). This is, in part, because concentrated flow interacts with less riparian buffer area (Dosskey et al. 2002).

In recent years, the importance of the riparian buffer’s location in relation to flow paths has been recognized not only by scientists (Weller and Baker 2014, Hancock et al. 2015), but also by water resources managers and stakeholders. However, little attention has been given to the importance of permanent gullies, which is the worst form of soil degradation in agricultural areas, especially in developing countries in tropical regions with unsustainable management practices (Castillo and Gomez 2016).

Permanent gullies ("well defined channels too deep to easily ameliorate with ordinary farm tillage equipment", SSSA 2008) are particularly problematic to environmental management because they basically function as extensions of prevalent drainage networks, and potentially dissect entire stretches of existing riparian buffers widths. Permanent gullies can, therefore, act as direct pathways for the transport of excess runoff, and associated sediment generated in upslope source areas to stream channels (De Santisteban et al. 2005, Torri et al. 2006); differently from concentrated flow and sediment draining through rills and ephemeral gullies that can still be partially dispersed and retained within the riparian region (Dosskey et al. 2002, Helmers et al. 2005). Therefore, the detrimental effects of concentrated flow draining through permanent gullies on the effectiveness of riparian buffers may be much greater to stream ecosystems than the impacts from other types of water flow paths changes associated with intensive agriculture.

Geomorphological imbalances leading to gully erosion can have potential cascading effects through the drainage network when occurring in headwater catchments. Headwater streams support unique biodiversity because of their geographical isolation, and are important sources of water, sediment, nutrients, and organic matter to downstream reaches (Gomi et al. 2002). Although the biota of headwater streams is adapted to the episodic hydrologic, and geomorphic changes (Gomi et al 2002), excess sedimentation and stronger scour from more frequent, and magnified storm flows can decrease stream's biodiversity (Wantzen 2006). Moreover, magnified sediment and water transport to headwater streams can impair downstream systems (Freeman et al. 2007).

Unfortunately, most of our current understanding of the potential impacts of gully formation on headwater streams in the tropics is from studies including very few catchments (up to 3) for which the gully impact on hydro and sedimentological variables has been inferred from the presence of a gully in a catchment (Costa and Prado Bacellar 2007, Duvert et al. 2010). Multi-catchment studies from which direct relationships between gully formation and changes in instream storm flow, and sediment dynamics may be drawn are needed to advance knowledge.

In the traditional region of sugarcane agriculture in Brazil, rates of soil erosion are among the highest on Earth (up to 40 t/ha/yr, Sparovek and Schnug 2001, Montgomery 2007). Despite the potential impacts to freshwater ecosystems, growing domestic and international demands for biofuels have been stimulating the expansion and intensification of sugarcane agriculture in this and other regions of the country at an unprecedented rate. Many believe that such rates of sugarcane expansion should be sustainable with the adoption of soil conservation practices (Macedo 2005, CGEE 2012), and the conservation or restoration of riparian buffers required by Brazilian environmental laws (Brasil 2012). However, evidence of extensive geomorphic modifications in headwater catchments and the formation of permanent gullies associated with sugarcane agriculture [Bezerra, chapter 1] suggest that the effectiveness of riparian buffers at controlling water and sediment transport from sugarcane fields, and protecting stream ecosystems may be seriously compromised.

In light of the above, the objectives of this study were threefold: (1) to estimate the amount of surface runoff that is potentially transported from sugarcane fields directly into stream channels via permanent gullies cutting through riparian buffers; (2) to assess the extent to which these gullies affect the capacity of riparian buffers to intercept surface runoff; and (3) to examine the potential impacts of gully formation on streams because of changes in streams' (i) hydrologic regime and (ii) sediment transport.

To achieve the research objectives, I studied 11 first and second order catchments with varying degrees of gully formation in the State of Sao Paulo, Brazil. For objective 1, I used the map of permanent gullies that cut through riparian buffers (hereafter connected gullies) generated for chapter 1 of this dissertation, and estimated the amount of surface runoff that is potentially generated in upslope source areas (sugarcane and dirt roads) and directly transported to streams via gullies. For objective 2, I compared the amount of surface runoff that is potentially generated from upslope source areas in relation to the amount of surface runoff in connected gullies. For objective 3, I examined changes in the hydrological regime and sediment transport of streams during storm flows and correlated to landscape characteristics supposed to control these variables in the catchments.

Study area

The study was focused on 11 first to second order catchments draining to the Barro Frio stream (quadrant delimited by the following coordinates 22º36'55.9"S—22º37'14.8" S and 47º40'2.5"W—47º40'38.3"W, Figure 2.1, Table 2.1). These catchments are located ~15 km from Piracicaba city, São Paulo. This region was traditionally and is currently part of the most important sugarcane production region in

Brazil (IBGE 2006). Before sugarcane was introduced to the region in the 18th century (Dean 1976, Victor et al. 2005), the study catchments' land cover was deciduous and semi-deciduous forests, savanna, and swamps (Rodrigues 1999). During the study period (2013-2014), the only two land cover types in the catchments were sugarcane and secondary native forest [Bezerra, chapter 3]. Dirt roads for the transport of harvested sugarcane to the mills were also commonly present in the catchments, including at the margins forest fragments.

Gully formation was variable among the study catchments [Bezerra, chapter 1]. Across all sites, there were 126 mapped erosional features (Table 2.1), and the majority of them initiated at the margin of dirt roads bordering existing riparian vegetation. Seventy six (60%) of these erosional features were classified as permanent gullies but only 27 cut through the entire buffer width. These 27 gullies clearly expanded the prevalent drainage network by dissecting the existing riparian buffer soils (connected gullies).

Out of the 11 study catchments, seven had connected gullies (CC, CF, CM, P1, P5, P6 and P7) and three (P2, P3 and P4) had gullies that did not cut through the riparian buffers (i.e., zero connected gullies). The control catchment (CA) had no mapped gullies. The land cover in 99% of the catchment CA was natural forest regenerating since 2006 from sugarcane agriculture.

The catchments lie at 500–600 m elevation (Figure 2.1), and are representative of the sugarcane cultivation region of Sao Paulo state with regard to soil type and topography. The underlying geology is sedimentary sequences composed of arenitic, silty, argillic and conglomeratic materials of meso-palaeozoic age that were deposited in large syneclise-type sedimentary basins (CPRM 2004). More specifically, the catchments on the North side of the mainstem (CA, CF, CM, P5, P6 and P7) are characterized by silic-pelito-shale material with low dissected hills, and those on the South side (CC, P1, P2, P3 and P4) by silicic-argillic sediments irregularly intercalated with fine sandy-calcareous layers with broad smooth hills (CPRM 2010).

The dominant soil type is ultisol (Figure 2.1) with low cation exchange capacity and textural B horizon immediately below the horizon A or E (official soil map-1:500,000, Oliveira 1989). Ultisols are naturally susceptible to erosion because their coarse-textured topsoils have poor aggregation capacity and low resistance to shear force of rain splash (Brady and Weil 2014). Soil depth to bedrock is variable, and impediment clay layers at shallow depths (~ 50 cm) are common. Water percolation in Brazilian ultisol soils varies from good to poor (EMBRAPA 2013).

The study channels were classified as first- and second-order streams according to the definition of Horton (1945) and Strahler (1957), and were severely incised. Climate in the study region is equatorial winter dry (Aw) (Köppen-Geiger classification, Rubel and Kottek 2010), with average temperatures varying from 20°C during the coolest dry months (April – September) to 24°C during the warmest wet months (October – March). Average annual rainfall in the dry season is 230 mm, and in the wet season it is 1000 mm (Sentelhas et al. 1999).

Management in sugarcane agriculture is variable in Brazil, depending on the region and property size. However, management was quite similar in the study catchments during the study period and in recent years (personal communications with farmers). Management included land preparation by first leveling the terrain and forming contour terraces usually in the dry season, and then planting sugarcane using stalks. The contour terraces are formed by a trench followed by a downslope ridge; terraces run perpendicular to the slope and follow the topographic contour lines in order to reduce the volume and velocity of excess runoff water generated within sugarcane fields. Land preparation and planting using stalks is typically repeated every 3 to 5 years in the study region. During the study period, there was no land preparation as sugarcane farming was in the ratoon cane crop season (growing crop from stubble of the previous crop).

Methods

Estimation of surface runoff directed to streams via connected gullies

Two types of data were needed to estimate the amount of concentrated surface runoff from sugarcane fields potentially entering the study streams via connected gullies (objective 1): (i) a map of the location of connected gullies in each catchment, and (ii) a map of the flow accumulation within the catchments describing the catchment hydrological pathways. Item (ii) follows the methodology used in other studies analyzing the relationship between flow concentration and riparian buffer effectiveness (e.g., Hancock et al. 2015).

The flow accumulation map assumes that topography drives flow, and predicts the patterns of flow concentration in a catchment (Beven and Kirkby 1979). The size of the area generating the accumulated flow serves as a proxy to estimate surface runoff volume. Therefore, the flow accumulation area (FAC) above a connected gully represents the potential amount of water generated in upslope source areas and flowing directly into a stream (Figure 2.3). Given the spatial distribution of land cover and dirt roads within the study catchments, the FAC above a particular connected gully incorporated only areas covered with sugarcane and dirt roads. Other landscape characteristics that influence flow generation besides topography (e.g., vegetation cover and antecedent soil moisture) were not accounted for in this approach because it was beyond the scope of this study to precisely quantify the actual runoff volume entering gullies.

Method’s detail on mapping connected gullies is found in chapter 1 of this dissertation. Briefly, gullies were geo-located in a point shape file using a high precision GPS (GPS TRIMBLE PRO XT with accuracy < 1m) during field surveys from July 2nd to August 8th, 2013. All permanent gullies were marked, and the majority of them classified as connected if they cut through the entire extension of the riparian buffers. Connection for six gullies (2 in each catchment CC and P7, and 1 in each catchment CF, and P6) had to be inferred because obstacles such as steep drop in elevation along the gullies precluded direct inspection of their entire extension. Inspection from within the channel was avoided to prevent impact on the streams’ morphology and habitat. Those four gullies were considered connected if their knickpoint (i.e., head) was located at most 10 m from the existing stream.

The flow accumulation map was produced for a fine resolution (2-m) digital elevation model (DTM) using the multiple flow D-infinity algorithm (Tarboton 1997) in ArcGIS 10.3 (ESRI 2011). The DTM was generated by a Brazilian Company (Geo Agri Tecnologia Agrícola Ltda) using pictures taken with a VANT drone at an altitude of 80 m and 75% overlap. The final DTM produced with the PostFlight Terra 3D software described elevation after filtering the existing vegetation. The AGREE surface reconditioning method (University of Texas 1997) was applied to the acquired DTM to have the surface elevation around existing streams and connected gullies consistent with the flow pattern observed in the field. Representation of the elevation along connected gullies was needed because the drop in elevation associated with them was not usually represented in the acquired DTM. The vector coverage for AGREE included streamlines representing (i) existing streams and (ii) connected gullies. Item (i) was obtained by manually digitalizing the streamlines described in the 1979-contour map that were adjusted to match the stream pattern observed in the 2011 one-meter-resolution aerial orthophoto (São Paulo 2010). Item (ii) was created manually by following the steepest downhill descent from the cell where the gully head was located; this line was extended to cross the associated dirt road to match field observations of flow direction when needed. Conservative settings were used in AGREE (buffer width set to 5 m, smooth drop set to 5 m and the sharp drop set to 0 m) just enough to force flow paths into the streamlines without drastically altering the flow path pattern at their borders.

To extract the flow accumulation value associated with each connected gully, the gully point shape file was overlaid onto the flow accumulation map. The cumulative upslope flow accumulation area associated with gullies (hereafter cumulative gully FAC) was the sum of the flow accumulation areas associated with each connected gully in a given catchment (Figure 2.3). The cumulative gully FAC was assumed to represent the relative magnitude of surface runoff volume generated in upland source areas and that potentially flow directly into stream channels via gully without being intercepted by the riparian buffer.

Estimation of the gully's influence on the riparian buffer interception capacity

The extent to which concentrated flow in connected gullies affected surface runoff interception by riparian buffers (objective 2) was assessed based on the flow accumulation area of source areas that was assumed to represent the source area of excess surface runoff that should be intercepted by riparian buffers. Source areas included the area cultivated with sugarcane and dirt roads (total flow accumulation source area). Thus, the ratio between the cumulative gully FAC and the total flow accumulation source area provided an estimation of the proportion of surface runoff generated in upslope source areas that is not intercepted by riparian buffers.

The total flow accumulation source area was determined using land cover map. The land cover map was derived from the 2011 1-m resolution aerial orthophoto. Details on the land cover analysis can be found in chapter 3. Land cover patterns were similar across sites, with forests located predominantly adjacent to streams and sugarcane covering the remaining catchment area. Size of source areas was estimated as the difference between catchment area and riparian forest area.

Precipitation data

Precipitation data were collected to determine rainfall depths during storm events and to distinguish between individual events (Figure 2.2). Precipitation data were also used to calculate the event-based direct runoff coefficients (see later) for each catchment (objective 3). Rain data were collected using a tipping bucket rain gauge (RainLog, RainWise, Inc) with a data logger (of the same brand) set to record a minimum of 0.254 mm of rain in 5-min intervals. The tipping bucket was installed in an open area centrally located the study area. A rainfall event was operationally defined as any period of rainfall accumulating at least 0.5 mm in half an hour and separated by a period of at least two hours of no precipitation (definition used in other studies in the Atlantic and Amazon regions, e.g., Germer et al. 2009). Three 120-mm volumetric rain gauges were used to assess the rainfall spatial variability in the study area.

Assessing the impacts of gully formation on streams

1. Streams' hydrologic response to storm events

Hydrologic changes in streams associated with gully formation (objective 3) were assessed by calculating the rate of change in flow (flashiness) and direct runoff coefficients. For both metrics, I used observed discharge data collected from each stream during the study period. Continuous discharge in 15-minute intervals was calculated for each stream using stage data and rating curves. Rating curves were derived from both instantaneous streamflow data obtained in the field during periods of normal flow (i.e., when streamflow was not increasing or decreasing substantially), and from modeled peak discharges calculated with the Manning equation because logistical constraints and hazardous conditions precluded direct measurements during high flows. Rating curves were represented as power functions following methods described by the World Meteorological Organization (WMO 2010). The rating curve and associated confidence interval for each study stream is presented in Figure S2.1.

In all 11 streams, stage data were collected with pressure transducers (pressure transducers HOBO model U20-001-04) installed as close to the streams' outlet as possible, in a confined channel reach. In nine streams, the pressure transducers were attached to a 2-meter tall "T" bar. In streams CC and CA, transducers were installed in a

PVC pipe well adjacent to concrete H flumes constructed in the channel. The H flumes were regularly cleaned to prevent build-up of sediment and debris. Data were collected from July 2013 to August 2014, but the starting date for each stream varied depending on the presence of surface flow in the channel; the latest starting date was October 2013 in P7. The pressure transducers in the channels were paired with a pressure transducer installed in the open area centrally located the study area that recorded barometric pressure at 15 min intervals in order to correct for atmospheric pressure on the stage pressure data.

The accuracy of the peak flow data in each stream was checked in the field. For some individual storms, I compared the height of the highest bottle filled with water after a storm event (see below) with the stage height data recorded with the pressure transducers during peak flow. Peak flows recorded with pressure transducers were, on average, 3 cm (±9 cm) below the peak flow height observed in the field.

Streamflow was measured regularly in the field during normal flow conditions throughout the study period. In most streams (CF, P1, P2, P3, P4, P5, P6 and P7), discharge was determined using the velocity-area method with a floating device (WMO, 2010). In streams with H flumes (CA and CC) and at CM, discharge was measured using the volumetric method (WMO 2010).

During high flows, peak discharge in all study streams was estimated using the Manning's equation (Eq. 1).

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \qquad \text{Eq. 1}$$

where Q is discharge (m^3/s), n = Manning's flow resistance coefficient, A is cross sectional area at peak flow (m^2), R is hydraulic radius at peak flow (m), and S is slope (m/m). With the exception of Manning's n and slope, equation parameters were obtained from the study streams during high flows occurring in four dates (01/17/14, 03/10/14, 03/11/14, and 03/21/14). Cross section area and wetted perimeter to calculate R were obtained from stream cross-section surveys in 10-cm intervals to the maximum water level. The maximum water levels at those four events were determined by the height of the highest sample bottle filled with stream water (see below), and subsequently checked based on the watermarks on stream banks. Slope data for the Manning's equation was obtained from GIS data for each stream. Finally, Manning's n was obtained from a single discrete discharge measurement taken during a storm flow event in one of the streams with an H flume (0.24). This value is within the typical range (0.1 to 0.3) for steep headwater streams at bankfull flows (Yochum et al. 2012). The single Manning's n was applied in Eq. 1 to calculate peak discharges in all study streams for those four high flows.

Despite the possibility of under or overestimating discharge, using a single roughness coefficient was justifiable because the study streams have similar hydraulic characteristics (personal observation), and flow resistance is supposedly reduced during high flows (Bathurst 1985, Lee and Ferguson 2002). Furthermore, errors were probably small in comparison to those that would have been generated using an alternative approach, i.e., estimating roughness coefficient for each stream based on a composite value that includes all resistance components of a stream (Cowan 1956, Chow 1959, Brunner 2010), which typically overly estimate discharge for steeper streams (Yochum et al. 2012). Even direct measurements of discharge in the field during high flows are associated with large errors if structural devices such as flumes are not used (Rantz 1982).

Flashiness described how quickly streamflow changed during any given storm event, and was calculated as the dimensionless R-B flashiness index (Baker et al. 2004).

$$R - B\ index = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \qquad \text{Eq. 2}$$

where q is stream discharge (mm) in time intervals of 15 min.

Direct runoff coefficient (DR) represents the proportion of the rainfall volume falling on to a watershed that becomes stream quickflow in a given event. Quickflow is defined as the direct runoff consisting of channel runoff, surface runoff, and subsurface flow in unknown proportions, thus with high probability to be discharged to streams via connected gullies. DR was calculated as the ratio between total stream quickflow volume and the total areal precipitation falling in a catchment at a given rainfall event (Eq. 3).

$$DR = \frac{total\ quickflow\ volume\ (mm)}{total\ areal\ precipitation\ (mm)} \qquad \text{Eq. 3}$$

The total quicklow volume was calculated as the difference between total stormflow volume and baseflow volume in a given storm event following previous studies (Epps et al. 2013). The total stormflow volume was calculated by taking the integral under the hydrograph of a given event. The baseflow volume was calculated using the constant discharge method (Linsley et al. 1958). This method assumes that baseflow is constant during the storm hydrograph. The minimum streamflow immediately prior to the rising limb is used as the constant value until the end of the recession limb. However, the baseflow calculated with the constant discharge method may underestimate the actual baseflow contribution to the total stormflow volume. Given that the research interest was on the relative differences between streams, and not on the most accurate quantification, the procedure was considered reasonable because any error would be evenly distributed across all sites. The total quickflow was given by the equation below.

$$Total\ quickflow\ volume = total\ stormflow - (minimum\ flow\ rate\ prior\ to\ storm * duration\ hydrograph) \qquad \text{Eq. 4}$$

2. Impact on sediment transport during storm events

Changes in sediment transport in the study streams (objective 3) were assessed based on concentrations of suspended sediment on the rising limb during storm events. The suspended fraction of sediment load included both the suspendible bed material and the washload (the finer fraction, clay, silt and fine sands, that can be carried higher in the flow column by turbulent mixing, Hicks and Gomez 2005). Suspended sediment is the fraction commonly associated with any type of erosion in catchments (e.g., gully, streambank and upland erosion), while it also represents most of the sediment transported in streams draining agricultural catchments (Waters 1995b). I focused on the rising limb of the hydrograph to capture sediment readily available for transport during high flows. Readily available material usually represents local sources, e.g., streambed erosion, bank collapse, and sediment inputs from gullies (Lefrancois et al. 2007, Duvert et al. 2010).

Water samples along the rising limb of the hydrograph were collected with a rising-stage sampler: HDPE 250-mL bottles were fixed at different elevations of a 2-meter "T" bar (Figure 2.4, adaptation of the rising-stage sampler US U-59, Brakensiek et al. 1979). Each attached bottle had a Styrofoam ball inside it and the bottle mouth was closed with plastic stopper that had an aperture with a diameter of approximately 2 cm; hence, the maximum size of suspendible bed material collected was sediment of 2 cm of diameter. With this system, water and suspended sediment entered the bottle until the ball blocked additional water to enter the bottle after it was filled. The intake of first bottle was attached at ~10-15 cm from the surface water that allowed for the collection of suspended-bed sediments being transported in a narrow region near the bottom of the stream. The last bottle was attached at ~ 1 m away from the surface water; stream flow never exceeded 1 m in any site during the study period. Rising-stage sampler such as the one used for this study is the most suitable for flashy very small headwater streams at remote sites for which it is difficult to predict and be present when runoff occurs (Gordon et al. 2004).

In every stream, stormflow water samples were collected whenever rainfall events generated sufficient surface runoff to elevate the water level above the maximum level observed during normal flow conditions in the wet season (October 1st 2013 – April 7th 2014). Samples were retrieved from the field within 48 hours after the end of the storm event. Prior to sample recovery, the distance between of the streambed and the mouth of each sampling bottle was measured and used as an indicator of the water depth at the time of streamwater sampling; this information was used to calculate sediment loads (see below). Water samples were also collected manually at least bimonthly during normal flows with a syringe to prevent streambed disturbance. Immediately after collection at both high and normal flows, samples were transported to the laboratory in an ice cooler.

Total suspended sediment (TSS) concentrations were determined gravimetrically (Standard Method, APHA 1999) on the next day after collection. Water samples were poured into pre-weighted combusted 0.7-µm glass fiber filters after shaking. Sample filters were then dried at 105 °C for 24 hours and re-weighed. After weighing for TSS, the same filter was combusted in a muffle furnace at 550 °C for 30 minutes (APHA 1999). The organic material (VSS) escaped as gas and what was left in the filter was the fixed sediment (FSS) that is considered a proxy of inorganic sediment and the focus of this research. The FSS concentration was also determined gravimetrically.

Size distribution of suspended sediments was assessed by sieving selected water samples through a 63-µm sieve. The material passing through the 63µm-sieve was the fine sediment (silt/clay fraction), and was directly filtered through pre-weighted combusted 0.7-µm glass fiber filters. The coarse material remaining in the sieve was filtered through another pre-weighted combusted 0.7-µm glass fiber filter. TSS, FSS and VSS concentrations were quantified gravimetrically in each filter using the same method described above.

Changes in sediment transport during individual storm events were assessed using mass loads (Eq. 5) and yields.

$$Mass\ load = \sum C_i Q_i t_i \qquad \text{Eq. 5}$$

where i is 1 to n samples in a storm event, C_i is the sample suspended sediment concentration (mg L^{-1}), Q_i is the instantaneous discharge (Ls^{-1}), t_i is time interval (s) between samples. The instantaneous discharge was determined based on the water level at the time of sample collection, as explained above.

Event-based yields (kg/ha) were calculated by dividing the mass load for an individual storm event by the watershed area upstream of the sampling station. Yield allow for general comparisons of material export from watersheds with differing sizes. For both metrics, I only considered the inorganic suspended sediment (FSS) to account for the mineral portion of TSS, and thus more closely related to soil particles.

3. Explanatory metrics

The goal of objective 3 was to determine the influence of gully formation on the stream's response and sediment transport of streams during storms. Note that stormflows can account for significant amounts of the annual discharge of streams in the study regions (Silva, unpublished data). The explanatory variables used in the analyses (see below) described gully formation as conveyors of runoff and sediment, and also described landscape features known to control the stream's response to storm events and sediment transport during storms. Different groups of explanatory variables were used depending on the response variable being analyzed.

For flow regime variables, the specific landscape variables used included (i) gully patterns (ii) land use and land cover (LULC), and physical characteristics of the catchments. The gully patterns were described by the cumulative gully FAC (ha). The hypothesis was that the stream's response to storm events would increase with increasing cumulative gully FAC. The influence of LULC was represented by the percent cover of sugarcane and dirt roads in 2013 as the agricultural cover and transportation surfaces have been associated with decreases in water infiltration and increase in stream flashiness and magnitude of peak flows (Poff et a. 2006). Finally, the physical characteristics of catchments were represented by terrain slope and catchment elongation, which are considered key variables controlling stream's hydrology (Post and Jakeman 1996).

To understand variables controlling sediment transport, analysis included landscape characteristics related to important sediment sources to streams such as the gullies themselves, soil erosion on sugarcane fields, and soil erosion on dirt roads. These variables were represented for each catchment, respectively, as the total number of mapped gullies because all gullies may be a source of sediment; as the area (ha) of sugarcane and dirt road surface in 2013. Since streambed erosion may also be an important source of sediments to streams, I used the length of the existing stream channels (m) to represent this sediment source in the model. Terrain slope was another variable included in the analyses given that the more inclined terrains are more prone to erosion they are than flatter terrains (Sidle et al. 2006).

Landscape metrics were obtained using the GIS tools of ArcMAP 10.2 (ESRI 2011). The average catchment slope was obtained by taking the mean of the elevation data within the boundaries of the each study catchment. Catchment elongation was the ratio between diameter of the circle with the same area as that of the basin divided by the maximum basin length (Kumar 2014). The length of existing streams (as in the 1979 contour map) was obtained directly from the attribute table of the polyline shape file representing this feature. Area and percent of sugarcane cover was obtained as described in chapter 3. Percent dirt road was obtained by dividing the area of dirt roads in a given catchment by its total area. The dirt road area was obtained by drawing polygons encompassing the boundaries of the roads as in the 2011 aerial photo. The percent sugarcane and percent dirt road were summed to represent one unique value, i.e., percentage altered cover in a catchment. Likewise, the area of sugarcane and the area of dirt road were summed to represent one unique value, i.e., total altered area.

Data analyses

All statistical analyses were done with the RStudio softwater version 1.0.136 (RStudio, Inc) implemented with R software version 3.3.2 (R Core Team 2016b). Differences among the study catchments in the amount of concentrated surface runoff potentially generated from source areas (sugarcane fields and dirt roads) and transported directly to streams via connected gullies (objective 1) were assessed by comparing cumulative gully FAC across the study catchment using descriptive statistics (mean, minimum, and maximum). In addition, the relationship between number of connected gullies and the cumulative gully FAC was examined using a non-linear regression analysis to determine if the number of connected gullies increased the upslope area connected directly to streams. The non-linear model was fitted with the ‘nls’ function (‘stats’ package, R Core Team 2016a).

To assess the degree to which connected gullies decreased the capacity of riparian buffers to intercept runoff (objective 2), I compared the ratio between the metric cumulative gully FAC and the total source area of runoff across all study catchments to determine the degree (percentage) to which gullying influenced the amount of runoff that was potentially not intercepted by riparian buffers.

Finally, to assess changes in streams' response to storm events and sediment transport during storms associated with gully formation (objective 3), I used a combination of simple and generalized linear models including discharge and sediment data from the wet season (October 1st 2013 and April 30th 2014). I focused on the patterns in the wet season because this is when most surface runoff occurs in the region given high, intensive rainfall events.

Changes in the hydrologic regime were examined using the R-B index and direct runoff coefficient calculated for the largest storms observed during the study period; a total of 23 storms representing 66% of the total rainfall depth occurring in the wet season were used in the analysis (Table 2.2). These 23 storms were selected based on the threshold of flow generation in the study streams for small rain events. This threshold was obtained for each stream by determining the structural breakpoint in the relationship between rainfall totals (mm) and total stormflow volume (mm) for each stream. The structural breakpoints were identified with multivariate adaptive regression splines (MARS, Friedman 1993) which identify nonlinearities (i.e., breakpoints) in the predicted *y* by using hinge functions. MARS was performed with the 'earth' command ('Earth' package, Milborrow 2016) applied to the dataset of each stream.

Differences among streams with regard to their distribution of R-B index and direct runoff coefficient data were tested using Tukey Honestly Significant using transformed data (ln(x+1)). I used the 'TukeyHSD' command ('stats' package, R Core Team 2016a).

The influence of landscape variables on the hydrologic variables was tested using generalized linear model (GLM). The explanatory landscape variables included were the cumulative gully FAC, percent altered cover (percent sugarcane cover plus percent dirt road), average catchment slope, and catchment elongation for each study site. The response variables were the average R-B index and average direct runoff coefficient found for each stream that was calculated using data from those 23 storm events. Different models representing all possible combinations of explanatory variables were estimated for each response variable starting from the full model (Eq. 6). All models were estimated assuming Gaussian distribution and *log* link function. Diagnostic plots (residuals versus fitted and Normal Q-Q) were inspected to check the GLM assumptions.

Full model: $Y = ß_0 + ß_1$ cumulative gully FAC + $ß_2$ percent altered cover + ß3 catchment slope + $ß_4$ catchment elongation + e Eq. 6

where Y is the stream hydrologic variable (average R-B index or average direct runoff coefficient), $ß_0$ is the constant, $ß_1$, $ß_2$, $ß_3$, and $ß_4$ are the coefficients of each explanatory variable, and e is the residuals.

The second-order Akaike's information criterion (AICc) was used to compare the performance among the models for each hydrologic variable. The model with the smallest AICc can be interpreted as the best-fitting model to the data. Models were considered different if the AICc difference was ≥ 2 (Burnham and Anderson 2002) and the coefficients of all explanatory variables were significant ($p \leq 0.10$). For the best-fitting models, interactions between explanatory variables were added to the model, and its performance compared via AICc. Interactions were retained in the model if the AICc difference was ≥ 2. The overall model fit of the best-fitting model was tested by comparing it to the reduced model, containing only the intercept term, using a likelihood ratio test (LRT).

I also analyzed the relationships between rainfall characteristics (volume and intensity) and the hydrologic variables because rainfall characteristics may also affect the stream's response to storm events (Stanfield and Jackson 2011, Rodriguez-Blanco et al. 2012, Epps et al. 2013). For that, I used non-linear models ('nls' function, R Core Team 2016a).

Changes in sediment transport were examined by analyzing FSS data associated with five storm events that generated runoff concurrently in all streams (10/18/13, 11/29/13, 05/12/13, 01/17/14, 03/11/14), and therefore resulted in successful sampling in at least 10 of the 11 sites. There was no sediment data for CA in 12/05/13, CF in 10/18/13, and P2 in 01/17/14. Loads and yields of these three missing data were estimated based on the relationships between FSS load and peak discharge (Rankl 2004) to have complete datasets.

The relationship between FSS yield (kg ha^{-1}) and peak flow discharges (L s^{-1}) was estimated to compare sediment transport across sites following previous studies (Hughes et al. 2012). Linear and non-linear models were fitted to the data. For the linear models, a pair-wise analysis of covariance was used to test the differences in slopes and intercepts. Variation in slopes may indicate different sediment transport patterns and variation in intercepts may suggest different sediment availability (Rankl 2004).

The factors influencing the sediment transport in the streams were tested using generalized linear models (GLM) following similar steps explained before. The explanatory variables included were the total number of mapped gullies, stream length of the existing stream (m), total altered area (sugarcane area plus dirt road area, ha), and average terrain slope for each study site. The response variable used was the average FSS load found for each stream that was calculated using the FSS loads from the five storm events. Different models representing all possible combinations of explanatory variables were estimated starting from the full model (Eq. 7). All models were estimated assuming Gaussian distribution and *log* link function. Diagnostic plots (residuals versus fitted and Normal Q-Q) were inspected to check the GLM assumptions.

Full model: Y = $ß_0$ + $ß_1$ total number of gullies + $ß_2$ total altered area + $ß_3$ catchment slope + $ß_4$ stream length + e   Eq. 7

where Y was average FSS load, $ß_0$ is the constant, $ß_1$, $ß_2$, $ß_3$, and $ß_4$ are the coefficients of each explanatory variable, and e is the residuals. Again, the AICc was used to compare the performance among the models with similar criterion as described before. For the best-fitting model, interactions between explanatory variables were added to the model, and its performance compared via AICc with similar criterion as described before. The overall model fit of the best-fitting tested against the reduced model using LRT

For all bivariate statistics used to achieve objective 3, the potential effects of gully formation on the response variables (hydrology and sediment) were exemplified by examining the patterns in streams that differ mainly by gully incidence (CA, CC, P7).

These three catchments represented a gradient of gully formation while other factors controlling the response variables area are held constant. Respectively, CA, CC and P7 had increasing number of connected gully and cumulative gully FAC. These three catchments also had similar size, elongation, and average catchment slope (Table 2.1). The CC and P7 had similar percentage of sugarcane and riparian forest covers, while catchment CA had virtually no sugarcane cover.

I assumed significant results at $p < 0.10$ for all statistical analysis to minimize type II error (false negative) given the small sample size, i.e., low number of study catchments.

Results

Surface runoff transported to streams via connected gullies

The flow accumulation map generated for the study catchments revealed a similar pattern across all study catchments: flow paths starting in the uplands merged into a few concentrated flows along the stream channels (Figure 2.5). This pattern was independent of percent cover of sugarcane and riparian forest in the catchment since it was observed in all catchments, including the control (CA).

Flow paths concentrated particularly along dirt roads bordering riparian forests (Figure 2.6). Therefore, much of the flows from sugarcane fields were directed to the stream channel in specific locations along the riparian buffers. Often, dirt roads redirected flow paths from upland areas all the way to the watershed outlet, preventing contact with the riparian buffers (e.g., see patterns in catchments P2, P3, and P4, Figure 2.6).

The flow accumulation area (FAC) estimated for each connected gully varied from 0 to 2 ha, with an average of 0.5 ha across the catchments. In the majority of cases (56%), the FAC extended all the way to the drainage divide, encompassing dirt roads as well as extensive areas of sugarcane agriculture (Figure 2.6). In some catchments, all connected gullies had FACs extending to the drainage divide. This was the case for catchments CM (with only 30% of sugarcane cover) and P7 (with 79% of cane cover) that had respectively 2 and 8 connected gullies. The FAC of gullies in catchments CC, CF, P1, P5 and P6 was variable. Catchment CC, which had the highest percent cover of sugarcane, and the second greatest number of connected gullies (7) had only two connected gullies with a large FAC; there was virtually no FAC associated with the other five gullies in CC.

The total area of FAC above connected gullies (cumulative gully FAC) across catchments varied from 0.6 ha, for a catchment with two connected gullies (CF), to 5.2 ha for catchment P7 with eight connected gullies. Overall, there was a significant non-linear positive relationship between number of connected gullies and cumulative gully FAC (Figure 2.7).

Impact of gully formation on the riparian buffer interception capacity

The proportion of flow generated in upland source areas (sugarcane fields and dirt roads) and potentially transported to streams via connected gullies varied among catchments. In catchments CM and P7 the proportions were high, with about 88% to 100% of the flow from upslope source areas directed to connected gullies. In catchments CC and P6, 50% of the flow potentially generated in upslope source areas drained into connected gullies, but only two connected gullies were associated with significant large FAC. In the remaining three catchments (CF, P1, and P5), less than 30% of the flow drained into connected gullies.

Gully formation and stream's hydrologic response to storm events

Over the study period, the R-B flashiness index values calculated for the study streams for the 23 storm events indicated that flashiness in streams with moderate to high cumulative gully FAC (CF, P6 and P7) was significantly higher than in streams with no connected gullies (CA, and P2, Figure 2.8a, Table 2.3, $p \leq 0.05$). Direct runoff coefficient was also higher for streams more hydrologically connected to their uplands via gullies (Figure 2.8b). Higher direct runoff coefficients resulted in relatively more quickflow during storms in all study streams ($R^2 \geq 0.89$, $p < 0.001$). However, differences in direct runoff coefficients were only significant (Table 2.3, $p < 0.05$) between the control catchment (CA) and catchments with a high number of connected gullies and moderate to high cumulative gully FAC (CM, P5, P6, P7).

The relationship between gully formation and the hydrologic metrics was even more evident when three catchments with similar physical characteristics (elongation, slope, land cover) but different cumulative gully FAC were compared (Figures 2.8 and 2.9). The flashiest stream (in P7) had the highest number of connected gullies and the largest cumulative gully FAC. The proportion of rainfall transported as quickflow in the flashiest stream (P7) was also the highest while it was the lowest in the control stream (CA); the average direct runoff coefficient for the control catchment was 12 times lower than for catchment P7.

For the R-B flashiness index, the GLMs indicated that the cumulative gully FAC was not a significant predictor of this response variable (Table 2.4). The other three landscape variables (percent altered cover, catchment slope and elongation) were significant predictors of several models. Based on the AICc, there were two best-fitting models: (1) including percent altered cover, catchment slope and elongation and (2) including all these three explanatory variables plus an interaction between elongation and percent altered cover (Figure 2.10). Based on the statistically significant coefficients in those two models, the R-B flashiness index increased with increasing percent altered cover and catchment slope, and decreased with increasing elongation. In the model with interaction, the effect of the percent altered cover decreased for each unit of catchment elongation. Both best-fitting models were statistically different than the reduced model that included only the intercept ($p < 0.001$). Diagnostic plots (residuals versus fitted and normal Q-Q) and model statistics for these two best-fitting models are presented in Figure S.2.2 and Table S2.1, respectively.

For the direct runoff coefficient, the GLMs indicated that the cumulative gully FAC was the only significant predictor of this response variable (Table 2.5). In fact, the best-fitting model based on AICc was the one including only the cumulative gully FAC as explanatory variable, and indicated that the direct runoff coefficient increased with increasing cumulative gully FAC (Figure 2.11). The best-fitting model was statistically different than the reduced model that included only the intercept ($p < 0.01$). Pair-wise interaction between cumulative gully FAC with the other three explanatory variables did not yield significant coefficients. Diagnostic plots (residuals versus fitted and normal Q-Q) and model statistics are presented in Figure S.2.3 and Table S2.1, respectively.

There was a significant relationship between the total volume of quickflow estimated for each study stream and total depth of rainfall considering the 23 storm events (Figure 2.12a). Except for CM and P5, the volume of quickflow in the 23 storm events increased exponentially with rainfall volume (Figure 2.12a). The relationship between rain and quickflow volumes was even more clear when only catchments with similar characteristics but representing a gradient of cumulative gully FAC (CA, CC, and P7) were compared (Figure 2.12a). The influence of rain intensity on the direct runoff coefficients was less clear (Figure 2.13).

The R-B flashiness index in the majority of study streams increased significantly with rainfall depth (Figure 2.12b). For any given storm, the flashiness index was higher for streams with connected gullies than in the control stream (CA). The influence of rain intensity on flashiness was again less clear (Figure 2.13).

Gully formation and suspended sediment transport during high flows

Concentrations of suspended sediment in the study streams were determined during stormflow conditions in14 rainfall events, but the number of streams sampled during each event varied. In only five events all 11 streams (or at least 10) were sampled simultaneously.

According to stormflow samples collected during the 14 storm events, TSS was predominantly inorganic and composed of fine ($\leq$ 0.63 µm) materials. On average, 74% of the stormflow TSS was composed of fine particles and the inorganic fraction (FSS) accounted for 80% of the TSS (Table 2.6). Concentrations of FSS ranged from about 300 to 195,000 mg L^{-1} with a mean of approximately 14,500 mg L^{-1}. This average was 850 times greater than the average of 17 mg L^{-1} observed during normal flows.

There was a positive significant relationship between peak flows and total FSS yields for eight (CC, CM, P1, P2, P3, P5, P6, and P7) of the 11 study streams (Figure 2.14). Among those significant relationships, power functions described the patterns for five streams (CM, P2, P5, P6, and P7). The intercepts associated with the relationships of CM, P5, P6 and P7 were statistically higher relative to that of P2 (Table 2.7).

The GLMs indicated that the number of mapped gullies was a significant predictor of the FSS load along with the other explanatory variables (total altered area, stream length and terrain slope), but not when simultaneously included in the same model (Table 2.8). The best-fitting model based on AICc was the one including the number of mapped gullies, stream length and terrain slope plus an interaction between number of mapped gullies and stream length (Figure 2.15). The FSS load increased with increasing number of gullies, catchment slope, and increasing stream length. The impact of the number of gullies decreased for each unit of stream length. The best-fitting model was statistically different than the reduced model that included only the intercept ($p < 0.001$). Diagnostic plots (residuals versus fitted and normal Q-Q) and model statistics for the three best-fitting models based on the results in Table 2.8 are presented in Figure S2.3 and Table S2.1, respectively.

Discussion

The impacts of concentrated flow on the capacity of riparian buffers to control agricultural runoff have been broadly documented in recent years (e.g., Dosskey et al.

2002, Knight et al. 2010, Pankau et al. 2012, Hancock et al. 2015). In general, assessments have focused on flows concentrated in rills and ephemeral gullies, while the impacts of permanent gullies that completely dissect buffers (referred here as connected gullies) are poorly known. This lack of information is particularly problematic for tropical regions of developing countries, which may be more prone to gully erosion (Lal 1983, 1992). This study provides the first empirical evaluation of the effects of permanent gully formation on the capacity of riparian forests at mitigating the impacts of intensive agriculture on streams of a developing country of the tropics, Brazil. By examining changes in flow paths associated with gullying in small catchments cultivated with sugarcane and relating them to hydrologic and sediment transport changes in streams, this study provides evidence of the linkage between permanent gullies and stream degradation in the study region. The results of the study clearly show that the higher the number of permanent gullies in a catchment, the larger the amount of excess surface runoff potentially transported to streams from sources areas (inferred from cumulative gully FAC); consequently, the larger the level of disturbance in the hydrology and sediment transport of the stream draining the catchment. The results contribute with much needed information about how intensive agricultural practices associated with gully formation in certain regions of Brazil and possibly in other tropical regions of the world may be undermining the ecological function of riparian buffers and their capacity to protect stream ecosystems.

Gully formation and impacts on riparian buffer's capacity to intercept surface runoff

Permanent connected gullies in the study catchments were positioned along the margins of dirt roads bordering riparian buffers. Most of the connected gullies were associated with extensive upslope areas of flow accumulation, suggesting that large amounts of surface runoff were potentially transported directly to the stream channels during storm events. The flow accumulation at the heads of connected gullies originated in sugarcane fields and dirt road; both land use types that typically yield large amounts of surface runoff (Fernandes et al. 2013, Ramos-Scharron and LaFevor 2016). Runoff generated in sugarcane fields is supposed to be intercepted by contour terraces implemented in the region as best management practices for soil erosion control (Vitti et al. 2016). However, contour terraces can also serve as conduits of accumulated flow if not properly constructed, as suggested in the previous chapter of this dissertation.

In the study catchments, contour terraces directed flow paths from sugarcane in the direction of the riparian buffers; aerial photos overlaid with the flow accumulation map clearly showed this pattern in the study catchments (data not shown). Because dirt roads bordered the outer portion of the riparian buffers, most flow paths from sugarcane fields was intercepted by them and redirected. Therefore, dirt roads, and, to some extent, contour terraces are probably key elements in the catchments directing large amounts of excess surface runoff to streams. These two landscape elements have been suggested as key drivers of gully formation in the study area [Bezerra, chapter 1].

Although connected gullies can be an indication of hydrological linkages between contributing areas upslope and streams, it is important to recognize that the flow accumulation areas associated with the connected gullies were not always large. In the catchment with the highest percent cover of sugarcane (CC) and the second highest number of connected gullies, only two of seven connected gullies had large flow accumulation areas. This means that, in some cases, connected gullies may convey excess runoff from dirt roads only rather than from sugarcane fields.

The total area of sugarcane cultivation and dirt roads was assumed to be the most significant source of surface runoff generation in the catchment and, therefore, provide an estimation of the amount of runoff that could be intercepted by riparian buffers. In catchments with connected gullies, the proportion of the total source area associated with gullies was usually very high (≥ 50%), suggesting that the capacity of riparian forests to intercept excess material from sugarcane and dirt roads was reduced because of permanent gullies. The proportion of surface runoff from source areas that is potentially discharged directly into streams may be independent of the number of connected gullies present in the catchment. For instance, a catchment with only two connected gullies (CM) had the totality of its runoff source areas captured by connected gullies. Collectively, the results highlight the disruptive influence of gully formation on the capacity of riparian forests to reduce inputs of excess agricultural runoff and mitigate the impacts of sugarcane agriculture to headwater streams in the region.

Having argued that the results provide a reasonable assessment of the influence of permanent connected gullies on the volume of surface runoff transported directly to streams and, consequently, of the lost functional capacity of riparian forests, it is important to consider limitations associated with the methods used to estimate surface runoff. The estimation of surface runoff using flow accumulation maps calculated from high-resolution topographic data did not take into consideration the influence of important factors that control water infiltration in the watershed, such as rainfall intensity and landscape attributes, e.g. soil properties and LULC (Dunne and Black 1970a, b, Pearce et al. 1986, Montgomery and Dietrich 1994, McGuire et al. 2005). However, because these important factors were sufficiently homogeneous across all sites, the method was considered adequate for relative comparisons.

Impacts of gully formation stream's hydrologic response to storm events

The impacts of gully formation on the stream's hydrologic response to storm events were evaluated by comparing direct runoff coefficients (i.e. the percentage of rainfall that became direct runoff in the drainage area and moved quickly to the stream channel), and the rate of change in flow during a particular event (flashiness) in the stream channels. Direct runoff coefficient is a hydrologic variable that can be used to understand the controls of runoff generation in watersheds because it indicates how much of the rainfall depth becomes quickflow which is dependent on different factors affecting the catchment's hydrology (Hewlett and Hibbert 1967). Increases in direct runoff imply higher peak flows and higher quickflow volumes that, in turn, may eliminate sensitive taxa, and cause bank instability and erosion that reduces habitat quality, decreasing stream's biodiversity (Poff et al. 1997).

Results from the Tukey analyses suggest that direct runoff coefficients were associated with how hydrologically connected the streams were with their uplands via gullies (because of higher number of gullies and/or higher cumulative gully FAC) in the different study catchments. The more hydrologic connected streams were, the higher the runoff coefficients tended to be for the storm events analyzed. In fact, the cumulative gully FAC was the best proximate predictor of the direct runoff coefficient. However, the strong association of direct runoff coefficients with how hydrologically connected streams were with their upland via gullies may also incorporate the influence of both sugarcane cover and dirt roads because the higher the cumulative gully FAC, the higher the area of sugarcane and dirt roads.

Rain volume strongly influenced how much quickflow was generated in the streams during storms. The amount of quickflow generated during a storm event usually increases with rainfall depth in agricultural catchments (Stanfield and Jackson 2011, Rodriguez-Blanco et al. 2012, Epps et al. 2013). In the study streams, not only quickflow volume increased with rainfall depth but also the rate of increase was greater for streams draining catchments with high cumulative gully FAC.

Stream flashiness is an indicator of the rate of change in streamflow, and thus, it is useful to assess how quickly respond to storm events (Baker et al. 2004). Agricultural development in the watershed commonly leads to increased flashiness in streams (Poff et al. 2006). In the present study, the Tukey HDS test showed that two of the streams more hydrologically connected with their uplands via gullies (P6 and P7) responded more quickly to storms than the control stream (CA), corroborating the results of other studies in Brazil, where a stream draining a gullied catchment responded more rapidly to storms than a stream that drained a preserved catchment (Costa and Prado Bacellar 2007). However, the GLMs did not support that higher hydrologic connectivity between stream and its uplands via gullies translated into flashier storm flows.

The discrepancies between the results from the Tukey analysis and from the GLMs suggest that the study design in terms of number of catchments and the period of study might have been insufficient to detect the significance of gullying on the stream flashiness during storms. Nonetheless, the GLMs highlight the relevance of higher percent sugarcane cover and dirt roads and steeper terrain in increasing the rates of change of storm flows, following previous studies (e.g., Poff et al. 2006). Collectively, the findings suggest that flashiness is likely driven by the reduced interception capacity of sugarcane plants and decreased soil infiltration on cultivated and road areas than simply by runoff transport through gullies.

The results of the GLM also suggest that wider catchments had streams less flashy. In fact, the effect of the percent sugarcane cover and dirt roads on flashiness was exacerbated for narrower catchments. This is expected given that narrower catchments with similar soils and land use should have faster responses because of shorter flow paths (Post and Jakeman 1996).

The association between the degree to which streams were connected to their uplands via gullies and how streams responded to storm events was consistent with the dynamics of gully formation (Poesen et al. 2003). That is, catchments where more surface runoff can be generated and transmitted effectively downhill should also be those where gully formation is more common. Therefore, connected gullies in the study catchments possibly functioned as key entryways in streams for excess surface runoff generated in sugarcane fields and dirt roads. The results of this study help to elucidate that streams in areas prone to gully erosion in Brazil may be susceptible to the impacts of intensive agriculture, regardless of the existence of riparian buffers. Previous studies have shown that land cover and rainfall depth are important factors controlling flow regime in headwater streams (Germer et al. 2009, Stanfield and Jackson 2011, Epps et al. 2013), hence, they are included in many simulation models (e.g., Soil and Water Assessment

Tool – SWAT and TOPMODEL). My findings suggest that gully formation and connected gullies should also be included as a major driver of stream hydrology.

Impact of gully formation on sediment transport in streams

Previous studies have found a strong positive relationship between the magnitude of peak flow and sediment yield during storm events (e.g., Restrepo et al. 2006, Hughes et al. 2012, Rodrigues et al. 2013). This relationship was also observed for most of the study streams. This suggests that as peak flows increase, sediment export increases as well. Additionally, the streams that were more hydrologically connected with their uplands via gullies (CM, P5, P6, P7) had more sediment available for transport (higher intercept of the relationships), and thus exported more sediment during the storm events. Both findings suggest that gullying, as conveyors of high amounts of surface runoff, is a central factor exacerbating sediment export in sugarcane catchments.

The importance of gullies to sediment transport in the study streams was also suggested by the GLM pointing out that gullies are one of the significant predictors of sediment loads. However, the results indicate that impact of gullies on FSS load may be inversely related to stream length. This pattern may have occurred because those catchments having the longer streams were also those less connected to their uplands via gullies, thus having possibly less sediment available for transport and reduced sediment transport capacity.

The GLMs results also indicated that steeper catchments transported more sediment. This suggests that erosion in catchments with more inclined terrains are likely higher (Sidle et al. 2006), resulting in more sediment available for transport. The positive relationship between terrain slope and FSS load may also suggest that streams having limbs rising more quickly during storms have more rapid changes in the sediment load given the significant positive association between the R-B flashiness index and terrain slope.

Accelerated soil loss via gully erosion in arable lands and subsequent sediment transport downstream are two major environmental issues that increasingly concern land and water management authorities throughout the world (Lal 2000). Therefore, it is interesting to compare sediment yields found in this study with those from headwater streams draining other gullied lands in the world. Based on the few data available for lands with gully erosion, sediment yields reported here are within the range documented for catchments severely impacted by gullying (literature range: 0.56-27 t/ha/yr, Table 2.9). Considering studies in small agricultural watersheds that did not mention gully erosion in temperate (Walling et al. 2002, Lefrancois et al. 2007, Minella et al. 2009) and tropical regions (Riskin et al. 2017), sediment yields found by those studies were about 10 times lower than the average reported in this study. Such comparisons provide much needed scientific information about how gully formation associated with intensive agriculture in the study region and in other parts of Brazil may be impacting sediment transport in headwater catchments and degrading streams. Until now, this type of information was largely undocumented in Brazil.

The negative consequences of enhanced sediment yields to stream ecosystems can be enormous (Waters 1995a, Wood and Armitage 1997, Allan 2004, Bilotta and Brazier 2008, Poff and Zimmerman 2010). Impacts specific of gully erosion in Brazil include decreases in benthic communities caused by increases in rainfall-driven flood pulses and loads of suspended particles in streams of the Brazilian Cerrado (Wantzen 2006). Although the association between gullying and stream's biology has not been directly determined for sugarcane streams, we know that sedimentation impoverishes the stream's biodiversity (e.g., Schiesari and Correa 2016), and thus, gully erosion may be a significant cause of degradation of stream's ecological integrity.

Implications

In Brazil, private landowners must restore and protect riparian buffers by law. One of the objectives—as stated in the law—behind this requirement is the protection of water resources (Brasil 1965, Brasil 2012). However, this study shows that any protective function that riparian forests may provide can be disrupted by the detrimental impacts of gullying on the flow regime and sediment dynamics of streams. Therefore, the use of riparian forests as one of the primary management tools is probably not sufficient to protect water resources.

Protection and conservation of water resources from inputs of excess runoff and sediments from agricultural fields may require additional management strategies to prevent and mitigate gully erosion. First and foremost, excess runoff along dirt roads bordering riparian forests must be halted. This is especially relevant for catchments highly susceptible to gullying such as most sugarcane areas in the State of Sao Paulo, which are characterized by intense mechanization, steep slopes, and old tropical soils.

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Tables and Figures

Table 2.1 Landscape characteristics of the study catchments

Site	Geographic coordinates at sampling point	Area†	Mean slope	Elongation	Length existing stream	Cane cover†	Forest cover†	Dirt-road cover†	# all mapped gullies	# connected gullies	Cumulative gully FAC	Mean baseflow discharge
		ha	m m^{-1}		m	----------------	%	---------------			ha	L s^{-1}
CA	22°36'55.92"S 47°40'25.57"W	5.9	0.17	0.66	415	1.1	98.9	0	0	0	0.0	0.13
CC	22°36'55.26"S 47°40'10.15"W	7.2	0.07	0.53	412	89.2	9.4	1.5	13	7	2.0	0.09
CF	22°36'47.53"S 47°40'16.07"W	6.3	0.25	0.76	463	35.6	62.1	2.3	15	2	0.6	0.06
CM	22°36'51.60"S 47°40'21.22"W	5.1	0.21	0.60	252	29.6	68.6	1.8	8	2	2.5	0.19
P1	22°37'14.81"S 47°40'25.54"W	5.6	0.15	0.92	154	70.0	28.7	1.9	14	4	0.9	0.43
P2	22°37'06.27"S 47°40'20.50"W	7.6	0.10	0.83	366	80.9	17.8	1.3	4	0	0	0.27
P3	22°36'53.02"S 47°40'07.57"W	12.0	0.14	0.66	680	35.4	62.6	2.0	12	0	0	0.37
P4	22°36'45.10"S 47°40'02.50"W	16.5	0.19	0.69	741	43.4	55.5	1.1	10	0	0	0.44
P5	22°36'35.72"S 47°40'07.70"W	7.4	0.23	0.91	429	26.8	71.8	1.4	12	2	0.8	0.02
P6	22°36'42.33"S 47°40'08.49"W	2.9	0.19	0.63	112	73.6	24.7	1.7	11	2	0.8	0.05
P7	22°36'41.14"S 47°40'38.30"W	6.1	0.14	0.69	291	79.1	18.9	2.0	24	8	5.3	0.20

† Based on the area derived by hand-delineation of catchment boundary following the topography contour map from 1979.

Table 2.2 Rainfall volume and intensity of selected storm events

Rainfall event ID	Date and start time	Total volume (mm)	Intensity (mm h^{-1})
24	2013-11-29 18:45:00	39.57	5.5
25	2013-12-05 18:00:00	33.26	13.3
66	2014-03-11 19:15:00	32.00	64.0
37	2014-01-17 21:11:00	22.50†	90.0†
33	2014-01-13 12:15:00	22.10	29.5
5	2013-10-18 15:45:00	21.59	17.3
31	2013-12-30 13:45:00	20.40†	81.6†
30	2013-12-25 12:00:00	20.30†	81.2†
8	2013-10-24 21:45:00	19.30	4.8
11	2013-11-04 18:00:00	18.78	3.1
26	2013-12-07 21:00:00	17.53	10.0
78	2014-04-22 09:45:00	17.50	5.4
10	2013-11-04 07:00:00	16.75	2.7
72	2014-03-21 17:00:00	16.47	3.9
76	2014-04-15 05:15:00	16.00	2.4
61	2014-03-05 10:15:00	14.97	4.0
43	2014-02-14 22:00:00	14.70	2.2
65	2014-03-10 13:15:00	14.22	28.4
16	2013-11-21 12:30:00	13.96	14.0
73	2014-04-01 19:30:00	13.96	8.0
35	2014-01-17 00:30:00	13.70	6.9
32	2014-01-04 18:45:00	12.00	24.0
58	2014-02-28 23:45:00	11.42	3.8

† Estimated values based on patterns in Piracicaba due to malfunction of the tipping bucket

Table 2.3 Results of Tukey Honest Significant Differences for comparisons of means of the hydrologic variables (R-B flashiness index and direct runoff coefficient) among study streams. Only significant ($p < 0.1$) contrasts are shown

Contrast	Difference in means	Lower end point of the interval	Upper end point of the interval	*p*-value†
R-B flashiness index				
CF-CA	0.23	0.068	0.392	<0.001
CM-CA	0.18	0.016	0.340	0.018
P5-CA	0.17	0.008	0.332	0.030
P6-CA	0.28	0.116	0.440	<0.001
P7-CA	0.16	-0.002	0.322	0.058
P1-CF	-0.17	-0.332	-0.008	0.031
P2-CF	-0.23	-0.395	-0.071	<0.001
P2-CM	-0.18	-0.344	-0.020	0.014
P6-P1	0.22	0.057	0.381	<0.001
P5-P2	0.17	0.011	0.336	0.025
P6-P2	0.28	0.120	0.444	<0.001
P7-P2	0.16	0.001	0.325	0.047
P6-P3	0.18	0.020	0.340	0.014
P6-P4	0.17	0.009	0.333	0.029
Direct runoff coefficient				
CM-CA	1.03	0.057	2.014	0.028
P5-CA	1.09	0.116	2.073	0.015
P6-CA	1.12	0.143	2.100	0.011
P7-CA	1.05	0.071	2.028	0.024

† *p*-value after adjustment for the multiple comparisons

Table 2.4 Results of the generalized linear models (GLMs) on the average R-B flashiness index. Only those models containing at least one significant coefficient are presented. Significant coefficients and the best-fitting model (smaller AICc) are in bold. Cum.gully FAC is the cumulative gully FAC variable

	Explanatory variables						AICc
	Intercept		Elongation	% altered cover	Slope	Elongation* % altered cover	
estimate	-3.044		0.933	0.036	6.162	-0.039	**-10.375**
p value	**0.002**		0.286	**0.009**	**0.001**	**0.028**	
	Intercept		Elongation	% altered cover	Slope		
estimate	-1.60		-1.27	1.00E-02	6.48		**-12.182**
p value	**6.37E-03**		**0.02**	**0.011**	**0.001**		
	Intercept	Cum. gully FAC	Elongation	% altered cover	Slope		
estimate	-1.60	-2.54E-07	-1.28	1.01E-02	6.49		-1.192
p value	**0.012**	0.944	**0.035**	**0.024**	**0.003**		
	Intercept			% altered cover	Slope		
estimate	-2.34			9.01E-03	5.79		-9.967
p value	**2.32E-03**			**0.072**	**0.013**		
	Intercept	Cum. gully FAC		% altered cover	Slope		
estimate	-2.28	2.80E-06		7.87E-03	5.65		-3.196
p value	**0.004**	0.569		0.148	**0.021**		
	Intercept		Elongation		Slope		
estimate	-7.90E-01		-9.83E-01		3.69		-6.743
p value	1.56E-01		0.206		**0.052**		
	Intercept				Slope		
estimate	-1.41				3.25		-9.514
p value	**1.35E-03**				**0.078**		
	Intercept	Cum. gully FAC					
estimate	-9.15E-01	4.74E-06					-6.455
p value	**3.12E-05**	0.401					
	Intercept			% altered cover			
estimate	-9.09E-01			9.81E-04			-5.639
p value	**0.004**			0.808			
	Intercept	Cum. gully FAC		% altered cover			
estimate	-8.94E-01	5.07E-06		-4.57E-04			-1.233
p value	**0.005**	0.459		0.921			

Table 2.5 Results of the generalized linear models (GLMs) on the average direct runoff coefficient. Only those models containing at least one significant coefficient are presented. Significant coefficients and the best-fitting model (smaller AICc) are in bold. Cum.gully FAC is the cumulative gully FAC variable

			Explanatory variables			AICc
	Intercept	Cum. gully FAC				
estimate	1.60	2.04E-05				**65.774**
p value	**7.06E-05**	**0.015**				
	Intercept	Cum. gully FAC			Slope	
estimate	1.07	2.23E-05			2.92	70.224
p value	0.18	**0.021**			0.435	
	Intercept	Cum. gully FAC	Elongation			
estimate	1.65	2.03E-05	-8.20E-02			71.009
p value	0.172	**0.024**	0.958			
	Intercept	Cum. gully FAC		% altered cover		
estimate	1.58E+00	2.02E-05		2.41E-04		71.011
p value	**0.009**	**0.061**		0.978		
	Intercept	Cum. gully FAC		% altered cover	Slope	
estimate	4.30E-01	1.87E-05		7.03E-03	4.74	77.002
p value	0.789	**0.094**		0.618	0.401	
	Intercept	Cum. gully FAC	Elongation	% altered cover		
estimate	1.66	2.00E-05	-1.23E-01	4.76E-04		78.339
p value	0.217	**0.088**	0.941	0.96		
	Intercept			% altered cover		
estimate	1.359			9.23E-03		71.229
p value	**0.059**			0.352		
	Intercept		Elongation			
estimate	2.493		-0.872			72.332
p value	**0.09**		0.653			
	Intercept				Slope	
estimate	1.681				1.156	72.457
p value	**0.057**				0.792	

Table 2.6 Summary of concentrations of suspended sediment at all study streams at baseflow and storm flow

Site	TSS					FSS					VSS				
	n	Mean	SD	Max	Min	n	Mean	SD	Max	Min	n	Mean	SD	Max	Min
Baseflow															
CA	23	7.2	6.5	29.1	1.8	23	4.9	5.6	25.9	0.7	23	2.3	1.5	5.3	0.0
CC	19	12.2	10.1	44.3	2.0	19	9.5	9.3	39.9	0.9	19	2.8	1.8	7.56	0.7
CF	23	21.8	18.4	58.3	3.1	23	18.0	15.9	56.3	1.5	23	3.8	3.7	16.4	0.3
CM	23	11.2	8.1	31.8	2.1	23	8.0	7.3	28.9	0.9	23	3.2	2.3	8.8	0.0
P1	23	7.7	6.8	27.4	1.7	23	5.1	4.0	19.0	5	23	2.6	4.4	21.6	0.0
P2	21	20.0	21.2	100.5	1.7	21	16.4	7	82.9	1.0	21	3.6	3.8	17. 7	0.3
P3	23	16.0	32.7	122.0	1.263	23	13.2	29.8	110.5	9	23	2.8	3.3	12.5	0.0
P4	23	16.4	18.3	68.1	2.2	23	12.3	13.6	54.9	0.5	23	4.0	5.5	25.3	0. 5
P5	20	22.6	20.1	80.8	1.8	20	16.9	14.7	63. 2	0.7	20	5.7	6.8	29.5	0.6
P6	23	25.4	14.6	57.1	7.7	23	20.1	12. 5	48.5	5.7	23	5. 4	2.5	10. 3	1.7
P7	14	92.2	118.3	450.8	9.6	14	86.2	114.5	434.6	8.3	14	6.0	4.6	16.1	1.3
Storm flow															
CA	7	2464.3	975.7	3541.6	833.3	7	2112.0	894.1	3192.8	692.0	7	352.2	106.1	489.3	141.3
CC	25	7622.1	3912.2	14665.0	724.0	25	1	3781.1	14035.0	620. 7	25	402.0	152.3	630.0	103.3
CF	24	26113.9	45341.5	206572.6	3509.0	24	24858.1	43297.9	196504.2	3164.0	24	1255.8	2075.6	10068.4	160.9
CM	30	7501.3	7738.6	40477.34	1369.4	30	7046. 1	7470.2	39317. 7	1213.0	30	455.3	315.5	1427.89	151.3
P1	15	5619.6	3337.1	11988.9	1251. 7	15	5150.5	3091.8	10795. 6	1043. 9	15	469.1	287.6	1193.3	134.3
P2	8	3058.6	2707.9	9158.9	837.9	8	2763.67	2631.3	8786. 7	637.9	8	294.9	135.2	507.6	155.2
P3	22	7158.7	6487.6	29576.1	1905.9	22	6776.2	6310.0	28622.6	1745.2	22	382.5	202.3	953.5	114.7
P4	18	9825.9	8432.9	37389.1	1638.1	18	9314.2	8123.4	36174. 7	1559.4	18	511.7	430.7	1916.1	78.8
P5	21	29187.9	21502.7	91986.3	371.1	21	27716. 2	20649.7	88565. 3	287.6	21	1471.7	933.6	3753.8	83.4
P6	27	16374.8	15439.0	61383.0	2106. 7	27	15619.3	14950.8	59962.0	1921. 8	27	755.5	557.6	2059.7	184.9
P7	28	33007.9	50284.2	212455. 6	3464.4	28	30054.4	42353.0	195342.7	3282.2	27	761.2	790.1	4250.9	182.2

Table 2.7 Results of analysis of covariance to test differences in slopes and intercepts of significant linear models of the relationships between peak discharge and FSS yield (Figure 2.12)

Contrast	Statistics for differences in slope	Statistics for differences in intercept
CM-P2	n.s	t = -2.488 p = 0.042
CM-P5	n.s	n.s.
CM-P6	n.s	t = 2.992 p = 0.020
CM-P7	t = -2.562 p =0.042	n.s.
P2-P5	n.s	t = 2.864 p = 0.024
P2-P6	n.s	t = 3.885 p = 0.006
P2-P7	n.s	t = 2.123 p = 0.071
P5-P6	n.s	t = 2.224 p = 0.062
P5-P7	n.s	n.s.
P6-P7	n.s	t = -2.397 p =0.048

Note: n.s. is not statistically significant

Table 2.8 Results of the generalized linear models (GLMs) on the average FSS load. Only those models containing at least one significant coefficient are presented. Significant coefficients and the best-fitting model (smaller AICc) are in bold. # Gullies is the total number of mapped gullies

	Model parameters						**AICc**
	Intercept	# Gullies		Stream length	Slope	# Gullies* Stream length	
estimate	-310.99	17.08		0.40	762.69	-0.044	**225.02**
p value	**0.013**	**0.011**		**0.012**	**0.011**	**0.011**	
	Intercept	# Gullies		Stream length	Slope		
estimate	-1.39	3.42E-01		-1.63E-02	5.72E+01		254.12
p value	0.783	**0.055**		**0.015**	**0.026**		
	Intercept		Altered area	Stream length	Slope		
estimate	-1.60E+01		1.88E-04	-3.02E-02	1.47E+02		255.20
p value	**2.49E-01**		0.112	**0.048**	**0.062**		
	Intercept	# Gullies	Altered area	Stream length			
estimate	8.49	5.77E-01	-1.67E-04	-7.33E-03			256.01
p value	**0.002**	**0.097**	**0.076**	**0.025**			
	Intercept		Altered area	Stream length			
estimate	1.57E+01		-9.42E-05	-2.50E-02			259.23
p value	**0.023**		0.724	0.451			
	Intercept	# Gullies	Altered area				
estimate	9.57	1.67E-01	-5.85E-05				264.46
p value	**1.21E-05**	0.189	0.176				
	Intercept				Slope		
estimate	7.97				10.24		263.14
p value	**0.006**				0.35		
	Intercept		Altered area				
estimate	1.03E+01		-1.50E-05				263.85
p value	**8.14E-08**		0.515				
	Intercept	# Gullies					
estimate	9.24	4.69E-02					264.24
p value	**2.40E-05**	0.538					
	Intercept	# Gullies			Slope		
estimate	7.53	5.72E-02			9.00		267.71
p value	**0.018**	0.525			0.355		

Table 2.9 Suspended sediment yields measured in small agricultural catchments

Reference	Region	Catchment	Land cover	Gully	Area (ha)	Sediment yield (t/ha/yr)
This study	Tropical	CA	Regenerating forest	no		0.03*
This study	Tropical	P2	Cropland/forest	yes		0.20*
This study	Tropical	P4	Cropland/forest	yes		0.17*
This study	Tropical	P3	Cropland/forest	yes		1.06*
This study	Tropical	CC	Cropland/forest	yes		1.16*
This study	Tropical	P1	Cropland/forest	yes		2.02*
This study	Tropical	CM	Cropland/forest	yes		3.80*
This study	Tropical	P7	Cropland/forest	yes		21.59*
This study	Tropical	P5	Cropland/forest	yes		23.50*
This study	Tropical	CF	Cropland/forest	yes		25.40*
This study	Tropical	P6	Cropland/forest	yes		157.68*
Mathys et al. 2003	Temperate	Roubine	Devoid of vegetation	yes	0.13	70 - 277††
		Moulin	Devoid of vegetation	yes	8	14-100††
Chappnell et al. 2004	Tropical	P3	Forest logging	yes	19	3.6††
		P4	Forest logging	yes	4.6	14.7††
		P6	Forest logging	yes	0.75	0.14††
Duvert et a. 2010	Tropical	Huertitas	Cropland/rangeland	yes	300	0.90 - 15.00††
		Potrerillos	Cropland/grassland/forest	yes	1200	0.60 - 0.80††
		La Cortina	Cropland/forest	no	930	0.03
Walling et al. 2002	Temperate	Smisby	Cropland	no	360	0.08
		Rosemaund	Cropland	no	150	0.08
Lefrançois et al. 2007	Temperate	Moulinet	Cropland/cattle	no	453	0.26
		Violettes	Cropland/cattle	no	224	0.36
Minella et al. 2014	Temperate	Arvorezinha	Cropland	no	119	1.30
Riskin et al. 2017	Tropical	Tanguro	Cropland	no	2 to 3	0.05†

* Cumulative yield considering results from five storm events
† Average of sediment yield in four streams
†† Maximum values used to calculate average maximum sediment yield for catchments impacted by gullying

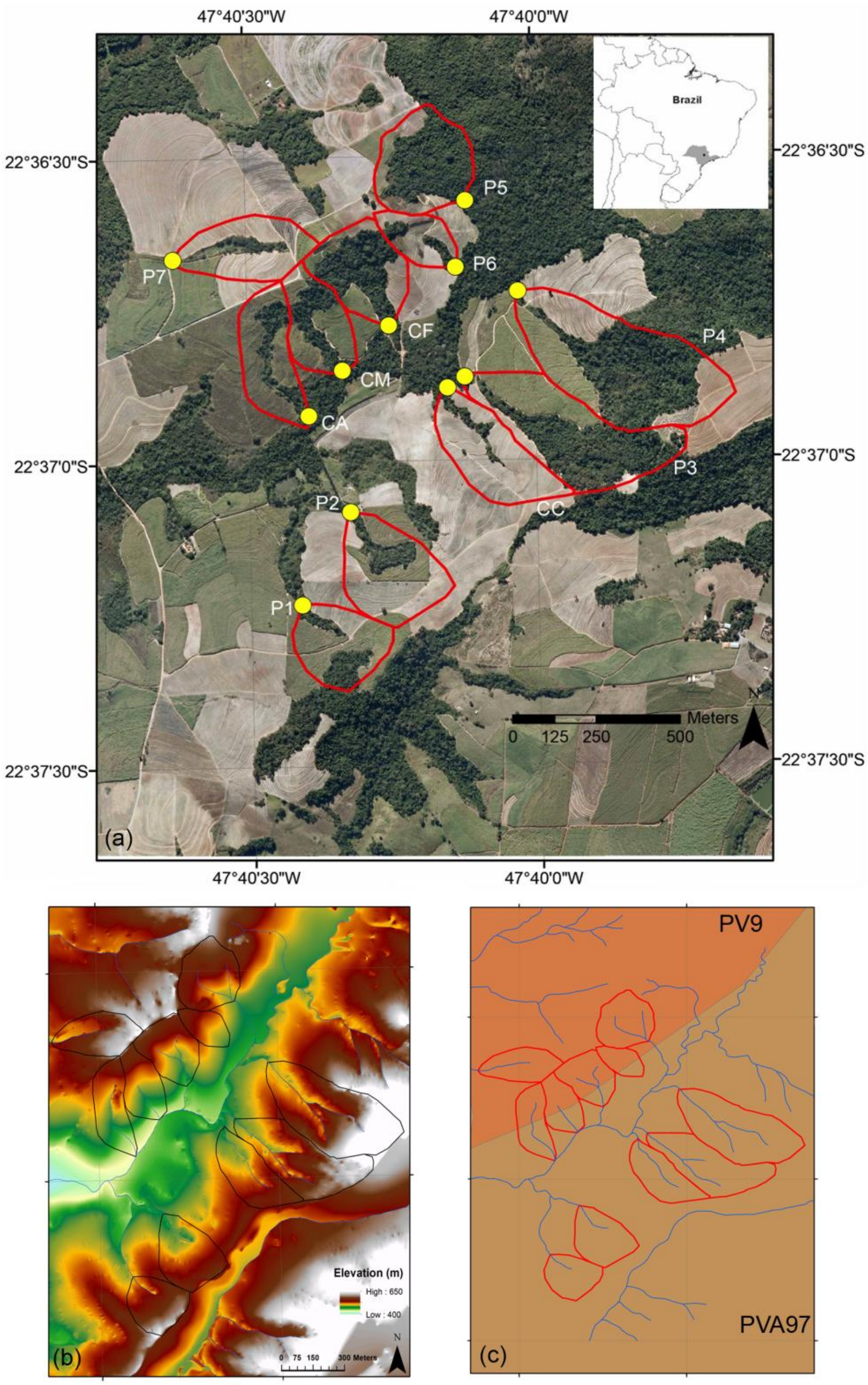

Figure 2.1 (a) Location of the study area in the State of Sao Paulo, Brazil (black dot in the top map) and detailed aerial imagine of the study catchments (orthophoto, EMPLASA 2010/2011). Redlines show watershed delineations. Yellow dot is downstream sampling point. (b) Elevation of the study area. (c) Ultisol types in the study area according to the Brazilian Soil Classification: PV9 (‘argissolo vermelho’ 9) and PV97 (‘argissolo vermelho amarelo’ 97)

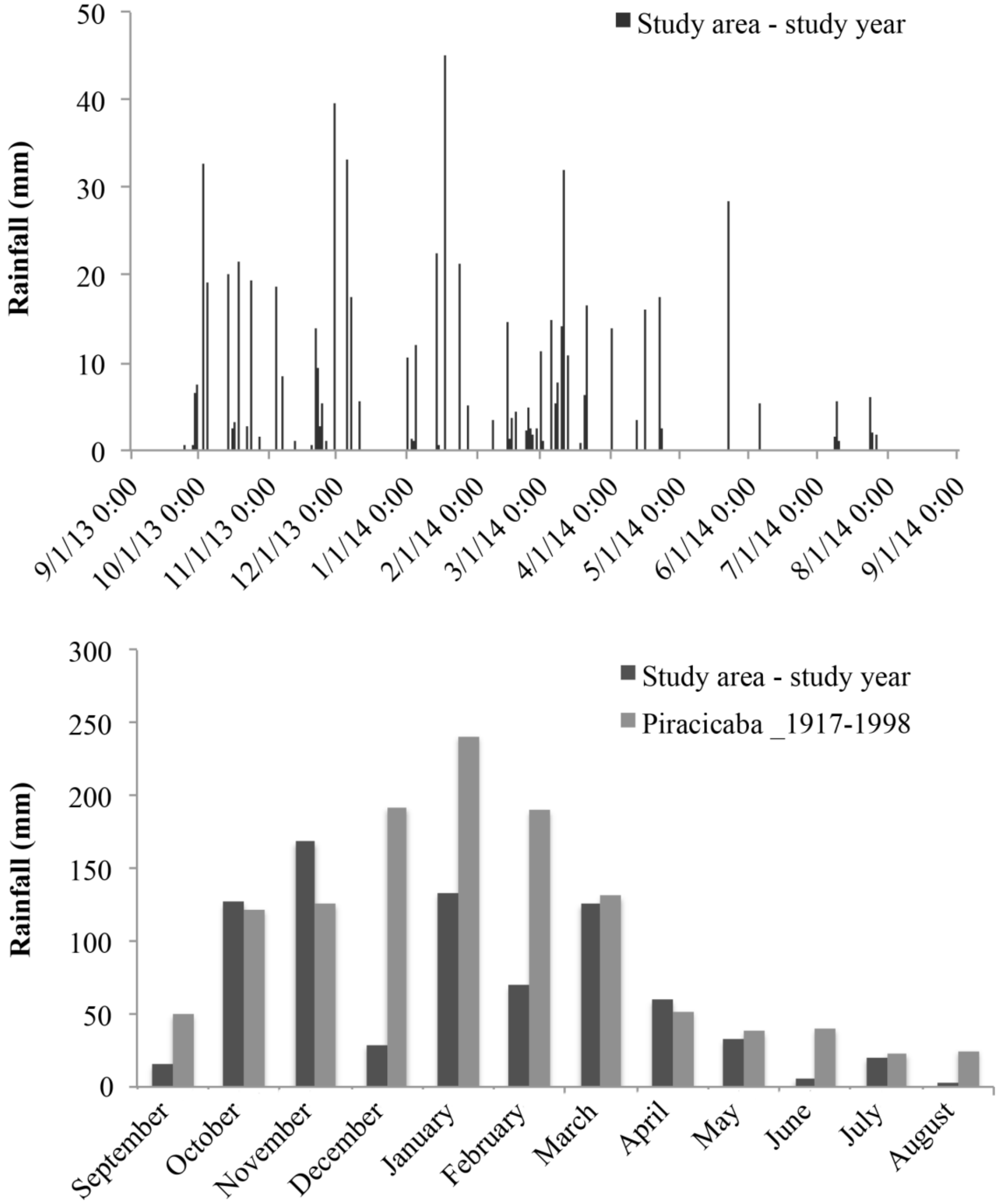

Figure 2.2 (a) Precipitation at the study area during the period of data collection and (b) comparison of total monthly precipitation at the study area during the period of data collection with the average monthly precipitation data based on 81 years of data for the city of Piracicaba

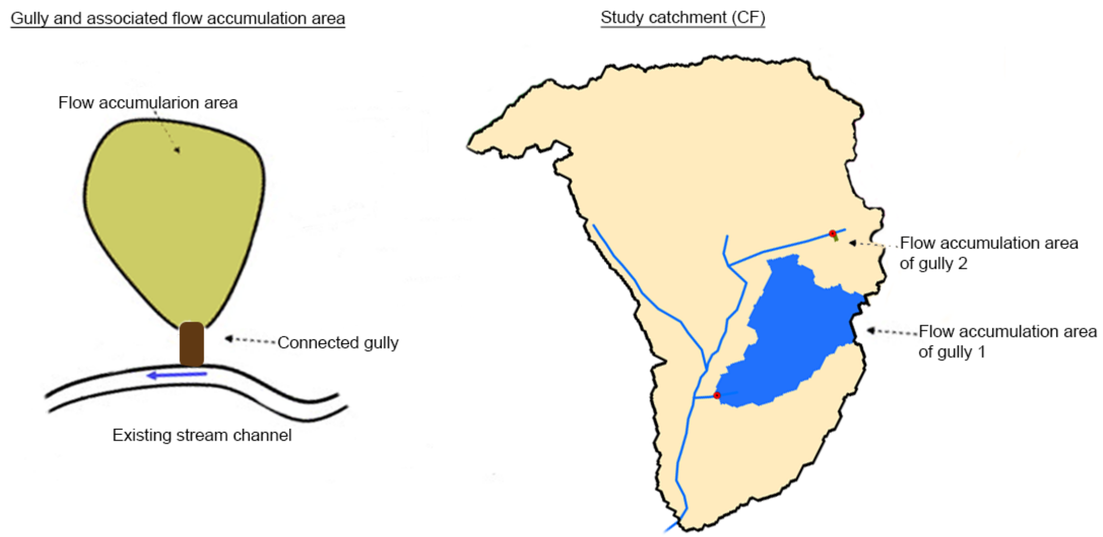

Figure 2.3 (a) Schematic of upslope flow accumulation area above a specific connected gully. (b) Example of a study catchment with the upslope flow accumulation area delineated for its connected gullies

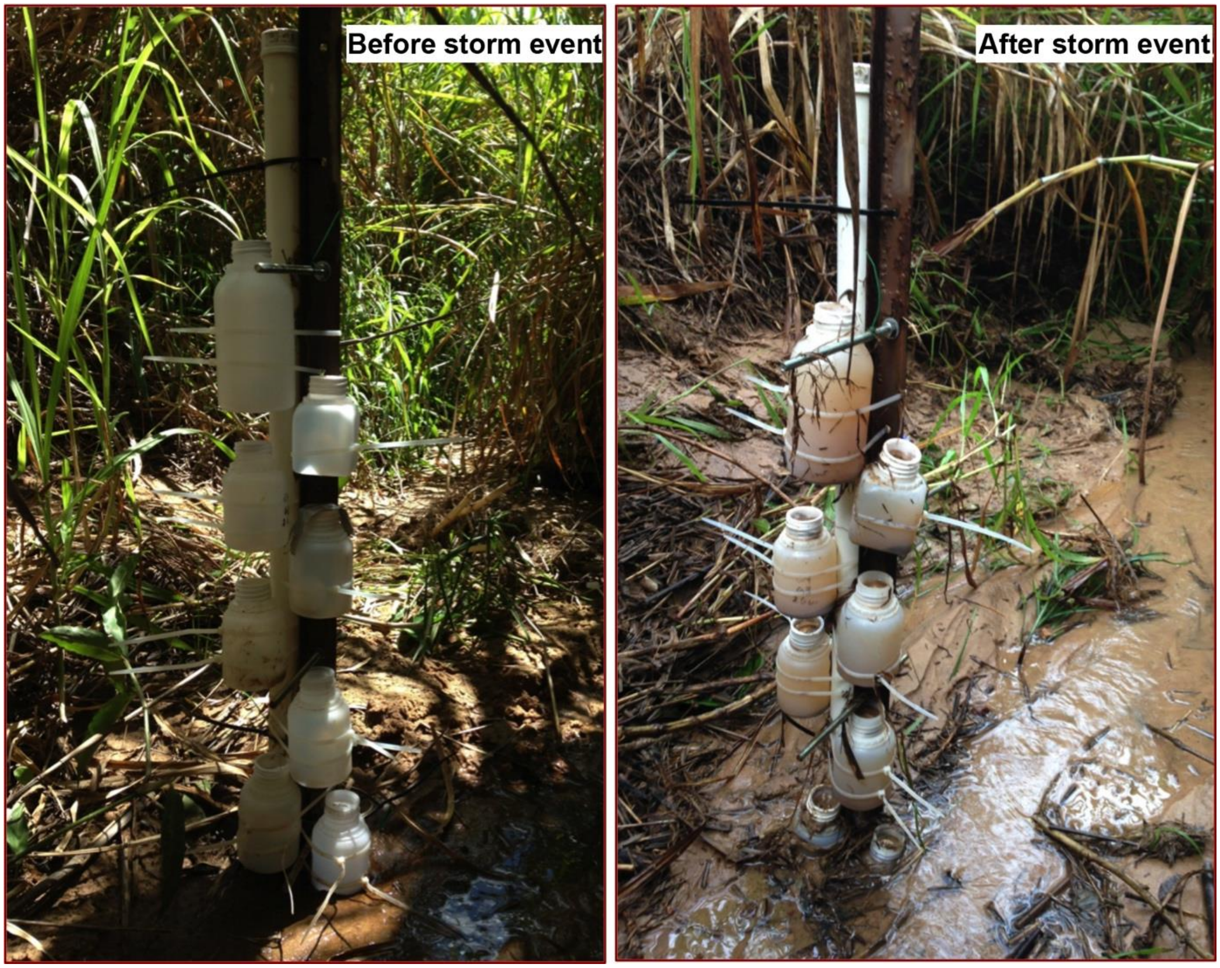

Figure 2.4 Example of the rising stage sampler used to collect suspended sediment in the study streams. Pictures depict the sampler in catchment P7 before and after a storm event

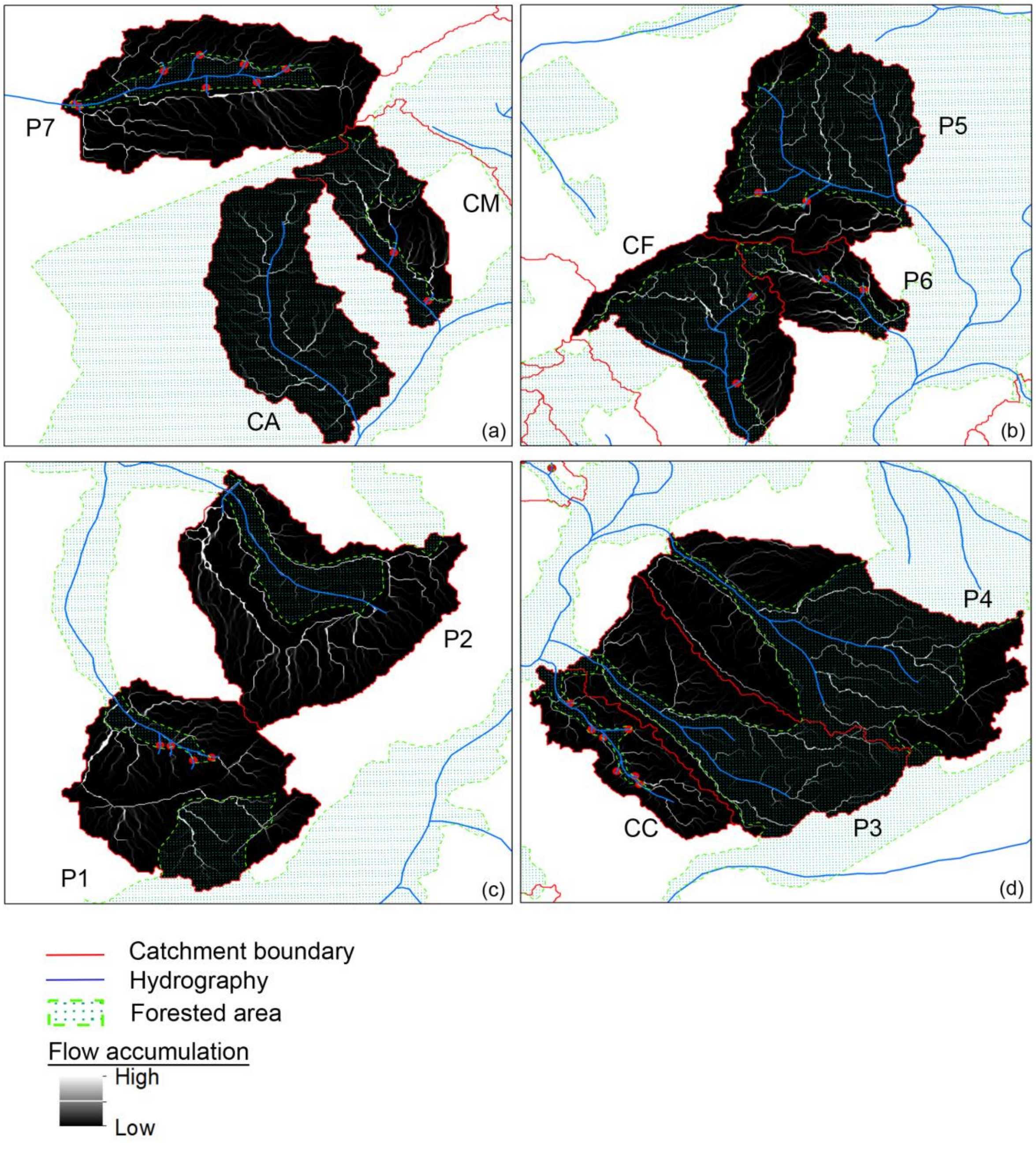

Figure 2.5 Flow accumulation map in each study catchments: (a) catchments CA, CM, and P7; (b) catchments CF, P5, and P6; (c) catchments P1 and P2; and (d) catchments CC, P3, and P4. Forested areas are highlighted in green. The catchment area not highlighted in green is covered in sugarcane or is dirt-road surfaces. Dirt road surfaces can be identified as continuous concentrated flow area (white) that is not existing stream channels. Some dirt roads margining riparian forest (e.g., in P3 and P4) do not appear in the figures because the way that forested areas were represented. Connected gullies are represented as red dots. The data is classified using standard deviation (0.1) to allow visual interpretability of the flow accumulation pattern on paper. The pattern of flow accumulation of catchments in pattern two different panels cannot be directly compared with this picture

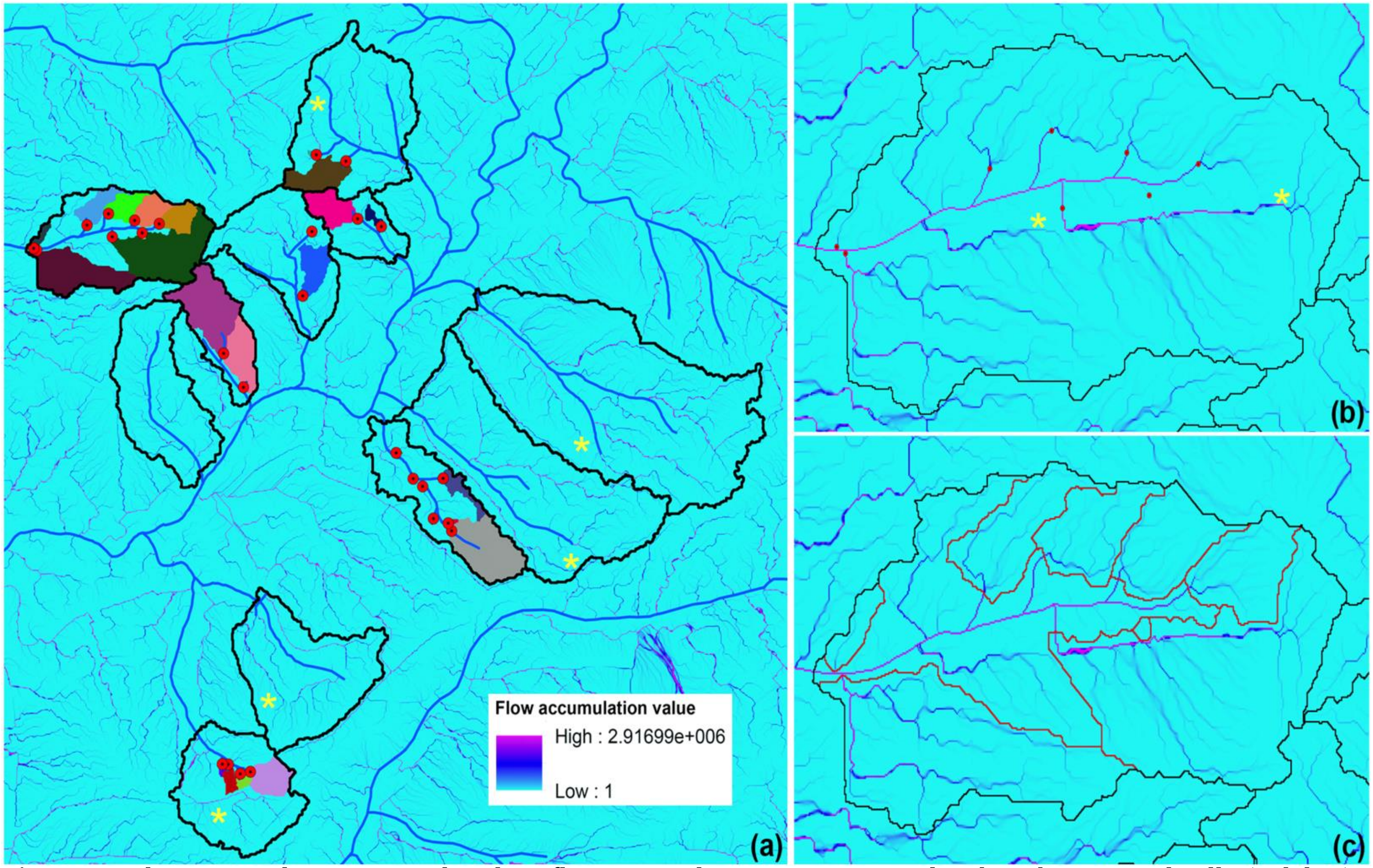

Figure 2.6 Flow accumulation map and upslope flow accumulation area associated with each connected gully (red dots) in (a) all study catchment, (b) at catchment P7 with no boundaries delineated; and (c) at catchment P7 with the upslope flow accumulation area delineated for each connected gully. Yellow asterisks identify flow accumulation along some dirt roads. The data is classified using standard deviation (0.1) to allow visual interpretability of the flow accumulation pattern on paper

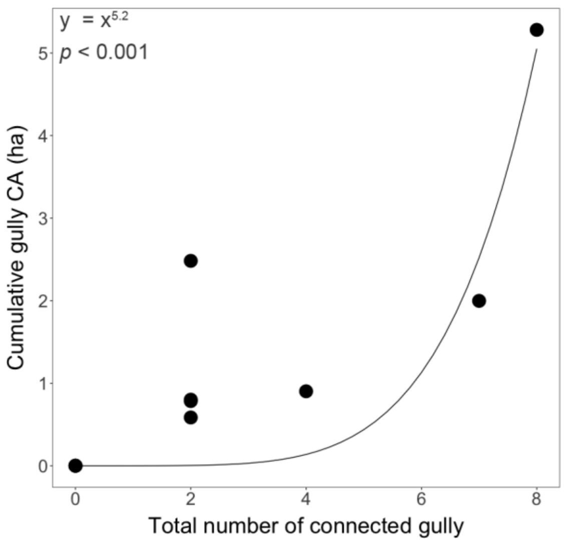

Figure 2.7 Non-linear relationship total number of connected gullies cumulative flow accumulation area above connected gullies (ha)

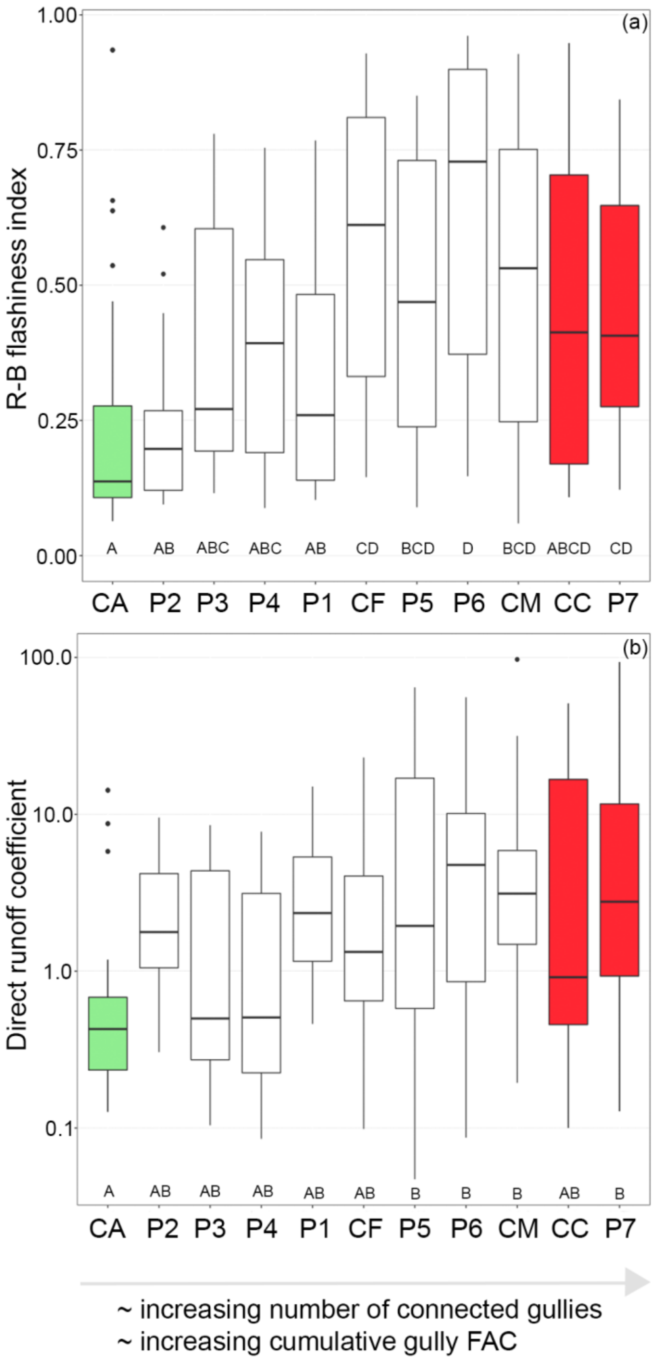

Figure 2.8 Distribution R-B index (a) and direct runoff coefficient (b) data across all study streams. Study streams are oriented based on the number of connected gullies and cumulative gully FAC. The three most comparable study streams to isolate the effect of gullying are highlighted: catchment CA in green, CC and P7 in red. Results of Tukey HSD test are presented in letters for probability ≤ 0.05

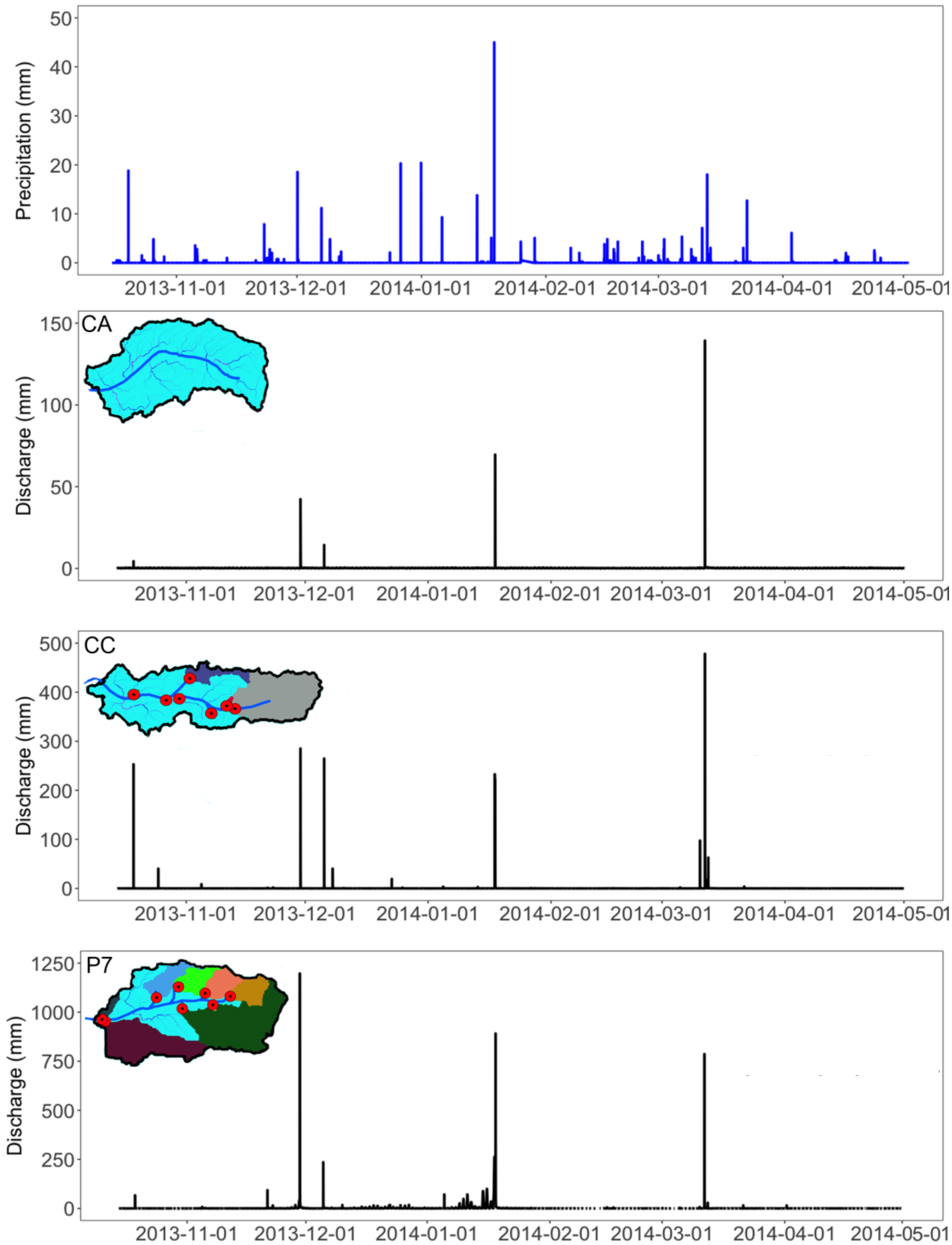

Figure 2.9 (a) Rainfall (mm) at the study area and (subsequent panels) hydrographs (mm) for the subset of streams during the period from 10/14/2013 to 04/30/2014. Hydrographs are arranged in increasing order of cumulative upslope flow accumulation area associated with connected gullies, starting with (b) the hydrograph of the "control" catchment CA; (c) catchment CC; and (d) catchment P7. Note that the limit of the y axis changes among panels

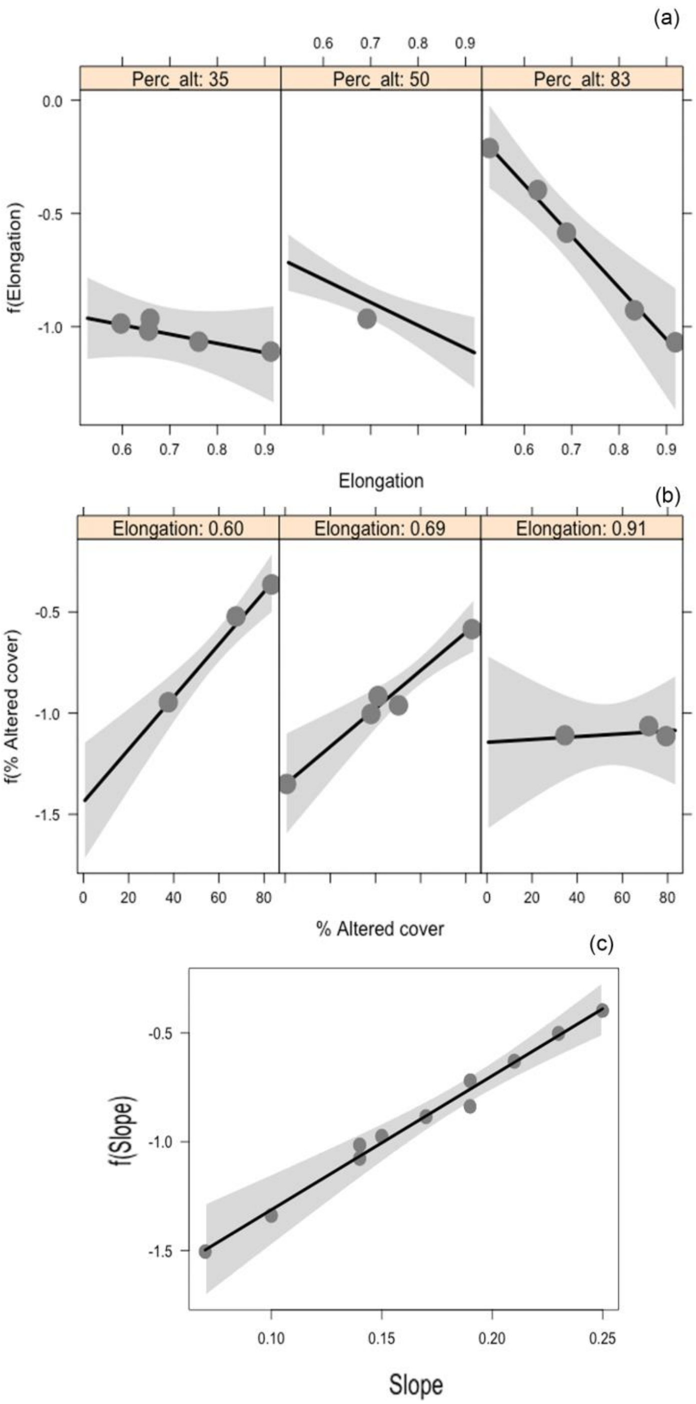

Figure 2.10. Fits for the generalized linear model on the average R-B flashiness index: average R-B flashiness index = -3.0 + 0.93*Elongation + 0.04*% altered cover + 6.2*Terrain slope -0.04 (Elongation*% altered cover). (a) Cross-sectional plots depicting the interaction between Elongation on the x axis and percent altered cover (Perc_alt). (b) Cross-sectional plots depicting the interaction between percent altered cover on the x axis and Elongation. (c) Plot depicting the relationship between response variable and slope. All models are plotted on the scale of the linear predictor (link function: log) and the confidence interval is in grey

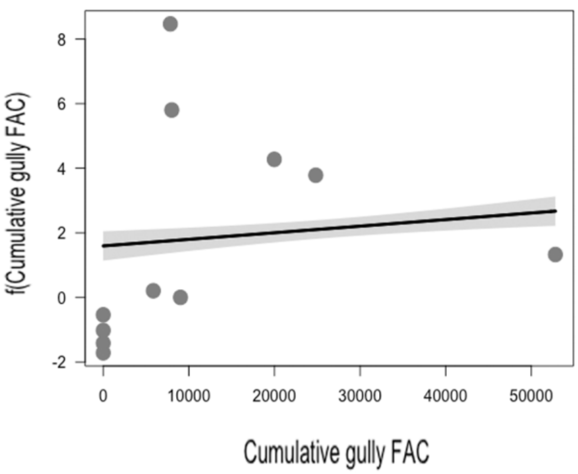

Figure 2.11. Fit for the generalized linear model on the average direct runoff coefficient: average direct runoff coefficient = 1.6 +2.05 $*10^{-5}$ * Cumulative gully FAC. The model are plotted on the scale of the linear predictor (link function: log) and the confidence interval is in grey

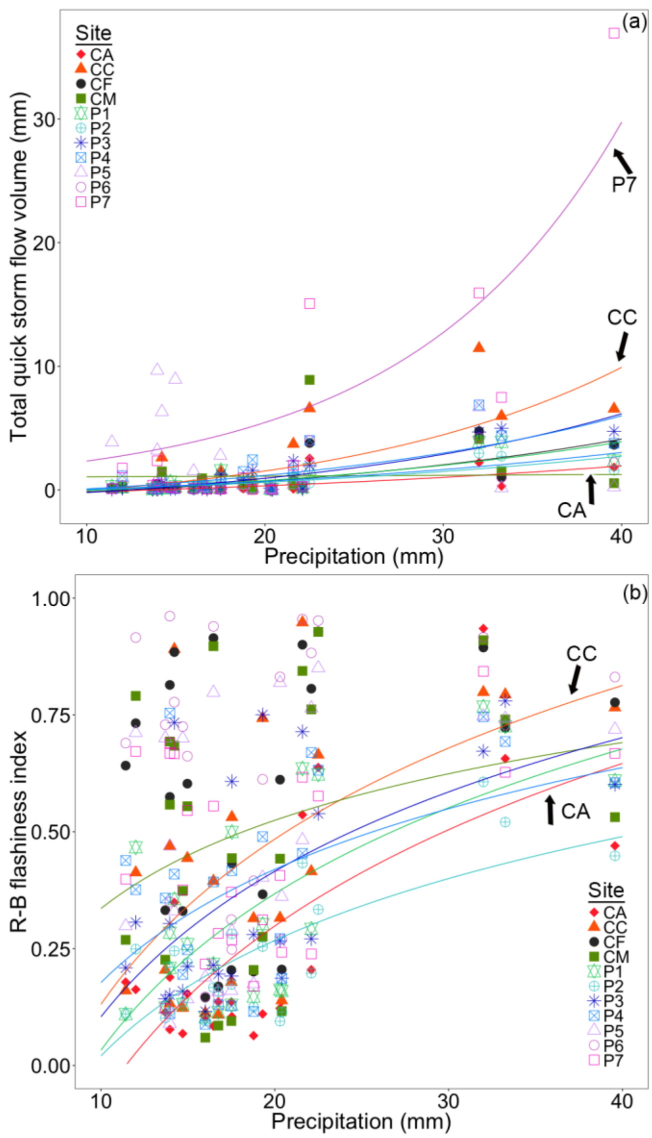

Figure 2.12 Non-linear relationships between rainfall total and the total volume of quick flow (a) and the R-B flashiness index (b) across the study streams. Significant non-linear fits are presented and the lines associated with the three most comparable streams (CA, CC, and P7) are highlighted

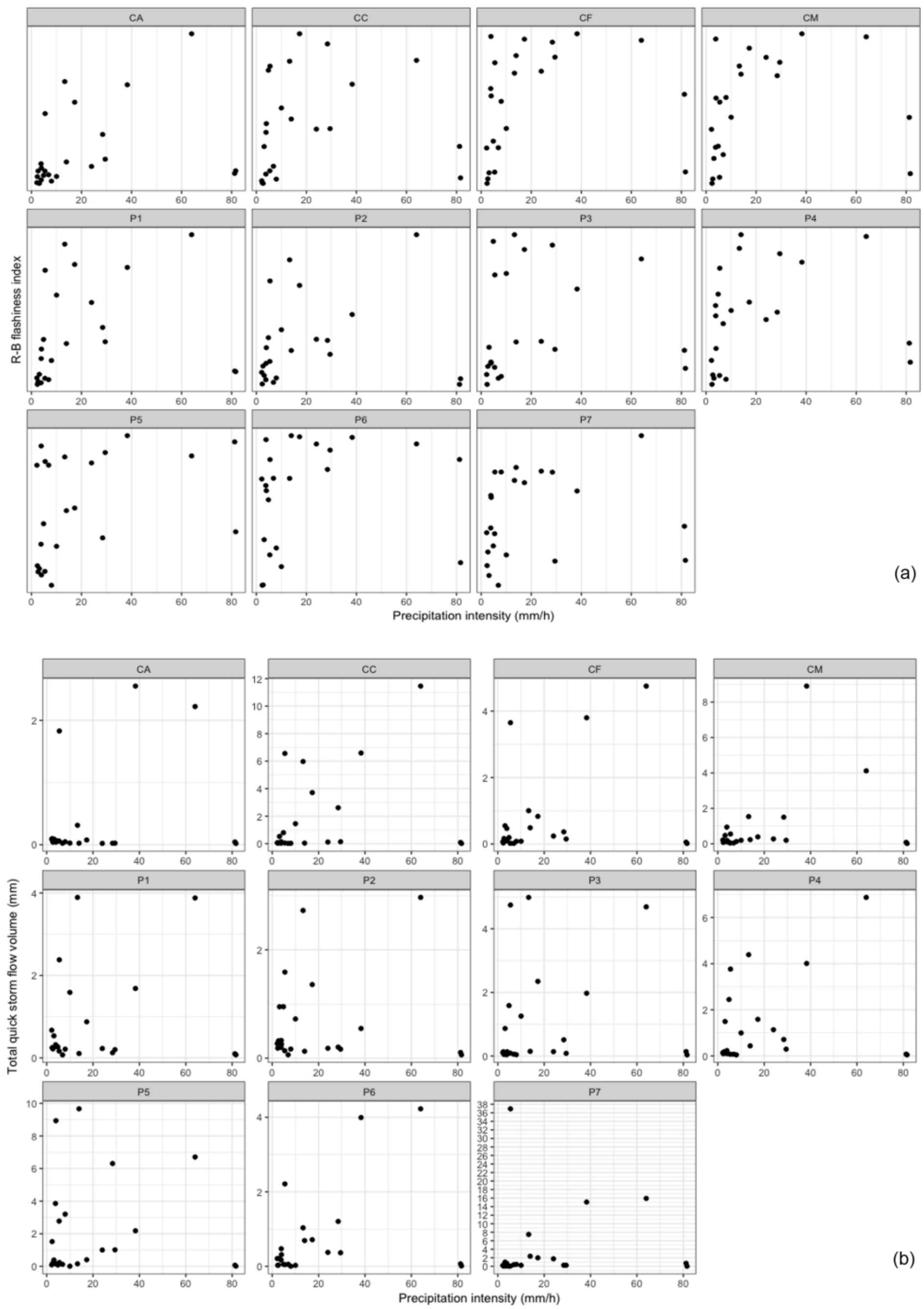

Figure 2.13 Relationships between rainfall intensity and the total volume of quick flow (a) and the R-B flashiness index (b) across the study streams

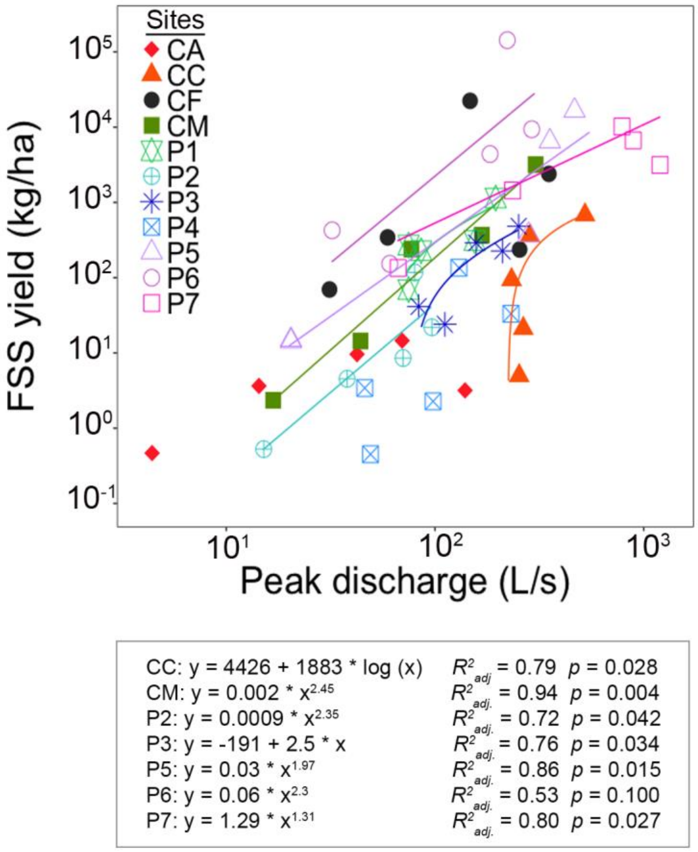

Figure 2.14 Relationships between FSS yield and peak discharge across all study streams for the five storm events that occurred concurrently at all sites. Significant linear relationships are presented

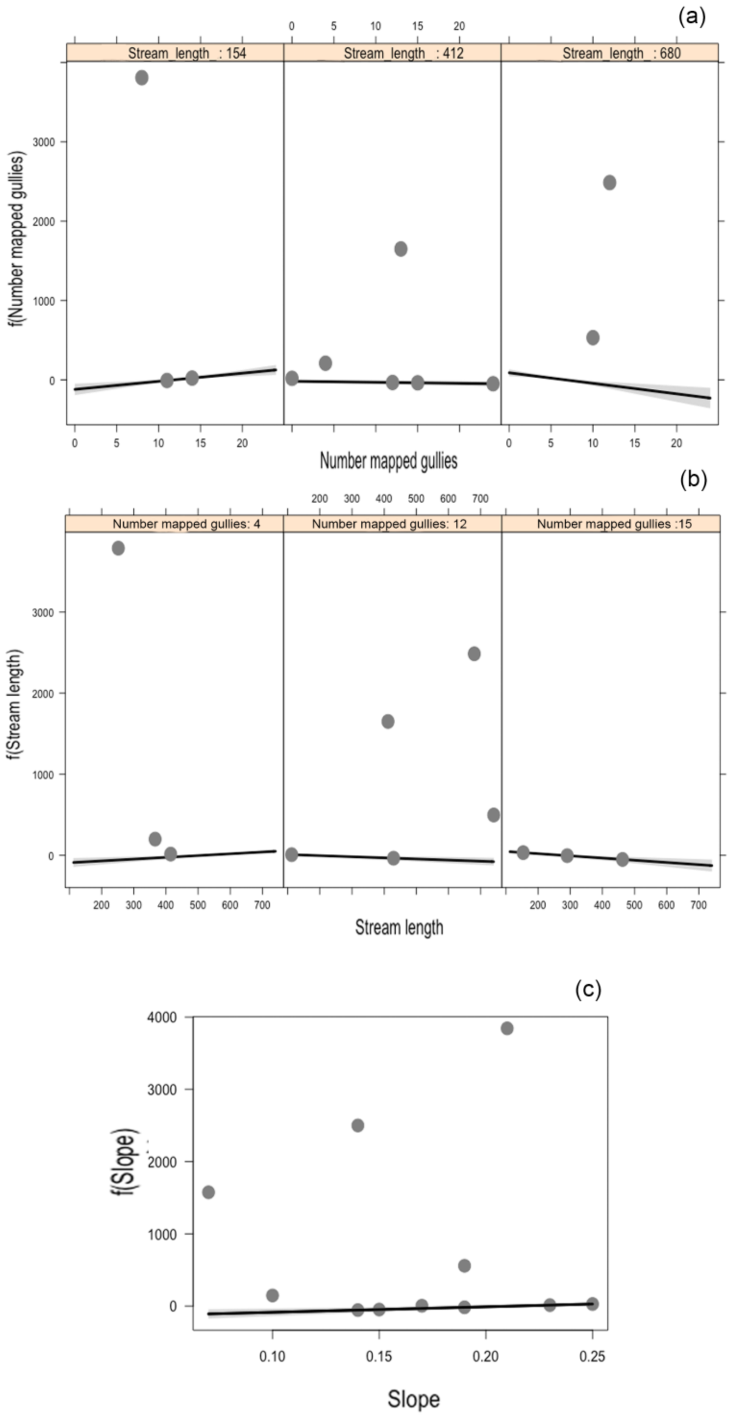

Figure 2.15. Fits for the generalized linear model on the average FSS load: average FSS load = -311 +17 * Number mapped gullies + 0.4 * Stream length + 762 * Slope -0.04 * (Number mapped gullies* Stream length). (a) Cross-sectional plots depicting the interaction between number of mapped gullies on the x axis and stream length. (b) Cross-sectional plots depicting the interaction between stream length on the x axis and number of mapped gullies. (c) Plot depicting the relationship between response variable and slope. All models are plotted on the scale of the linear predictor (link function: log) and the confidence interval is in grey

Supplemental material

Table S2.1. Statistics of the best-fitting generalized linear models on the R-B flashiness index, direct runoff coefficient and FSS load

Model: average R-B flashiness index = -1.6 – 1.3*Elongation + 0.01*% altered cover + 6.5*Terrain slope

Deviance Residuals:					
	Min	1Q	Median	3Q	Max
	-0.08705	-0.02867	-0.01691	0.04302	0.0853
Coefficients:		Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)		-1.60196	0.41708	-3.841	0.00637
Elongation		-1.26814	0.42312	-2.997	0.02002
% Altered cover		0.01001	0.0029	3.452	0.01066
Slope		6.48262	1.25451	5.167	0.0013
Null deviance		0.165026	on 10 df		
Residual deviance		0.028797	on 7 df		
AIC:		-24.182			
McFadden's pseudo R^2		0.826			

Model: average R-B flashiness index = -3.0 + 0.93*Elongation + 0.04*% altered cover + 6.2*Terrain slope -0.04 (Elongation*% altered cover)

Deviance Residuals:					
	Min	1Q	Median	3Q	Max
	-0.079694	-0.008891	-0.002987	0.020079	0.05155
Coefficients:		Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)		-3.044005	0.584477	-5.208	0.002
Elongation		0.933432	0.796819	1.171	0.28583
% Altered cover		0.036157	0.009407	3.844	0.00852
Slope		6.161749	0.893905	6.893	0.00046
Elongation:% Altered cover		-0.038826	0.013495	-2.877	0.02816
Null deviance		0.165026	on 10 df		
Residual deviance		0.012486	on 6 df		
AIC:		-31.375			
McFadden's pseudo R^2		0.924			

Table S2.1. continue

Model: average direct runoff coefficient = 1.6 +2.05 *10-5 * Cumulative gully FAC					
Deviance Residuals:					
	Min	1Q	Median	3Q	Max
	-3.308	-2.374	-1.507	1.977	6.712
Coefficients:		Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)		1.60E+00	2.31E-01	6.901	7.06E-05
Cumulative gullies FAC		2.04E-05	6.77E-06	3.012	0.0147
Null deviance		199.74	on 10 df		
Residual deviance		108.02	on 9 df		
AIC:		62.345			
McFadden's pseudo R^2		0.459			
Model: average FSS load = -16 +1.9 *10^-4 * total altered area - 0.03 * Stream length + 147 * Slope					
Deviance Residuals:					
	Min	1Q	Median	3Q	Max
	-8013.7	-4892.2	232.3	2119.8	25111.2
Coefficients:		Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)		-1.60E+01	1.28E+01	-1.258	0.2487
Total altered area		1.88E-04	1.04E-04	1.817	0.1121
Stream_length		-3.02E-02	1.26E-02	-2.391	0.0481
Slope		1.47E+02	6.63E+01	2.214	0.0624
Null deviance		7812753003	on 10 df		
Residual deviance		1037017326	on 7 df		
AIC:		243.2			
McFadden's pseudo R^2		0.867			

Table S 2.1. continue

Model: average FSS load = -1.4 +0.3 * Number mapped gullies - 0.02 * Stream length + 57 * Slope					
Deviance Residuals:					
	Min	1Q	Median	3Q	Max
	-10729.4	-2168.8	573.1	1878.3	27335.2
Coefficients:		Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)		-1.389489	4.852549	-0.286	0.7829
Number of mapped gullies		0.342155	0.149111	2.295	0.0554
Stream_length		-0.016289	0.005105	-3.19	0.0153
Slope		57.180454	20.214572	2.829	0.0255
Null deviance		7812753003	on 10 df		
Residual deviance		940584054	on 7 df		
AIC:		242.12			
McFadden's pseudo R^2		0.880			
Model: average FSS load = -311 +17 * Number mapped gullies + 0.4 * Stream length + 762 * Slope -0.04 * (Number mapped gullies* Stream length)					
Deviance Residuals:					
	Min	1Q	Median	3Q	Max
	-0.2	0	37.1	1129.7	3846
Coefficients:		Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)		-310.98655	88.73369	-3.505	0.0128
Number of mapped gullies		17.08467	4.71616	3.623	0.0111
Stream_length		0.39833	0.11092	3.591	0.0115
Slope		762.69099	208.4944	3.658	0.0106
Num. mapped gullies:Stream_length		-0.04465	0.01231	-3.626	0.011
Null deviance		7812753003	on 10 df		
Residual deviance		24544839	on 6 df		
AIC:		204.02			
McFadden's pseudo R^2		0.997			

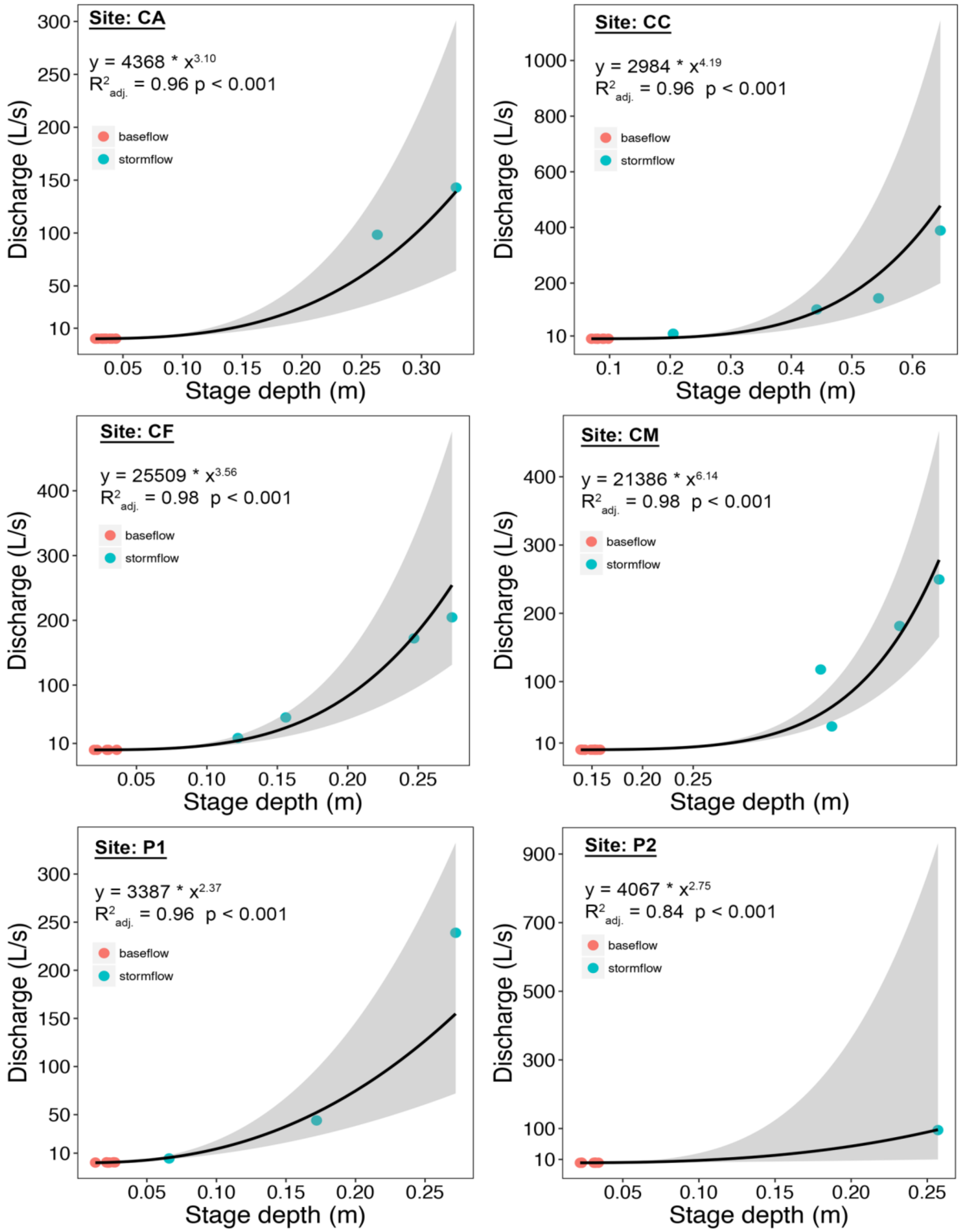

Figure S2.1. Rating curve and associated statistics for each study stream. Instantaneous baseflow measured in the field are in red and estimated peak flow in green. The grey area is the confidence interval around the smooth at the level of 0.95

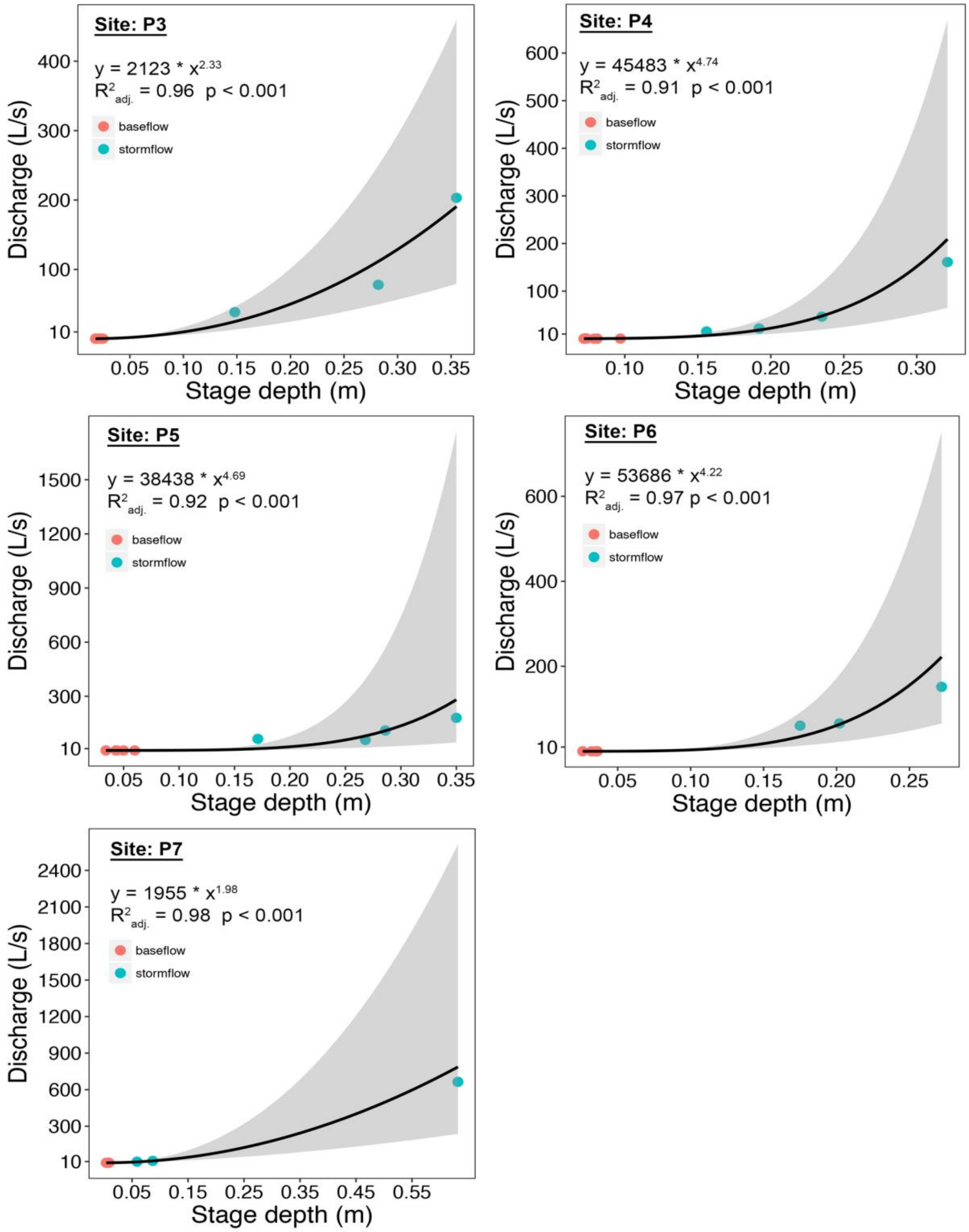

Figure S2.1. continue

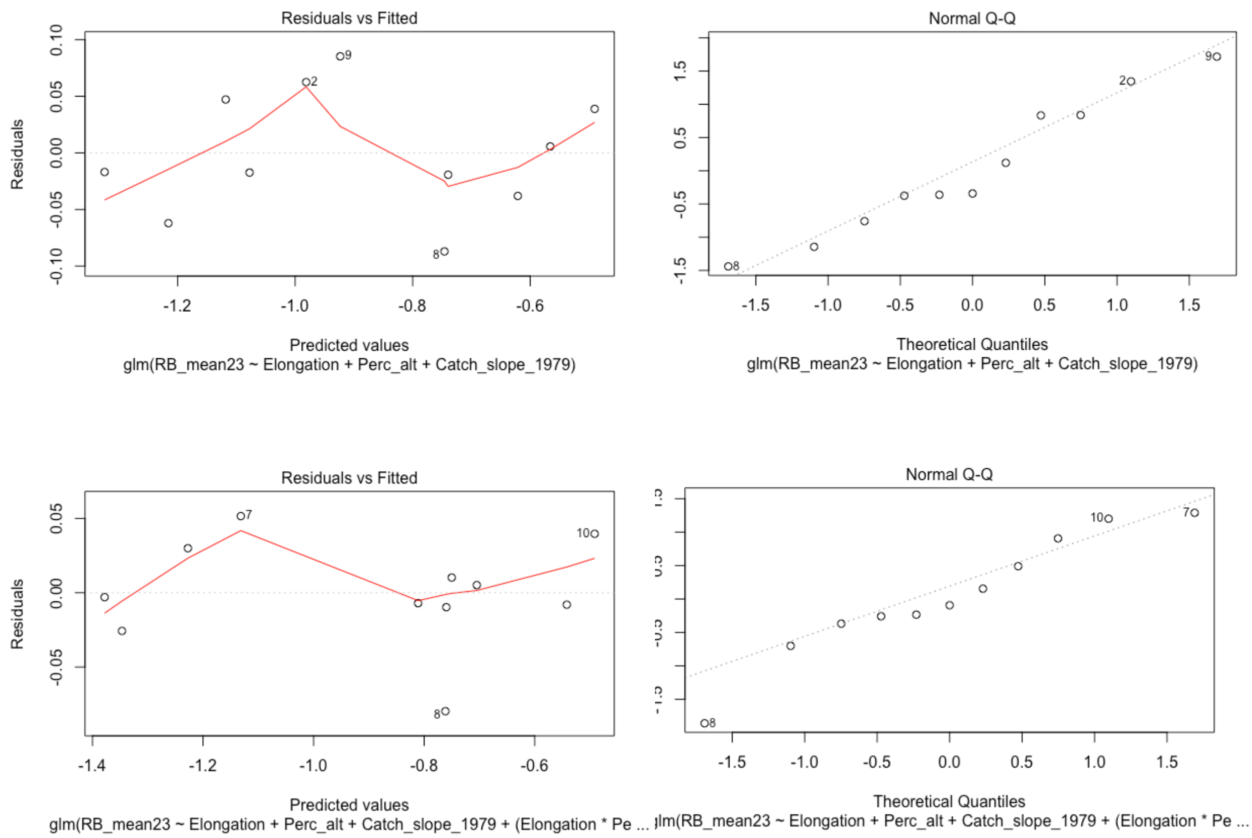

Figure S.2.2. Diagnostic plots: (left) residuals versus fitted and (right) normal Q-Q for the two best fitting models related to the R-B flashiness index. (top) Model: average R-B flashiness index = -1.6 – 1.3*Elongation + 0.01*% altered cover + 6.5*Terrain slope. (bottom) Model: average R-B flashiness index = -3.0 + 0.93*Elongation + 0.04*% altered cover + 6.2*Terrain slope -0.04 (Elongation*% altered cover)

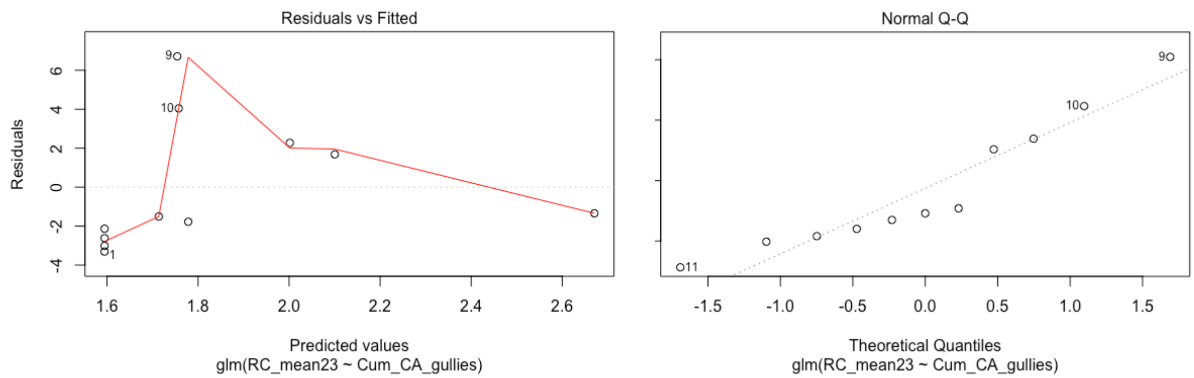

Figure S2.3. Diagnostic plots: (left) residuals versus fitted and (right) normal Q-Q for the two best fitting models related to the direct runoff coefficient. Model: average direct runoff coefficient = 1.6 +2.05 $*10^{-5}$ * Cumulative gully FAC

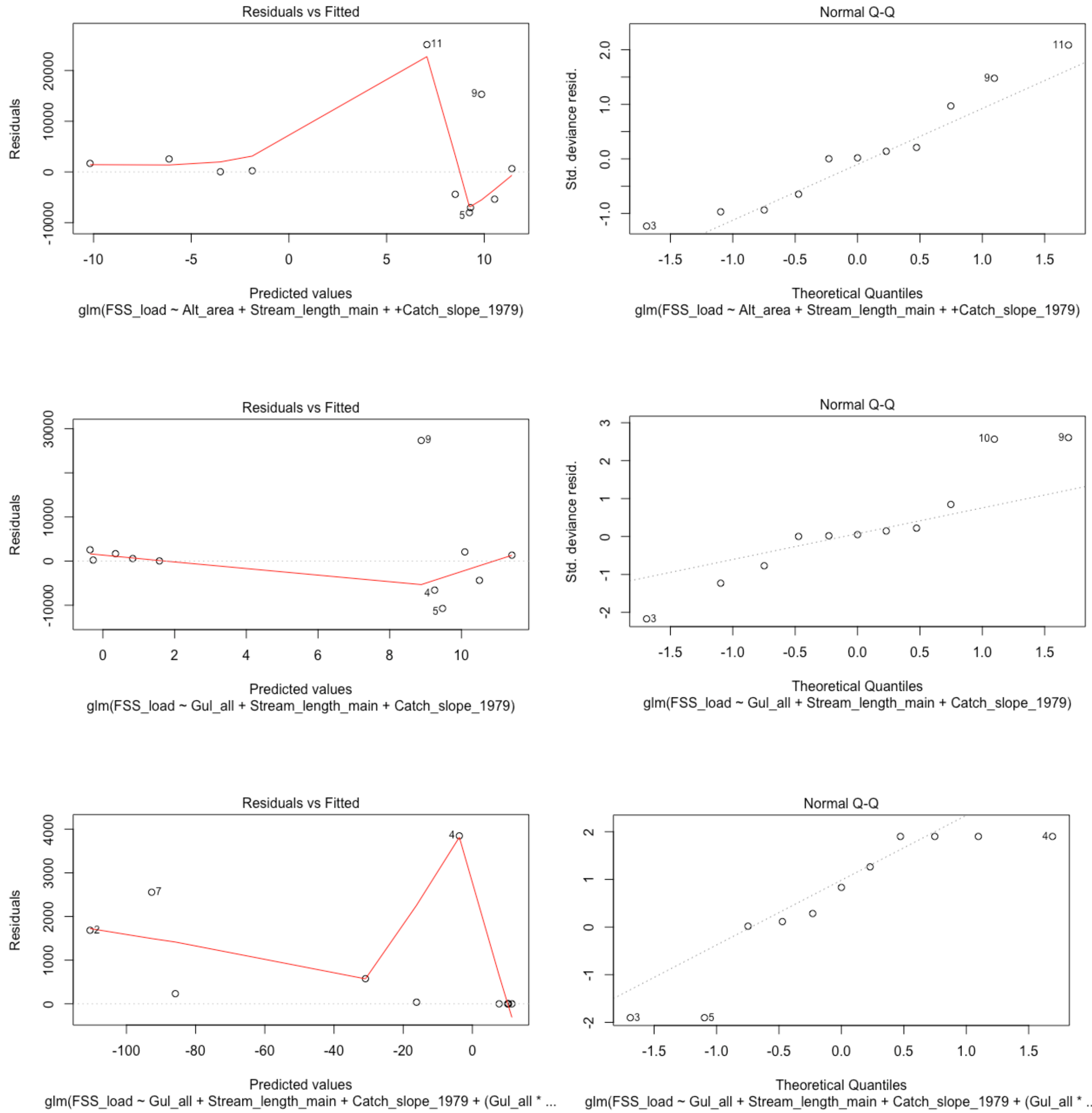

Figure S2.4 Diagnostic plots: (left) residuals versus fitted and (right) normal Q-Q for the two best fitting models related to the FSS load. (top) Model: average FSS load = -16 +1.9 *10^{-4} * total altered area - 0.03 * Stream length + 147 * Slope. (center) Model: average FSS load = -1.4 +0.3 * Number mapped gullies - 0.02 * Stream length + 57 * Slope. (bottom) Model: average FSS load = -311 +17 * Number mapped gullies + 0.4 * Stream length + 762 * Slope -0.04 * (Number mapped gullies* Stream length)

Chapter 3: Impact of long-term sugarcane agriculture and forest cover on N and P levels of headwater streams in Brazil

Introduction

Nitrogen (N) and phosphorus (P) leaching from agricultural land is known to decrease the water quality of riverine ecosystems and to increase export to coastal waters (Carpenter et al. 1998, OECD 2001, Scanlon et al. 2007). This is particularly true under agricultural intensification where production per unit of land is increased dramatically through industrial mechanization, agrochemicals and high-yielding crop varieties (Matson et al. 1997). The vast majority of research on the ecological impacts of agriculture has been undertaken in developed countries, particularly the U.S., Australia, and Europe. However, during the past few decades and into the future, agricultural expansion and intensification are expected to increase to meet the growing global food demand, and most of this intensification will happen in developing countries in tropical regions (Alexandratos and Bruinsma 2012). How this will influence water quality in tropical countries with diverse edaphoclimatic characteristics is not fully known because intensive agriculture in these regions remains understudied, especially in terms of the impacts on small headwater streams.

Headwater streams influence the supply, transport, and fate of water and solutes in watersheds (Vannote et al. 1980, Alexander et al. 2007). Despite their relatively small dimensions, they account for a large percentage of river drainage networks (Leopold et al. 1964) and play a disproportional role in collecting water and nutrients exported from adjacent terrestrial ecosystems (Bormann et al. 1968, Alexander et al. 2000, Peterson et al. 2001). Small headwater streams respond rapidly to land-use change (Likens et al. 1970, Webster et al. 1992), and studies comparing stream nutrient levels across gradients of land use has contributed substantially to understanding the detrimental effects of agriculture on water quality (e.g., Dillon and Kirchner 1975, Jordan et al. 1997b) as well as practices to potentially minimize the impacts (e.g., Johnson et al. 1997). Most of the research on headwater streams and land-use has been conducted in temperate regions, where researchers have shown that both contemporary and past agricultural practices can affect stream nutrient dynamics. Over time, as more N and P soil fertilizers are added than are removed by crops (Boyer et al. 2002, MacDonald et al. 2011), a surplus of nutrients accumulates in the soils and can be transported to both ground and surface waters (Vitousek et al. 1997, Howarth et al. 2002, Sharpley et al. 2013). Instream nutrient concentrations are a legacy of past catchment agricultural uses (Sharpley et al. 2013, Tesoriero et al. 2013), suggesting that the longer an area has been under cultivation and fertilization, the greater and more durable the impacts on water quality may be. Studies have shown that as the area of intensive agriculture and its longevity increase within a watershed, instream N and P concentrations increase (Omernik 1977, Johnson et al. 1997, Liu et al. 2000), contributing to degraded water quality, nutrient export to downstream systems (Jordan et al. 1997a) and, often, eventual eutrophication of many aquatic ecosystems (Bennett et al. 2001, Rabalais et al. 2009).

In contrast to the extensive research in temperate regions, information about the impacts of agricultural intensification and expansion on small headwater streams in tropical developing countries is limited. This is not only due to economic limitations but because the diversity of biomes, geomorphic characteristics and land use histories make the study of agricultural impacts in these regions difficult. Brazil, in particular, is highly heterogeneous with regard to agricultural development and practices, land use history and landscape characteristics. Most studies to date in Brazil have focused on regions of recent agricultural development (~20 years), particularly within the Amazon and Cerrado biomes in Central Brazil even though most long-term agricultural development (> 100 years) and intensification have been within the Atlantic Forest biome in the southeastern and southern regions of the country. What studies in Central Brazil show, however, contradicts what has been consistently demonstrated in temperate regions. Namely, despite intensive agriculture, nutrient concentrations in streams draining crop fields are low (Figueiredo et al. 2010, Silva et al. 2011, Neill et al. 2013). For example, research with soybean agriculture in the southern Amazon showed that streams draining soybean fields do not necessarily have higher concentrations of nitrate and phosphate than streams draining pristine Amazon forest (Riskin et al. 2017). Because we do not know if this pattern holds true for regions in Brazil with a long history of agricultural intensification, this study focuses on the potential impacts to Brazilian streams in regions with sugarcane production which is one of the oldest forms of agriculture the country; this production is cultivated primarily in the southeastern region of the country (Dean 1976, IBGE 2006a).

Sugarcane agriculture and Atlantic forest streams

Domestic and international demand for biofuels has led to unprecedented intensification and expansion of sugarcane production particularly in São Paulo state since the 1970’s (Filoso et al. 2015). Knowledge on how long-term sugarcane agriculture impacts nutrient levels (concentrations and exports) in small headwater streams is virtually nonexistent; most research addressing the stream-related impacts from sugarcane have not focused specifically on nutrient levels (Ferreira et al. 2012, Schiesari and Correa 2016). The research is usually focused on catchments with multiple land uses (Ometto et al. 2000) and are located in the Cerrado region (Silva et al. 2007). There are several reasons why findings from other biomes may not be transferable to areas in the state of São Paulo where most sugarcane is cultivated. First, even prior to intensive sugarcane agriculture, the southeastern region of Brazil was already degraded from centuries of deforestation (Dean 1995) as well as small sugarcane plantations and farm production of coffee or livestock since the 17th century (Dean 1976). Second, sugarcane agricultural practices typically involve the use of large amounts of N and P fertilizers for longer periods of time than for other croplands in Brazil (IBGE 2014a, b), and fertilizer application on sugarcane crops has been increasing in recent years (Martinelli and Filoso 2008). Third, other agricultural practices including, for example, the amount of tilling, the harvesting method or the use of fallowing differ among different types of intensive agricultures. Finally, the slopes of the landscapes where most sugarcane is cultivated in Brazil are steeper than the flat terrain where grain production occurs in Central Brazil, and steeper terrain of sugarcane areas may favor rapid delivery of materials from upland sources to streams (Castillo 2010). For all of these reasons, the research findings from agricultural streams in the Central Brazil particularly from the Amazon and Cerrado biomes may not be easily extrapolated to other regions of Brazil.

The most recent intensification and expansion of sugarcane to meet demand for biofuels have occurred since 2000 (Filoso et al. 2015). This is a time when the Forest

Code of 1965 was being revised (Tollefson 2011, Brasil 2012, Soares-Filho et al. 2014). The Code has historically required conservation and restoration of forests on farmlands, including along waterways since 1934 (Brasil 1934, Brasil 1965, Brasil 2012), and an expectation of maintenance and/or recovery of forest cover may have contributed to an assumption that water resources would be protected. This assumption is not unreasonable given the large number of studies in temperate regions showing that forests have high capacity for nutrient capture via several processes including deposition, adsorption, infiltration and nutrient processing (Dosskey et al. 2010, Vidon et al. 2010, Roberts et al. 2012). The water protective benefits of riparian forests in particular have been emphasized because they are located in the transition areas between agricultural uplands and streams (Lowrance et al. 1984, Peterjohn and Correll 1984). The presumption that the Brazilian Forest Code may protect streams from agricultural diffuse pollution is also compelling because studies in temperate regions have shown that those processes can be recovered with forest restoration (Switzer et al. 1979, Maloney et al. 2008, Piche and Kelting 2015), and public-private partnerships were planned to restore 13 million hectares of the Atlantic forest (Calmon et al. 2011)—the predominant natural vegetation of the southeastern region of Brazil. However, scientific information on the ability of Atlantic forests to protect water quality under the Forest Code is largely absent. Even in pristine regions in Brazil, few studies have evaluated the role of forests in reducing the inputs of inorganic nutrients from uplands (McClain et al. 1994, McClain et al. 1997), and the extent to which the Forest Code has actually resulted in preservation or restoration of forests has not been evaluated to date.

This project focuses on the State of São Paulo where there has been a long history of sugarcane production and for which land cover data are available at multiple time periods over the last ~ 50 years. The overall goal was to ask if land use history in this region is important in explaining contemporary stream nutrient concentrations. Use of inorganic fertilizers in sugarcane agriculture dates back to at least the 1950's (IBGE 2006a,b, ANDA 2015), and the expectation was that impacts to stream water quality could be significant unless forested buffers provided a protective effect. The specific objectives of this study were to: 1) quantify the contemporary concentrations of nutrients in streams draining catchments that have a long history of sugarcane agriculture; 2) determine if variability in these concentrations can be explained by the amount of sugarcane and forested land in the catchments over the prior 50 years; and 3) place the results of objectives 2 and 3 in context by asking how the nutrient levels compare to levels found throughout Brazil where headwater catchments are impacted by newer and other forms of intensive agriculture or are in natural vegetation.

Study area

The study focused on 11 first to second order catchments draining to the Barro Frio stream (Figure 3.1a, Table 3.1). These catchments are located ~15 km from Piracicaba city, São Paulo, which is a traditional and still the most important sugarcane production region in Brazil (IBGE 2006a). Before agriculture was introduced to the region in the 18th century (Dean 1976, Victor et al. 2005), the study catchments' land cover was deciduous and semi-deciduous forests, savanna, and swamps (Rodrigues

1999). During the study period (2013-2014), the only two land cover types in the catchments were sugarcane and secondary native forest.

The catchments lie at 500–600 m elevation (Figure 3.1b) and are representative of the sugarcane cultivation region of Sao Paulo state with regard to soil type and topography. The underlying geology is sedimentary sequences composed of arenitic, silty, argillic and conglomeratic materials of meso-palaeozoic age that were deposited in large syneclise-type sedimentary basins (CPRM 2004). More specifically, the catchments on the North side of the mainstem (CA, CF, CM, P5, P6 and P7) are characterized by silicic-pelito-shale material with low dissected hills, and those on the South side (CC, P1, P2, P3 and P4) are silico-argillic sediments irregularly intercalated with fine sandy-calcareous layers with broad smooth hills (CPRM 2010).

The dominant soil type is ultisol (Figure 3.1c) with low cation exchange capacity. There is a textural B horizon immediately below the A or E horizon described on official soil maps (1:500,000, Oliveira 1989). Soil depth to bedrock is variable, and low permeability clay layers at shallow depths (~ 50 cm) are common. Water percolation in Brazilian ultisol soils varies from good to poor (EMBRAPA 2013).

The study channels were first- and second-order streams and severely incised, according to the definition of Horton (1945) and Strahler (1957). Climate in the study region is classified as equatorial winter dry, Aw (Köppen-Geiger classification, Rubel and Kottek 2010), with average temperatures varying from 20°C during the coolest dry months (April – September) and 24°C during the warmest wet months (October – March). Average annual rainfall in the dry season is 230 mm, and in the wet season it is 1000 mm (Figure 3.2, Sentelhas et al. 1999).

Management of sugarcane agriculture varies significantly in Brazil, depending on the region and property size. However, management was quite similar in the study catchments in recent years (personal communications with farmers). It included first leveling the terrain and forming contour terraces usually in the dry season (land preparation) and then planting sugarcane using stalks. The contour terraces are composed of a trench followed by a downslope ridge; terraces run perpendicular to the slope and follow the topographic contour lines in order to reduce the volume and velocity of excess runoff water generated within sugarcane fields. Land preparation and planting using stalks is usually repeated every 3 to 5 years in the study region. During the study period, land preparation did not occur as farmers were in the ratoon cane crop season (growing crop from stubble of the previous crop).

Information on the use agrochemicals was obtained from personal communication with the farmers. Limestone is applied regularly to control soil acidity (~2 ton ha^{-1}); the last lime application before the beginning of this study was approximately in 2012. Fertilizers are applied yearly after sugarcane has been cultivated or planted and varied depending on the type of cane that is being cultivated. In recent years, including the period of this study, when sugarcane plants are cultivated (once every ~5 years), ~60 kg N ha^{-1} and ~90 kg P ha^{-1} of mineral fertilizers are applied. During the years when ratoon cane is being cultivated (~4 consecutive years after sugarcane plant was cultivated), ~100 kg N ha^{-1} and ~45 kg P ha^{-1} are applied. Nitrogen fertilizers have also been applied after the first development stage of sugarcane is complete at rates of ~75 kg N ha^{-1}. In total, the yearly N fertilizer application rate has varied from ~135 to 175 kg N ha^{-1}. In the study area, an organic residue from sugar and ethanol production, filter cake, has also been applied as fertilizer. Filter cake is a source of several nutrients, particularly P, and up to 100 kg of cake per ha can be applied (Vitti et al. 2005), but the specific rate applied in the study catchments is unknown. During the period between June and September of 2013, sugarcane was harvested manually in all catchments, and transported to mills via trucks on unpaved dirt roads; plowing between plant roots occurs after harvesting.

The 11 study catchments have similar edaphoclimatic and landscape characteristics, as well as comparable management practices. The goal was to control as many factors as possible other than land cover that may contribute to the variability in baseflow water quality data including: weather conditions, terrain topography, soil type, catchment size, and agricultural strategies.

Methods

Discharge

Baseflow was defined to be at least 72-hours after a rainfall event. Baseflow discharge (Q_B) varied temporally in the study streams and between catchments but the small size (20-50 cm across) and shallow stream depths (0.5-2.4 cm, Table 3.1) limited the use of flow probes throughout the study. Further, the sampling period included the third driest summer in a 97-year period in the region (ESALQ 2014), within which streams were dried up during nearly all of February 2014 (Figure 3.2). When sufficient water was present, instantaneous discharge could be estimated for eight catchments (CF, P1, P2, P3, P4, P5, P6 and P7) using the velocity-area method with a floating device (WMO, 2010); this was possible 4 to 8 times depending on the stream. At the remaining three catchments (CA, CC and CM), H or V-notch flumes were installed in the streams so discharge was estimated (n = 11 to 13 dates) using the volumetric method (WMO 2010). For logistical reasons, discharge was not measured on the same days water was sampled. Additional information on discharge patterns across study streams can be found in chapter 2 of this dissertation.

Water quality

Concentrations of N, P and DOC were measured in the study streams twice per month during normal flow conditions from June 29th 2013 to April 7th 2014 and always at least 72-hours after any rainfall. The aforementioned drought also prevented water sampling from April 2014 to July 2014 when most study streams were completely dried out except for short periods during storms; samples were not collected during storm events, which limits this study to groundwater sources of N and P.

Water samples were collected manually with a syringe without disturbing the streambed. A known volume of stream water (~500 mL) was filtered through a Whatman 0.7-µm GF/F filter in the field and water samples stored in HDPE Nalgene bottles for later quantification of dissolved N as nitrate (NO_3^-), ammonium (NH_4^+), and total dissolved nitrogen (TDN), and, for dissolved P as orthophosphate (SRP) and total dissolved phosphorus (TDP). For each sample, the 0.7-µm GF/F filter containing the particulate portion was folded in half and wrapped in aluminum foil to further quantify particulate P (PP). An additional known volume of stream water (~500 mL) was filtered through a combusted (30 min at 500^{o} C) pre-weighed Whatman quartz filter, and the filter was retained as described above to quantify particulate N (PN). Additional stream water was filtered through pre-combusted GF/F filters into pre-combusted amber glass vials to quantify DOC. All samples and filters were kept on ice until transport to the laboratory where they were frozen until analysis. Field data were also collected on electrical conductivity corrected to 25°C (E.C.), dissolved oxygen (D.O.), pH and temperature using an YSI 600 OMS sonde during each water sampling day.

Nitrate and NH_4^+ were determined via flow injection analysis (FIASTAR 5000); NO_3^- was quantified using the Cadmium-copper reduction method (USEPA 1979b, FOSS 2003b) and NH_4^+ via gaseous diffusion in alkaline pH followed by colorimetric detection (USEPA 1979a, FOSS 2003a). Total dissolved N was quantified via N combustion to nitrogen monoxide followed by chemiluminescence detection (TOC-V CSH/CSN Shimadzu). Colorimetry was used to quantify SRP via the ascorbic acid method (AOAC 1973) and TDP via potassium persulfate digestion followed by colorimetry (Spectrometer - SP 2000 UV - BEL2000UV) using the ascorbic acid method (AOAC 1973). The concentrations of PP were obtained using 24-h HCl extraction followed by colorimetric detection using the ascorbic acid method. PN was determined via elemental analysis (USEPA 1997) using a Carlo Erba elemental analyzer linked with a Finnigan Delta Plus mass spectrometer. Dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) were calculated as the difference between TDN and dissolved inorganic nitrogen (DIN, i.e., NO_3^- plus NH_4^+), and TDP and SRP, respectively. Total nitrogen (TN) and total phosphorus (TP) were determined as the sum of the total dissolved portion plus the particulate portion. Dissolved organic carbon concentrations were determined using high temperature combustion and infrared detection (TOC-V CSH/CSN Total Organic Carbon Analyser, Shimadzu). Analyses were periodically checked against matrix blanks and control standards.

Because nutrient data during storm flows were not collected, nutrient concentrations (rather than exports) are the focus of this study and were used to explore the relationship between land cover and impacts to streams. Baseflow concentrations were considered adequate because they presumably reflect long-term agricultural influences on groundwater, given the potential for accumulation of N in the groundwater (Wayland et al. 2002) and chronic releases of P from "legacy P" stores (Jarvie et al. 2013). Further, concentration data are widely used in studies on stream water quality (Omernik 1977, Hunsaker and Levine 1995, Johnson et al. 1997, Liu et al. 2000, Li et al. 2008, Wang et al. 2014), particularly when focused on impacts to higher trophic levels (EPA 2013) or more generally on ecological integrity of stream ecosystems (Osborne and Wiley 1988).

Stream discharge can affect the relationship between land cover patterns and nutrient concentrations. Although discharge in a stream channel increases as drainage basin area increases (Dunne and Leopold 1978), the small and comparable sizes of the 11 stream catchments (3-16 ha, Table 3.1) should have reduced such effects. However, for the third study objective in which concentration data from other larger catchments (some as large as 3600 ha) in Brazil were compared to concentrations from the present study sites, exports per catchment (yields) during baseflows for the 11 sites were estimated (see alter).

Land cover

Analysis of land cover over a 51-year interval involved two major steps. First, I determined land cover categories and, second, for regions within the forest cover category, I identified forest cover stages (Figure 3.3). Land cover data were obtained by producing a multi-temporal GIS land cover database using ArcMAP 9.3.1 (ESRI 2009). Orthophotographs were digitized manually and georeferenced to the datum UTM Córrego Alegre to create five land cover maps. Panchromatic, black-and-white, aerial, orthorectified photographs of the study area were available for 1962 (1:25000 scale), 1978 (1:35000 scale) (IGC 1962, 1978) and 1995 (1:25000); more recent orthorectified images were available for 2000 (1:25000) and 2011 (1-m resolution, São Paulo 2010) that contained three spectral bands (red, green, and blue). I used manual/visual interpretation techniques of the aerial imagery data in which the image was viewed on ArcMAP and polygons were drawn around areas identified as a particular land cover type (Horning et al. 2010a). Following the method described by the previous authors, data on vegetation types based on field surveys (completed in July and August 2013) were related with tone, texture, shape and pattern of aerial imagery to identify the different land cover classes.

Image interpretation was carried out based on five pre-defined land cover classes: (1) *Sugarcane cover* was the class for areas of uniform height and pattern or bare fields with geometric shapes with evidence of plowing. For images after 1978, evidence of contour terracing was also used as an indication of sugarcane cover. (2) *Forest cover* was the class for areas characterized by a pattern of variably structured forest types that represented different stages of forest succession. Five classes were included: (a) open areas with grass vegetation, (b) herbaceous vegetation, (c) grassy shrub vegetation, (d) woody shrub vegetation or scattered trees; and (e) arboreal vegetation characterized by closed forest with many small trees, though gaps maybe be present or continuous canopy of larger trees with crowns readily discernable; (3) *Pasture cover* was the class for areas mapped on the contour map of 1979; (4) *Cattail/grasses*; and (5) *Bare soil*. Photo interpretation was carried out backwards in time to ensure accurate cover classification over time. It was difficult to resolve early stages of forest succession (grass and herbaceous vegetation types) from other types of vegetative cover in the 1962 images, particularly in the areas surrounding streams, because very few forest fragments were present in that year and they most consisted of forest remnants with sparse trees. If the classification of the cover in a particular area was unclear but coincided with an area that was classified as forest in the 1978, 1995, 2000 and 2011 images, I assumed that area was grass and herbaceous vegetation in 1962. Given scarce information about forest age in regenerated patches within the Atlantic forest in general (Ribeiro et al. 2009, Teixeira et al. 2009), there was no way to verify my assumption however.

The focus of this study was on the potential impacts that a long history of sugarcane agriculture may have on stream nutrients. However, the impacts may have been buffered if over time, riparian forests were less disturbed (i.e., had less canopy openness, greater above-ground living biomass and higher percentage forest cover). Such areas can provide better nutrient "filtering" capacity than disturbed forests (Souza et al. 2013). Thus, I sought to distinguish the age of forest patches in the land cover images to identify old forest cover (> 30 yr old) that prior studies in the Atlantic Forest region have shown to be characterized by advanced arboreal species with better structure (e.g., greater diameter at breast height, total mean height, basal area and density) compared to younger fragments (e.g., Siminski et al. 2013). The classification into variable structured forest types as described above allowed distinguishing the age of forest patches in the land cover images. The forest fragments were thus classified into four successional stages based on their ages (stage I: 0 – 5 years, stage II: 5 – 15 years, stage III: 15 – 30 years, and stage IV: ≥ 30) using an iterative approach in which I intersected the aerial photos from the five time steps and compared forest cover in fragments across all years (Horning et al. 2010b). Land cover results are presented in terms of sugarcane cover and the cover of different stages of forest succession given the focus of this research on the history of land cover. Figure 3.3 provides a summary of the land cover classification procedure used for this research.

To quantify land cover, I generated the following metrics: catchment sugarcane cover (%), and catchment forest cover (%) at the four stages for each of the five time steps of land cover data. The data on catchment area needed to calculate the proportion of each land cover in a particular catchment was obtained by manual interpretation of topographic maps (arguably the most accurate method). I used the contour map describing the topography for 1979 (IGC 1979), the oldest official source of elevation data readily available for the study region that matched the second oldest aerial photo. This map was considered appropriate given the multi-temporal aspect of the study.

Water quality data in other parts of Brazil

For the third objective of this study, a literature survey to gather data on N and P concentrations in Brazilian streams was conducted in June 2016 using the Web of Science (ISI) and SciELO (journal collections from 14 Portuguese and Spanish-speaking countries). The search process used the three key words: *stream* AND *nutrient concentration* AND *Brazil* for each search engine. The search with the ISI engine was also complemented with the key words *stream* and *nutrient* and *Brazil*, while specifying the author field to include researcher names known to have worked with stream ecosystems in Brazil including: Michael McClain, Lilian Casatti, Luiz A. Martinelli, John Melack, Timothy Moulton, Christopher Neill, José G. Tundisi, and Michael Williams. Additional articles that met the criteria and did not show up in the search but were in the author's personal library were also included.

A subset of the papers with data on instream N and P concentrations were used if they met all of the following requirements: 1) described the land use of the study catchment sufficiently to determine the predominant vegetation cover as either forest or agriculture; 2) were focused on headwater streams (1^{st} to 3^{rd} order) according to what was described in the papers (if stream order was not provided but discharge data were and they were comparable to the Atlantic Forest streams under study, the research was included); 3) a stream draining biomes where agriculture expansion and intensification have concentrated in recent decades in Brazil, i.e., Atlantic and Amazon forests and Cerrado; and, 4) climate was tropical or subtropical. Data on N and P concentrations were directly extracted from the papers if presented in tables. If data were only presented in a figure, a web-base interface was used (http://arohatgi.info/WebPlotDigitizer/app/) that allows data recovery from figures. In some cases data were available on individual streams while in other studies data were reported as means for several streams.

Two datasets were generated based on the literature survey. One described nutrient concentrations in terms of land cover categories (agriculture, natural vegetation) and biomes (Atlantic Forest, Cerrado, Amazon Forest). Studies in this dataset provided nutrient data predominately on NO_3^- and SRP concentrations; only a few reported both TN and TP concentrations and yields or reported discharge data along with concentrations that allowed yields to be calculated. Since the number of concentration and yield observations in the larger dataset was somewhat limited for TN and TP, a second dataset including data only from Cunha et al. (2011) was used because they reported TN and TP concentration baselines for rivers and streams in the State of São Paulo which is more representative of my study region; however, they did not provide information on nutrient yields. Nutrient data units were converted to obtain concentrations in the units of mg L^{-1} of N-NO_3^- and SRP as needed.

Nutrient yields were estimated to better compare the nutrient levels found in this study with those of other streams in Brazil because headwater streams drained catchments with variable sizes. Nutrient yields were expressed as kg N-P ha^{-1} yr^{-1} and only represent baseflow yields. For each study stream, annual nutrient yields were estimated by multiplying average concentrations (mg L^{-1}) of a particular nutrient (i.e., nitrate-N, TN, SRP and TP) by average discharge (L s^{-1}) and $3.15 * 10^7$, and dividing by catchment area (ha). Average discharge was calculated using instantaneous discharge data collected during normal flows as described in the Discharge section of this chapter. Most of the studies from the literature survey do not report annual nutrient yields, and thus yields for those studies were also estimated using the same method described above, when baseflow discharge information was available. Accordingly, the annual nutrient yields calculated here is a rough estimate of nutrient exports for general comparison purpose only.

Data analyses

The RStudio softwater version 1.0.136 (RStudio, Inc) implemented with R software version 3.3.2 (R Core Team 2016) was used for all statistical analyses in this research. Descriptive statistics were used to represent the central tendency (mean and median) and variability (standard deviation, minimum and maximum) of the raw nutrient data at each study catchment (Objective 1).

Two statistical approaches were used to determine if contemporary (2013-2014) nutrient concentrations from catchments are statistically related to the amount (%) and type of historic land cover. For both approaches, the focus is on the oldest forest fragments and on concentrations of NO_3^-, SRP, TN and TP because these are the most detrimental nutrient forms for overall stream trophic status (Allan and Castillo 2007). In the first approach, I followed a common statistical procedure adopted by similar studies in which average nutrient concentrations are correlated with percent land cover (e.g., Osborne and Wiley 1988, Norton and Fisher 2000). The land cover data was represented on two time periods: the most recent (2013) and the oldest (1962). The land cover data included percent sugarcane cover, percent young forest cover (< 30 yr) and percent old forest cover (30 yr). Mean of nutrient concentrations for NO_3^-, TN, SRP and TP for each study stream was calculated using data from the entire period of study (June 2013 to April 2014); season did not generally affect nutrient concentrations ($p > 0.05$). Effect of seasonality was observed only at catchment CC regarding NO_3^- and TN concentrations and at CA in terms of SRP concentrations. The Pearson product-moment correlation was used for correlation analysis with transformed (ln(x+1)) nutrient data to reduce skewness.

The second approach was a more robust statistical strategy to take into consideration more information about the land cover dynamics over time; it required multiple steps. The focus was again on the forest cover that was at least 30 years old (Stage IV). The first step was to use a principal component analysis (PCA) to reduce the number of land cover variables and essentially cluster catchments into categories based on patterns in land cover over time because the amount of sugarcane and the amount of old forest cover in each catchment varied over the 50 year time period. Second, labeling catchments within the PCA biplot with respect to their median nutrient concentrations was used to explore whether median nutrient concentrations were related to historical land cover patterns in each catchment. Third, generalized estimating equations (GEE, Liang and Zeger 1986) were used to statistically test whether the nutrient patterns observed within the PCA biplot were significant.

The PCA was used to detect gradients of sugarcane cover extent, its persistence throughout the years, and patterns of old forest cover over time. Specifically, the observed correlation matrix used as input for the PCA included the percent sugarcane cover and percent old (> 30 yr) forest cover for each study catchment at each of the five land cover dates (1962, 1978, 1995, 2000 and 2011) i.e., 10 land cover variables (two land covers in each of the five time steps) for the 11 study catchments, totaling 110 observations. PCA was appropriate because it evaluates the similarities among objects (catchments) based on the variability of a set of variables (land cover metrics). Multicollinearity between variables is not a problem in PCA (Tabachnick and Fidell 2013). With the PCA, I was able to interpret the aggregate effect of land cover dynamics in terms of the persistence of sugarcane cover extent throughout a 51-year period concomitantly with the patterns of old forest cover over the same time period while arranging catchments based on their similarities within the PCA plot. Unrotated PCA components with eigenvalues larger than 1 explain a good proportion of the variance in the original data (Kaiser 1961) and thus were retained and interpreted using the matrix of unrotated factor loadings to draw conclusions about the gradient of sugarcane cover and old forest cover over time. A rotation technique of the PCA components was unnecessary because unrotated factor loadings was considered to show a clear pattern (Tabachnick and Fidell 2013) of land cover dynamics for the purpose of this research. If two or more catchments consistently varied in the same direction with respect to the mean for many land cover characteristics, they can be said to have similar land cover histories. PCA analysis was performed using the ‘PCA’ command of the ‘FactoMineR’ package (Husson et al. 2012) with scaled data.

To understand whether nutrient concentrations vary as a function of the persistence of sugarcane (over the 51 yr period) and patterns of old forest cover, the resulting PCA ordinations were evaluated with nutrient data (ter Braak 1995) by labeling sites within the PCA biplot with their median nutrient concentrations. The PCA approach used here follows previous studies (e.g., Martin et al. 2011) that used PCA to synthesize time-specific land cover data and related PCs with water chemistry to investigate temporal land cover change effects (i.e., legacy effects) on aquatic systems.

Generalized estimating equations were used to understand which principal component (PC), i.e., which land cover history pattern(s), explains more of the variability in nutrient data. The GEE is an adequate model when repeated measures exist (here, sampling dates) for the same study object (here, catchments) because it incorporates the dependence structure of the within-subject observations (Liang and Zeger 1986). GEE relaxes the distribution assumption and only requires the correct specification of the mean of the response variables and variance as well as specification of the link function (Hardin and Hilbe 2013). GEE may be preferred over a mixed effect model (another model that can deal with repeated measurements) when the overall treatment effect (here, land cover history, i.e., PCs) is of primary interest (Wang 2014). GEE models have been popularly applied in clinical trials and biomedical studies (Diggle et al. 2002) but are equally appropriate for the analysis of ecological data with repeated measurements (Zuur et al. 2009). Additionally, GEE models have been used in other studies evaluating associations of land use with stream water quality data (Walters et al. 2011). In this study, evaluations of the associations between a significant PC (i.e., with eigenvalues larger than 1) and nutrient concentrations were conducted for each nutrient (NO_3^-, SRP, TN and TP) separately. The GEE formulations used for each nutrient are as following:

Model 1: $Y_{is} = ß_0 + ß_1 \text{PC1}_i + ß_2 \text{PC2}_i + (ß_3 \text{PC1}_i * \text{PC2}_i) + e$

Model 2: $Y_{is} = ß_0 + ß_1 \text{PC1}_i + ß_2 \text{PC2}_i + e$

Model 3: $Y_{is} = ß_0 + ß_1 \text{PC2}_i + e$

Model 4: $Y_{is} = ß_0 + ß_1 \text{PC1}_i + e$

where Y_{is} is concentration data (dependent variable) in catchment *i* at time *s* (sampling day), $ß_0$ is the constant, $ß_{(1 \text{ or } 2)}$ is the coefficient of the principal component (PC1 or PC2 that are the explanatory variables) for catchment *i*, $ß_3$ is the coefficient of the interaction between PC1 and PC2 for catchment *i*, and *e* is the residuals. For GEE modeling, the type of association structure between different sampling days on the same object (catchment) must be specified. Here, I used the exchangeable correlation structure because I assumed that nutrient concentrations for a given catchment would be more similar, on average, than those from other catchments. To perform the GEE analyses, I used the 'geeglm' command of the 'Geepack' package (Højsgaard et al. 2016).

Independence model criterion (quasi-likelihood under the independence model information criterion, or QIC) for GEE (Pan 2001) was used to compare the performance among the four models for each nutrient variable. QIC is similar to other information criterion for model selection such as Akaike's information criterion (AIC) but takes into account that the GEE is a non-likelihood based estimation of parameters (Pan 2001). The model with the smallest QIC can be interpreted as the best-fitting model to the data. QIC analyses were performed using the 'model.sel' command of the 'MuMIn' package (Barton 2015).

To place the nutrient data from the 11 study catchments in the context of what is known for other Brazilian streams that drain intensive agriculture, I determined if nutrient levels (concentrations or yields) from the larger literature dataset were related to land use, biome and their interaction using Tukey HSD test. All Tukey HSD tests were weighted to control for the fact that some studies had data on multiple streams but only one value was possible to retrieve from the paper. To determine if average nutrient levels (concentrations and yields) found from the 11 study streams were significantly different from averages calculated from the larger literature dataset a two-way Welsh T test was used to test the hypothesis that there is a significant difference between the two means. To determine if nutrient levels from the study streams differed significantly from those reported by Cunha et al. (2011), a one-way Welsh T test was used to test the hypothesis that nutrient concentrations from this study were greater than those reported by Cunha et al. Average nutrient concentrations and yields were transformed (ln(x+1)) to reduce skewness as needed. All Tukey tests were performed using the 'TukeyHSD' command of the 'Stats' R package. I assumed significant results at $p < 0.10$ for all statistical analysis to minimize type II error (false negative) given the small sample size, i.e., low number of study catchments.

Results

Water quality

The study streams draining sugarcane agriculture were characterized by a wide range of nutrient concentrations, spanning several orders of magnitude (Figure 3.4, Table S3.1). Across all study catchments, average TN concentrations varied from below the detection limit to more than 5 mg N L^{-1} (C.V. = 1.24) and were dominated by NO_3^- in all but 3 study catchments (P2, P6 and P7). These three streams also had the lowest concentrations of NO_3^- and TN despite their high percent sugarcane cover (≥ 70%). Concentrations of TP ranged from 0.04 to 0.67 mg P L^{-1} (C.V. = 1.04). Contrary to N concentrations for which TN was mostly composed of inorganic N, the inorganic and organic forms of P contributed similar portions to TP when accounting for all study sites. When considering nutrient exports, annual nutrient yield estimates ranged from 0.09 to 6.3 kg ha^{-1} yr^{-1} for TN and from 0.01 to 0.28 kg ha^{-1} yr^{-1} for TP (Table 3.2). There was no significant correlation between average nutrient concentrations (i.e., NO_3^-, TN, SRP and TP) and average baseflow discharge (Spearman's rank correlation using raw data, $p > 0.10$), which may justify the use of average concentrations and average discharges to estimate annual nutrient yields.

Relevant patterns emerged from additional analysis of the relationships between concentrations of N, DO and DOC. The relationship between concentrations of NO_3^- and DO (Figure 3.5a) showed that streams with the widest range in DO concentrations (from 1.9 to 8.2 mg O_2 L^{-1}) also tended to have the lowest NO_3^- concentrations (≤ 0.4 mg N L^{-1}). Streams in which DO concentrations did not fall below 4 mg L^{-1} usually had the greatest average NO_3^- concentrations (> 1 mg N L^{-1}). Overall, NO_3^- concentrations tended to increase with increasing DO concentration. In some streams the increasing trend was particularly pronounced; in the stream draining catchment CC, for example, NO_3^- concentrations remained low below 6 mg O_2 L^{-1} but increased exponentially with DO after that breakpoint. Finally, the relationship between concentrations of NO_3^- and DOC was significantly inverse (Figure 3.5b).

Land cover over time

There was evidence that sugarcane has been cultivated in all catchments since 1962 but the percent of catchment area with this crop was highly variable throughout the 51-year period (Figures 3.6 and Table S3.2). While some catchments had varying sugarcane cover (e.g., CA and CM), others had more persistent high sugarcane cover (e.g., P2, P6 and CC). In 2013, in particular, the percent sugarcane cover varied from 1% to 90%. Forests were also present in all catchments dating to 1962; in most of them, forest was in the early stages of succession (Figures 3.6 and 3.7). Over time, catchment forest cover at stage I decreased on average across all study sites while the percentage with forest at stage IV increased continuously during the 51-year period of the study (Figure 3.8). As a result, most forest cover in 2013 was older than 30 years within nearly all catchments and was located predominately at the transition area between streams and sugarcane uplands (Figures 3.6, 3.7 and 3.8).

The first two components of the PCA extracted more than 80% of the total variance in the patterns of sugarcane and old forest cover over the 51-year period (Table 3.3). Principal component 1 (PC1) explained most of the variance (~75%) and the majority of both land cover variables (sugarcane and old forest) had a similar influence on PC1. PC1 identified a gradient of sugarcane and old forest cover in which the extent of sugarcane cover in 2000 contributed the most to variability on the positive side of PC1 and old forest cover in 2013 contributed the most on the negative side of PC1 (Table 3.3). While PC1 displayed a combined effect of the temporal land cover dynamics in a simple structure, the second principal component (PC2) was characterized by a much more variable land cover pattern in which the influence of the most recent land cover (2013) was relatively more pronounced than that of previous years (Table 3.3).

Catchments clustered into five main groups within the PCA biplot (Figure 3.9). Group 1 includes catchments with high +PC1 and low +PC2, which characterizes persistent high sugarcane cover (mean *(M)*=80%, standard deviation (*SD*)=6%) and low old forest cover over the 51-year period (catchments CC, P2, and P7). Group 2 includes catchments with intermediate/low +PC1 and intermediate +PC2 and describes persistent high sugarcane cover (*M*=75%, *SD*=7%) that decreased slightly over time and little old forest cover (P1 and P6). Group 3 is composed of catchments with intermediate –PC1 and intermediate +PC2, which depicts relatively constant intermediate amounts of sugarcane cover (*M*=39%, *SD*=6%) and intermediate amounts of old forest cover (*M*=29%, *SD*=19%) that increased significantly over time (CF, P3, P4). Group 4 has catchments with intermediate/low –PC1 and intermediate/low –PC2 having highly variable intermediate sugarcane cover (*M*=42%, *SD*=25%) that peaked in 1995 and 2000 and relatively constant intermediate old forest cover (*M*=24%, *SD*=10%) over the 51-year period (CA and CM). Finally, group 5 includes one catchment (P5) with high –PC1 and very low +PC2, pattern describing persistently high old forest cover over the 51-year period (*M*=51%, *SD*=20%). All statistics presented in parentheses above include land cover data from all five land use time steps (1962, 1978, 1995, 2000, 2011) for the catchments in that group.

Long-term sugarcane agriculture, forests and water quality

There was no significant association between catchment area and baseflow discharge (r = 0.48, p = 0.13). This suggests that the effect of discharge on nutrient concentrations as minimal for the 11 catchments and thus use of concentration data to explore the link between nutrients and land use was acceptable.

Simple correlation analysis between land cover in 2013 and 1962 and average nutrient concentrations showed significant relationships only for P (Table 3.4), and contrary to expectations both SRP and TP concentrations were negatively correlated with sugarcane cover in 2013 and in 1962 with the coefficients almost identical. In contrast, SRP and TP concentrations were positively correlated with the percent young forest cover in 2013.

The analysis of the overlay of the median nutrient concentrations on the PCA ordination results (Figure 3.10) and the GEE models (Table 3.5) indicated that significant relationships between land cover and nutrient concentration again only occurred for P, reinforcing the correlation results. For all GEE models, a significant negative association was found with PC1 loadings and SRP and TP concentrations i.e., as the extent of sugarcane cover and its persistence within a catchment increased over time, P concentrations decrease. For both SRP and TP, the model that provided the best fit was the most parsimonious one (Model 1) that included both PC1 and PC2, and their interaction as covariates. However, only the coefficients of PC1 and PC1*PC2 were significant in Model 1.

Contrary to expectations, catchments with high sugarcane cover that persisted over time did not tend to have the highest NO_3^- and TN (Figure 3.10, Table 3.5). In fact, most of the catchments with the highest sugarcane cover had the lowest N concentrations, particularly catchments P2, P6 and P7.

Water quality in sugarcane streams in relation to other Brazilian headwater streams

The literature survey resulted in 19 peer-reviewed articles (Table S3.3). Across all literature studies, the average NO_3^- and SRP concentrations were 0.19 mg N L^{-1}, 0.02 mg P L^{-1}, respectively. There was no significant effect of land use, biome or their interaction on nutrient concentrations, thus I used the mean nutrient concentration using all data in the larger dataset to characterize the headwater streams.

Nutrient (NO_3^-, TN, SRP and TP) concentrations in the eleven sugarcane streams from the present study were higher ($p < 0.05$) than those found in the literature for other streams in Brazil regardless of land cover (i.e., forest and agriculture, Figure 3.11). Nitrate concentrations in particular were up to six times higher ($t(11) = 2.28$, $p = 0.04$) and SRP three times higher ($t(46) = 3.43$, $p = 0.001$) in the study streams compared to the levels found elsewhere in Brazil where catchments are impacted by newer and other forms of intensive agriculture or where catchments are in natural vegetation. Concentrations of TN and TP were also much higher in the study's sugarcane streams than the baseline value for streams and rivers in the State of Sao Paulo reported by Cunha et. (2011); mean TN and TP concentrations in the catchments were, respectively, 2.9 ($t(10) = 5.06$, $p = 0.0002$) and 4.6 ($t(10) = 6.63$, $p < 0.0001$) times greater than those determined by Cunha et al. (2011).

For the nutrient data collected from the literature review, land use affected NO_3^- and SRP yields. Therefore, I used two different mean yields, one describing average yield for catchments impacted by intensive agriculture and another one for catchments with natural vegetation. Mean yields found in this study were compared to both groups. The differences in terms of yields varied depending on the nutrient form (Figure 3.12). Nitrate yields in study streams were equivalent to those found in other agricultural and forested streams. As opposed to N, SRP yield in the study sugarcane streams was smaller than that in other agricultural streams, but greater than forested streams; TP yields in the study streams were not higher than those in forested streams.

Discussion

Nutrient concentrations in the context of other Brazilian streams

Based largely on research in developed countries, we know that streams draining agriculturally dominated catchments typically show higher nutrient concentrations than undisturbed ones (Vitousek et al. 1997, Carpenter et al. 1998, OECD 2001). Some researchers have argued that Brazilian streams are resilient to the impacts of intensive agriculture and land use change on nutrient concentrations (Biggs et al. 2004, Neill et al. 2013); however, this study does not support that argument. N and P concentrations in the 11 study streams draining intensive sugarcane agriculture can indeed be much higher than previously reported. Average TN and TP concentrations are at least three times higher than baseline values for the State of São Paulo (Figure 3.11). These levels suggest the streams may be ecologically impaired because the N and P concentrations are within the range to cause stream water eutrophication (Correll 1998, Dodds and Smith 2016).

From a regulatory standpoint, NO_3^- concentrations in streams draining the study sites with long-term sugarcane agriculture were half as much as the legal limits determined for potable water and protection of aquatic communities in lotic systems in Brazil (Brasil 2005) and TP concentrations six times greater (legal limits: 10 mg L^{-1} for N and 0.1 mg L^{-1} for P). The collective of these comparisons implies that current literature has not provided a representative description of the effects of intensive cropping on nutrient concentrations of small headwater streams in Brazil.

Many factors could explain the magnified concentrations found for the study streams in relation to those in other regions of Brazil where catchments are impacted by newer and other forms of intensive agriculture. Since use of fertilizer in catchments is known to increase stream N concentrations (Howarth et al. 2002), the long-term use of mineral and organic fertilizer in sugarcane fields is probably a significant factor.

Application of inorganic fertilizers in the sugarcane fields within the study area possibly dates back to 1940 (following national trends, Figure S3.1) as the area was already under sugarcane in that period (personal communication with farmers). Then, significant increases in fertilization rates likely occurred after 1970 but particularly after

2000 following national patterns (Filoso et al. 2015). Since the 1970's organic residues from sugar production has also been used as fertilizers (Rossetto and Santiago w/o year). Currently, N fertilization rates in the study sites of 135-175 kg N ha^{-1} are within the range applied by the greatest users of inorganic N fertilizer in the world (Liu et al. 2010); which is at least twice the amount usually applied in cornfields in Central Brazil (IBGE, 2014a,b) and the amount reported by studies included in the literature survey (60 kg N ha^{-1} yr^{-1}, Silva et al. 2010). In terms of P, the amount of P fertilizer used in the study sites is slightly higher than the range described in the literature survey of 50-65 kg P ha^{-1} yr^{-1} (Silva et al. 2010, Neill et al. 2013). Note that only two studies reported fertilization rates among all 19 surveyed studies. Therefore, persistent higher nutrient application rates over time might partially explain the higher N and P in the study streams.

Despite higher stream nutrient concentrations, estimated export rates (stream nutrient yields) from the 11 small watersheds in sugarcane indicated that they are actually exporting on average similar amounts of NO_3^- and lower amounts of SRP yearly to the agricultural streams reported in the literature during baseflow conditions; which is probably a result of differences in baseflow discharge. However, comparisons need to be improved with nutrient data sampled during storm flows when the majority of nutrient exports is likely to occur (Vanni et al. 2001).

Land cover and stream phosphorus

While concentrations of N and P are high, amount or age of land cover in sugarcane was not a good predictor of N. It was a statistically significant predictor for P; however P declined rather than increased which was expected based on many other studies focused on nutrient concentrations and agriculture (Omernik 1977, Johnson et al. 1997, Liu et al. 2000, Miller et al. 2011). The significant tendency of streams draining catchments with the highest amount of sugarcane cover to have the lowest P concentrations (Tables 3.4 and 3.5) suggests that assessing the relationship between sugarcane cover and stream P concentrations is more complex than anticipated. One possibility is that this finding is a result of the interaction between among long-term P accumulation and catchment hydrology with predominantly quick surface flows that move rapidly to streams via gullies [Bezerra, chapter 2]. Additionally, the positive sign of the interaction between PC1 and PC2 in the GEE model 1 (Table 3.5) implies that riparian forests may act as a source of excess P from sugarcane fields to streams. The following two paragraphs explore these ideas.

Continuous fertilization of sugarcane fields can increase both inorganic and organic P in topsoils (Araújo et al. 1993); in only ten years, about 145 kg ha^{-1} of P can accumulate in the first 30 cm of ultisols, with half of it concentrated in the first 7.5 cm (Ballcoelho et al. 1993). Such accumulation occurs because added P fertilizer strongly binds to iron and aluminum oxides which are abundant in the ultisols of the study area, making P less available to crops (Sanchez et al. 2003, Roy et al. 2016). Accumulated residual P (or legacy P) in the first layers of the soil profile is readily available for transport when soil erosion is high (Sharpley et al. 1994) such as in the study sugarcane fields. Given the rapid transfer of surface flows to streams through gullies [Bezerra, chapter 2], the majority of excess P is potentially being flushed out without entering the stream biogeochemical pathways; only some excess P may be retained within the stream channel as a result of a combination of biogeochemical and physical processes that temporarily remove and/or transform P during downstream transport (Vanni et al. 2001). The gully flow mechanism as an explanation of lower P levels seems particularly plausible since catchments with the highest sugarcane cover tended to be the ones with greater number of gullies and greater amounts of storm flows [Bezerra, chapter 2].

The tendency of streams draining catchments with the greatest amount of forests in 2013 to have the highest P concentrations points in the direction of P saturated riparian soils that may not only act as P storage but also as P sources. Transect studies along hydrological flow paths extending from agricultural fields laterally to streams have documented a significant reduction capacity of particulate P by riparian forests (Zhang et al. 2010). However, riparian soils can become saturated with SRP retained from constant overland flow, and subsequent remobilization may lead to increased SRP deliver to streams (Roberts et al. 2012). The study catchments with greater extent forest cover may, therefore, have stored more P in riparian zones than in the other catchments but more P has been also potentially available for terrestrial processing and subsequent release to streams.

Land cover and stream nitrogen

The lack of a significant relationship between land cover history and stream N concentrations was surprising but there was very high variability in nutrient concentrations (C.V. = 1.24), which could have made it difficult to detect a pattern. It is important to elucidate, in particular, why most catchments with a high percent sugarcane cover that was persistent through time had the lowest stream N concentrations (P2, P6 and P7). Potential factors explaining this include high rates of instream processing

(Taylor and Townsend 2010) by macrophytes. Small fine sediment bars (~3m^2, personal observation) colonized with aquatic lilies of the genus *Hedychium* were observed in most catchments including in those catchments with very low N concentrations and with persistent high sugarcane cover. Others have shown a known positive relationship between fine sediment deposition and the establishment of rooted macrophytes (Bunn et al. 1998). Catchment P7 with an average of 78% sugarcane cover over the 51 yr period, the greatest number of gullies and amounts of suspended sediment [Bezerra, Chapter 1 and 2] also had a continuous silted area (700 m^2) colonized with wetland-like vegetation including cattail of the genus *Typha* located upstream of the sampling point. The high level of agriculture and associated high suspended sediments and gullies imply extreme stream sedimentation [Bezerra, Chapter 2]. The presence of agriculturally-induced wetlands can reduce N concentrations significantly in streams in the Atlantic forest region (Salemi et al. 2014). Not surprisingly, almost 80% of the water samples collected at P7 had NO_3^- concentrations below the detection limit of 0.5 µg N L^{-1}.

The reduced surface water and flow velocity likely associated with sedimentation may also support enhanced microbial processing due to increased water residence time (more time for processing to occur) and potentially low enough oxygen levels to permanently remove N from the stream water (e.g., via denitrification and annamox, Burgin and Hamilton 2007). The tendency of the study streams with low DO to have low N concentrations supports this idea (Figure 3.5a). Interestingly, catchments with higher average sugarcane cover were also those with the lowest DO concentrations. Because N processing is also closely related to the coupling of N and dissolved organic carbon (DOC) cycling (Burgin and Hamilton 2007), N removal processes are likely only relevant if sufficient carbon is provided. Here, those streams that had the lowest N concentration (P2, P6 and P7) also tended to have higher DOC concentrations in relation to the other streams (Figure 3.5b). Taylor and Townsend (2010) have suggested that an inverse association between stream N and DOC suggests N processing (Taylor and Townsend 2010). In summary, long-term geomorphic changes via gully formation from sugarcane agriculture [Bezerra, chapter 1] that has contributed to high sedimentation on the streambed [Bezerra, Chapter 2] potentially leads to establishment of vegetation that together with longer hydrologic residence times enhances instream N processing.

Forest age, riparian effectiveness and nutrients

The focus of this study was on forest cover that was old (> 30 yr, Stage IV) because of interest in understating whether less disturbed fragments may better protect streams from diffuse agricultural pollution. The 30-year threshold was supported by the ecological functions provided by older forests. Carbon and nutrients are known to quickly accumulate in vegetation, litter and soil, particularly during the first 20 years of growth (Brown and Lugo 1990), and rapid recovery of physical properties (lower bulk density and higher macro-porosity) of surface soils are also observed during the early years of forest succession (2-20 years) after agricultural abandonment (Montagnini et al. 1995, Gageler et al. 2014). Given the associated recovery of nutrient processing as soil characteristics recover (Davidson et al. 2007, Ribeiro et al. 2013), I expected Stage IV forest cover ("old forest") would provide sufficient nutrient processing to reduce diffuse pollution from the sugarcane. As highlighted in the previous paragraphs, that was not found. This does not imply that riparian forests are unimportant in reducing diffuse nutrient pollution from sugarcane fields but it highlights a more complex relationship between the upslope-riparian continuum and stream nutrient concentrations.

Implications

The research findings on the relationships between land cover history and stream nutrient concentrations analyses suggest that the use of agricultural land cover metrics to assess whether and to what extent intensive cropping affects stream N and P concentrations, and the importance of riparian forests in mediating the agricultural influence, may be problematic for some areas in Brazil. Regardless, the findings of this research do have important implications for the use of environmental laws—most importantly the Forest Code—to guarantee sustainable production of agricultural products.

The first Forest Code in Brazil was implemented in 1934 to encourage planting and discourage destruction of "protective forests" with one of the major goals being protection of water resources (Brasil 1934). The criteria for establishing protective forests, e.g., their location and size, were specified in a 1965 law (often called "the New Forest Code; Drummond and Barros-Platiau 2006) and resulted in one of the most important legal mechanisms for natural resource protection on private lands in Brazil: Areas of Permanent Protection (APP). The APPs are defined as those areas "with the environmental function of preserving water resources, landscape, geological stability and biodiversity, facilitating gene flow of fauna and flora, soil protection, and ensuring the well-being of the people" (Brasil 1965, Brasil 2012). Because riparian buffers were officially designated as APPs, the Code now provided a clear means for protecting

Brazilian water resources (Ahrens 2005) from non-point source pollution from agricultural fields.

Beginning in 2012, the Forest Code was formally entitled the Native Vegetation Protection Law – NVPL (Brasil 2012); this resulted from a 13-year debate in the National Congress to reformulate the 1965 Code (Martinelli 2011, Tollefson 2011, Nazareno 2012, Soares-Filho et al. 2014, Brancalion et al. 2016). One of the main quarrels was from the agribusiness sector that alleged shortage of land for agricultural expansion if the forest requirements of the 1965 Forest Code were maintained (Metzger et al. 2010, Martinelli 2011). Despite the fact that the major forest conservation requirements were retained, new provisions drastically reduced or even completely removed the obligation to protect certain areas of key environmental importance that were protected under the preceding Code; this included riparian buffers along intermittent springs (Brancalion et al. 2016).

Because the small headwater streams of this study could be considered intermittent waterways, one probable outcome from changes to the Forest Code may be an excessive number of streams with high nutrient concentration. This would exacerbate the eutrophication potential through a significant portion of the drainage network. This is particularly problematic given that long-term forest recovery did not necessarily translate into streams with low nutrient concentrations. Take catchment P4 as an example: significant forest recovery in terms of age and amount of forest cover over the 51 yr period, which led to 54% of the catchment area being covered with old forest in 2013 (Figures 3.6 and 3.7), did not result in low stream N concentrations. On the contrary, the stream draining catchment P4 had the highest N concentration among all study streams (Figure 3.4).

Further revisions of the Brazilian Forest Code need, therefore, to be based on local studies addressing the effectiveness of riparian buffers to reduce non-point source nutrient pollution from crop fields if the protection of water resources is to be achieved. Diminishing the forest protection as debated and actualized previously is a contradictory step toward the sustainable agriculture that the Brazilian government proclaims to pursue.

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Tables and Figures

Table 3.1. Characteristics of the study catchments and stream physico-chemistry during the study period (June 2013 – March 2014)

Site	Geographic coordinates at sampling point	Area	Slope	Mean baseflow width	Mean baseflow depth	Mean baseflow discharge	Temperature	E.C.	pH	D.O.	Sugarcane cover in 2013	Forest cover in 2013
		ha	m m^{-1}	cm		L s^{-1}	°C	µS cm^{-1}		mg L^{-1}	%	
CA	22°36'55.92"S 47°40'25.57"W	5.9	0.17	na†	na†	0.13	19.6 (4.1)	79.9 (18.7)	6.8 (0.2)	5.7 (1.6)	1.1	98.9
CC	22°36'55.26"S 47°40'10.15"W	7.2	0.07	na†	na†	0.09	19.9 (3.7)	123.8 (13.4)	7.0 (0.2)	6.3 (2.4)	90.7	9.4
CF	22°36'47.53"S 47°40'16.07"W	6.3	0.25	20	0.8	0.06	19.1 (3.9)	109.2 (26.1)	6.9 (0.3)	6.1 (1.5)	37.9	62.1
CM	22°36'51.60"S 47°40'21.22"W	5.1	0.21	31	2.0	0.18	18.5 (2.9)	125.38 (17.5)	7.1 (0.3)	7.6 (0.8)	31.4	68.6
P1	22°37'14.81"S 47°40'25.54"W	5.6	0.15	47	1.3	0.39	21.3 (2.5)	236.0 (39.7)	7.3 (0.1)	6.1 (1.2)	71.9	28.7
P2	22°37'06.27"S 47°40'20.50"W	7.6	0.10	32	0.9	0.31	19.6 (3.6)	217.5 (44.2)	7.4 (0.2)	5.9 (2.1)	82.2	17.8
P3	22°36'53.02"S 47°40'07.57"W	12.0	0.14	35	1.9	0.28	21.4 (3.2)	194.8 (29.5)	7.0 (0.2)	5.4 (1.8)	37.4	62.6
P4	22°36'45.10"S 47°40'02.50"W	16.5	0.19	49	2.4	0.32	20.7 (2.9)	135.4 (15.8)	6.5 (0.1)	6.3 (0.8)	44.5	55.5
P5	22°36'35.72"S 47°40'07.70"W	7.4	0.23	23	1.9	0.02	18.1 (2.9)	205.8 (32.3)	7.3 (0.2)	5.3 (2.0)	28.2	71.8
P6	22°36'42.33"S 47°40'08.49"W	2.9	0.19	54	1.9	0.04	18.4 (2.6)	60.7 (12.9)	6.4 (0.2)	4.1 (1.8)	75.3	24.7
P7	22°36'41.14"S 47°40'38.30"W	6.1	0.14	22	0.5	0.16	20.3 (1.4)	93.5 (25.6)	6.8 (0.2)	6.2 (1.6)	81.1	18.9

Note: Shown are mean of values and 1 standard deviation appears in parentheses
† CA and CC had H flumes

Table 3.2. Average nutrient export per unit of area (kg ha^{-1} yr^{-1}) estimate for each study catchment (see text for full explanation)

Catchment	Nitrate	TN	SRP	TP
CA	0.45	0.68	0.07	0.15
CC	0.61	0.76	0.01	0.05
CF	0.38	0.44	0.03	0.07
CM	1.60	1.74	0.09	0.22
P1	6.55	7.16	0.14	0.30
P2	0.20	0.64	0.07	0.17
P3	0.30	0.59	0.01	0.04
P4	2.31	2.70	0.01	0.05
P5	0.03	0.09	0.01	0.02
P6	0.04	0.25	0.02	0.05
P7	0.01	0.54	0.02	0.07

Table 3.3. PCA results showing eigenvalues, variance explained and factor structure summary for the retained factors. Bold values highlight the variables composing factor structure. Each variable is described as the land use (SC for sugarcane and F for forest) followed by its year

Axis	Eigenvalue	Individual percent	Cumulative percent
PC1	7.5	74.97	74.97
PC2	1.1	10.88	85.86

Variables	PC1	PC2
SC_62	0.882	0.330
SC_78	0.889	0.295
SC_95	0.906	-0.336
SC_00	**0.911**	-0.305
SC_13	0.829	**0.451**
F_62	-0.872	-0.189
F_78	-0.764	-0.372
F_95	-0.841	0.184
F_00	-0.864	0.293
F_13	**-0.890**	**0.435**

Table 3.4. Results of Pearson-product moment correlations between land cover in 2013 and 1962 and average nutrient concentrations including data from the entire period of study (August 2013 to April 2014). Significant correlations are shown in bold

Nutrient	Correlation coefficient	*p*
With sugarcane cover in 2013		
$N\text{-}NO_3^-$	-0.11	0.75
TN	-0.04	0.90
SRP	**-0.55**	**0.08**
TP	**-0.52**	**0.10**
With young forest cover (< 30yr) in 2013		
$N\text{-}NO_3^-$	-0.09	0.79
TN	-0.17	0.62
P-SRP	**0.59**	**0.05**
TP	**0.53**	**0.09**
With old forest cover (> 30yr) in 2013		
$N\text{-}NO_3^-$	0.25	0.46
TN	0.25	0.45
SRP	0.06	0.86
TP	0.08	0.82
With sugarcane cover in 1962		
$N\text{-}NO_3^-$	-0.07	0.82
TN	-0.02	0.96
SRP	**-0.58**	**0.06**
TP	**-0.55**	**0.08**
With young forest cover (< 30yr) in 1962		
$N\text{-}NO_3^-$	0.02	0.95
TN	-0.05	0.88
P-SRP	0.31	0.35
TP	0.35	0.30
With old forest cover (> 30yr) in 1962		
$N\text{-}NO_3^-$	-0.06	0.87
TN	-0.04	0.90
P-SRP	0.45	0.17
TP	0.44	0.18

Table 3.5. Coefficients of the generalized estimating equations for each model and nutrient. QIC results are also provided. In both is the model with the lowest QIC, i.e., the best-fitting model

Nutrient	Model	*ß₀*	*ß₁ PC1*	*ß₂ PC2*	*ß₃ PC1*PC2*	QIC
Nitrate	Model 1	1.16***	-0.08	0.41	-0.01	162
	Model 2	1.16***	-0.08	0.42	-	125
	Model 3	1.16***	-	0.42	-	**113**
	Model 4	1.16	-0.08	-	-	123
TN	Model 1	1.56***	-0.07	0.36	-0.10	157
	Model 2	1.56***	-0.08	0.47	-	127
	Model 3	1.57***	-	0.47	-	**119**
	Model 4	1.56***	-0.08	-	-	129
SRP	Model 1	0.05***	-0.005***	-0.006	0.01**	**-1090**
	Model 2	0.05***	-0.004**	-0.019***	-	-1074
	Model 3	0.05***	-	-0.019***	-	-1060
	Model 4	0.05***	-0.004*	-	-	-1007
TP	Model 1	0.14***	-0.008**	-0.012	0.017**	**-676**
	Model 2	0.14***	-0.007*	-0.032***	-	-673
	Model 3	0.14***	-	-0.032***	-	-671
	Model 4	0.14***	-0.007*	-	-	-657

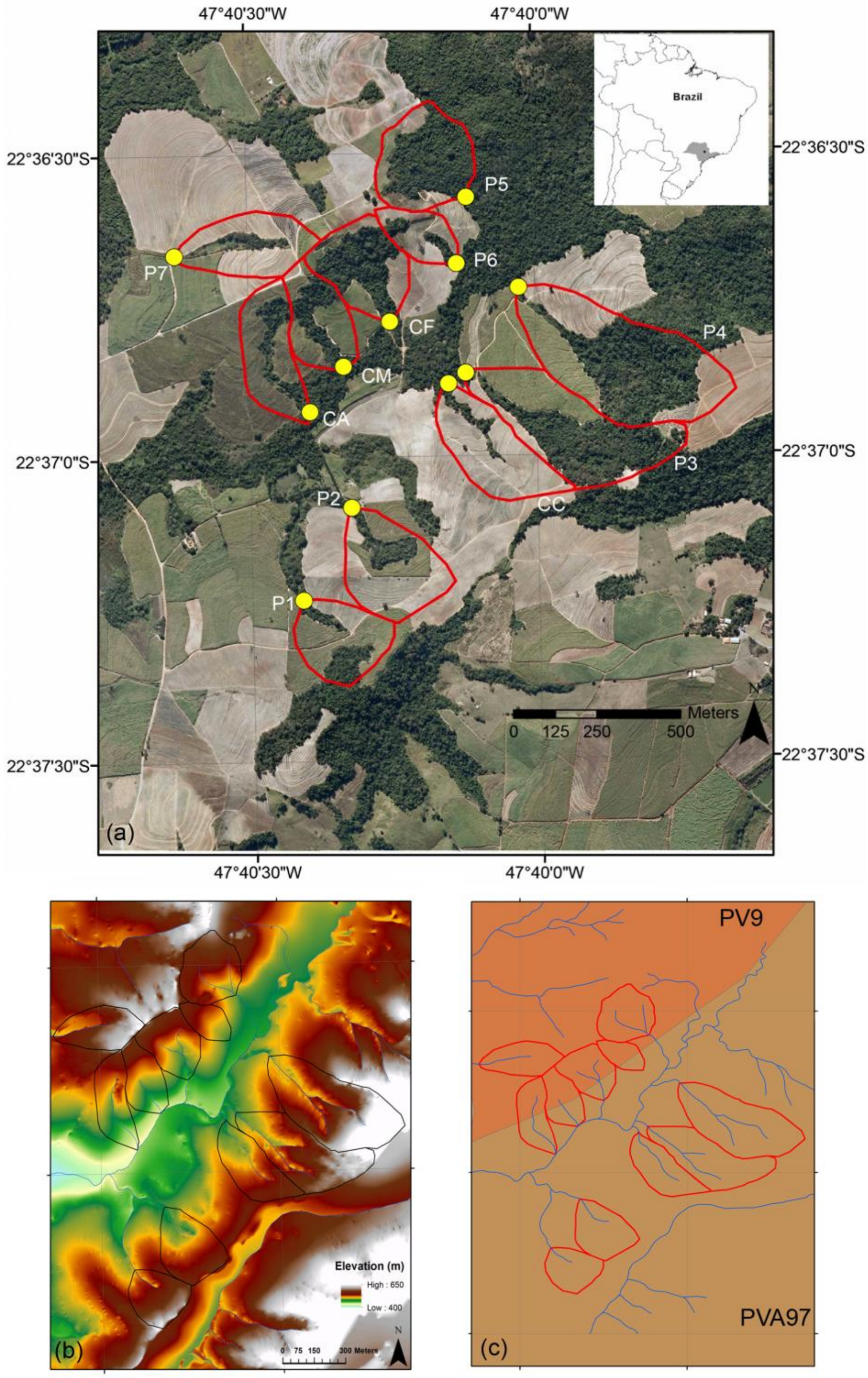

Figure 3.1. (a) Location of the study area in the State of Sao Paulo, Brazil (black dot in the top map) and detailed aerial imagine of study catchments (orthophoto, EMPLASA 2010/2011). Redlines show watershed delineations. Yellow dot is downstream sampling point. (b) Elevation of the study area. (c) Ultisol types in the study area according to the Brazilian Soil Classification: PV9 ('argissolo vermelho' 9) and PV97 ('argissolo vermelho amarelo' 97)

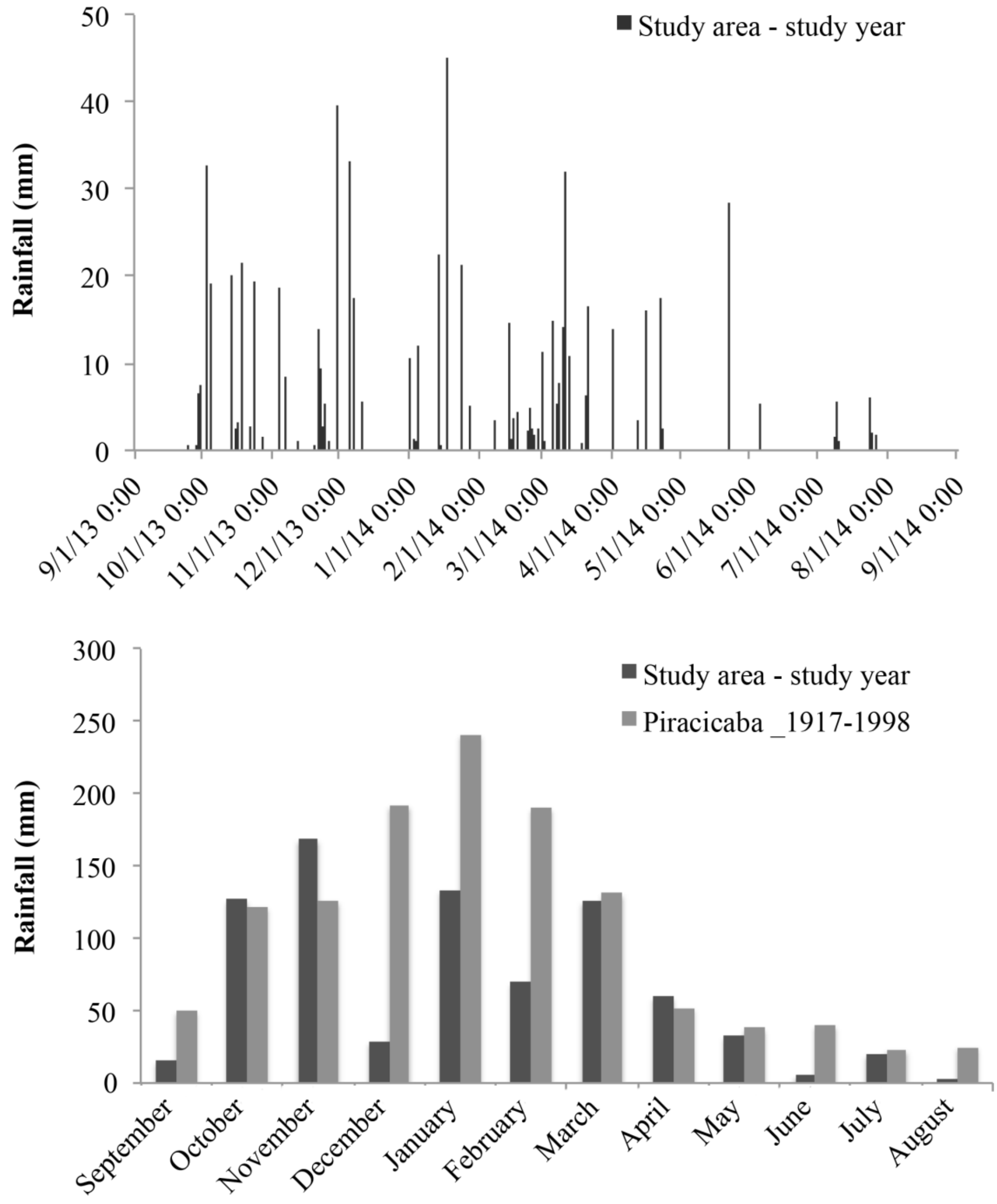

Figure 3.2. (a) Precipitation in the study area during the period of data collection and (b) comparison of total monthly precipitation at the study area during the period of data collection with the average monthly precipitation data based on 81 years of data for the city of Piracicaba

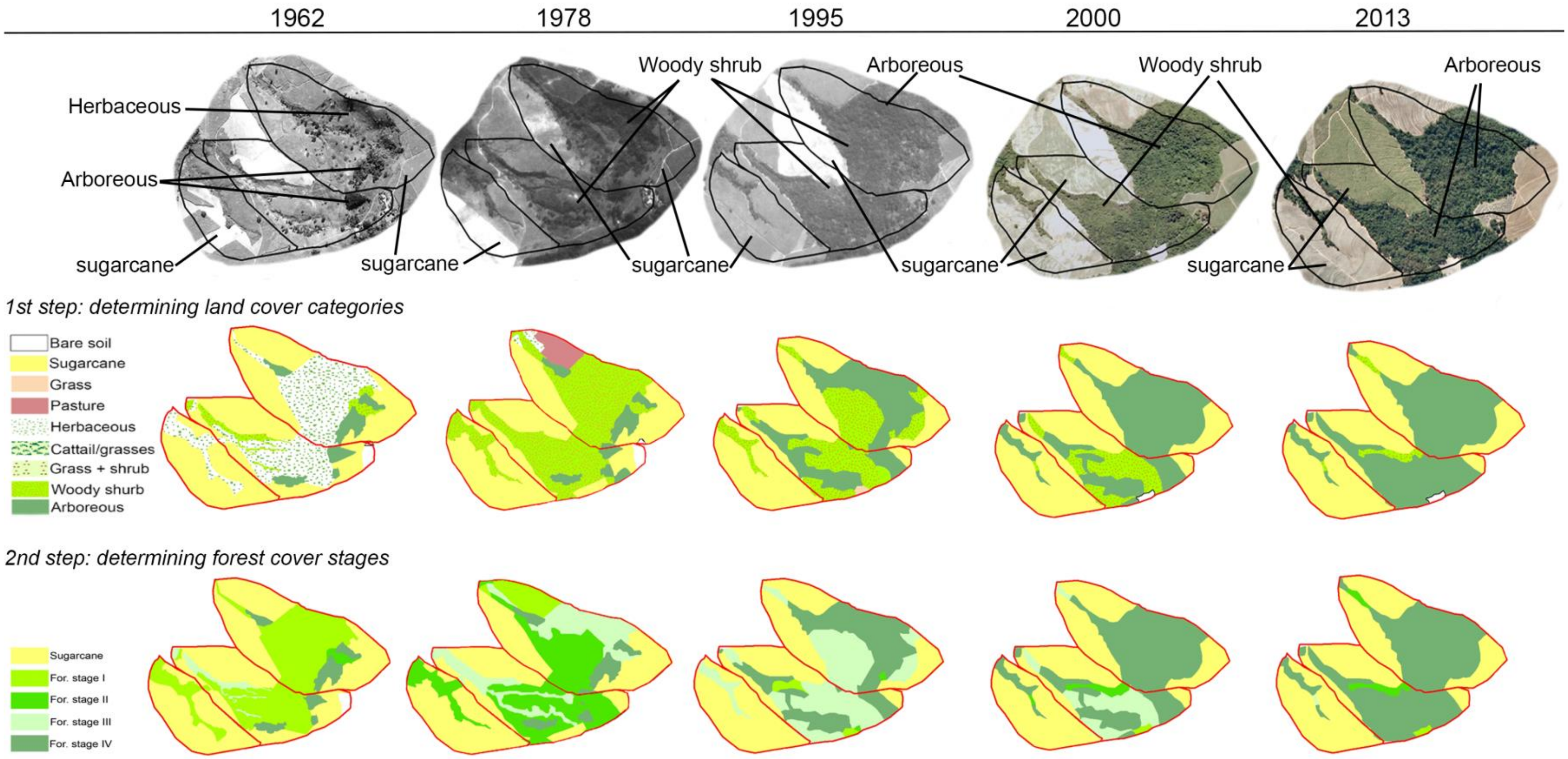

Figure 3.3. Schematic of the land cover classification process

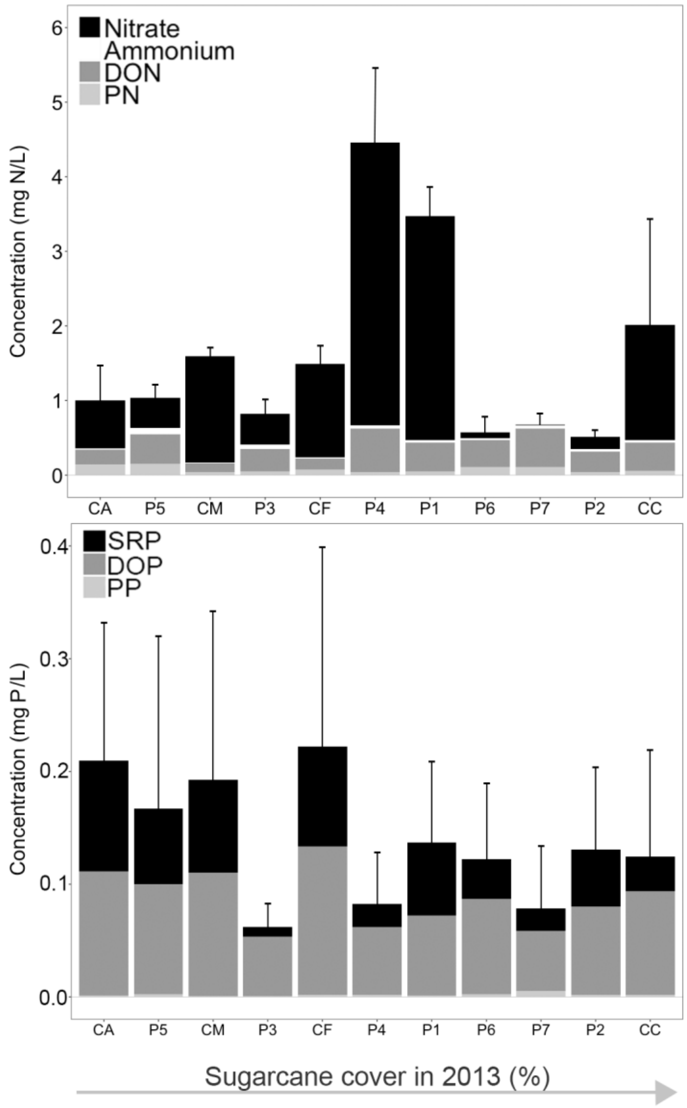

Figure 3.4. Average concentrations of nutrient species in the study streams for N (top) and P (bottom). Error bars are 1 standard deviation of the TN and TP means for each stream. Sites are oriented from lowest (left) to highest (right) catchment sugarcane cover in 2013. Number of observations for each nutrient species in each stream can in Table S3.1

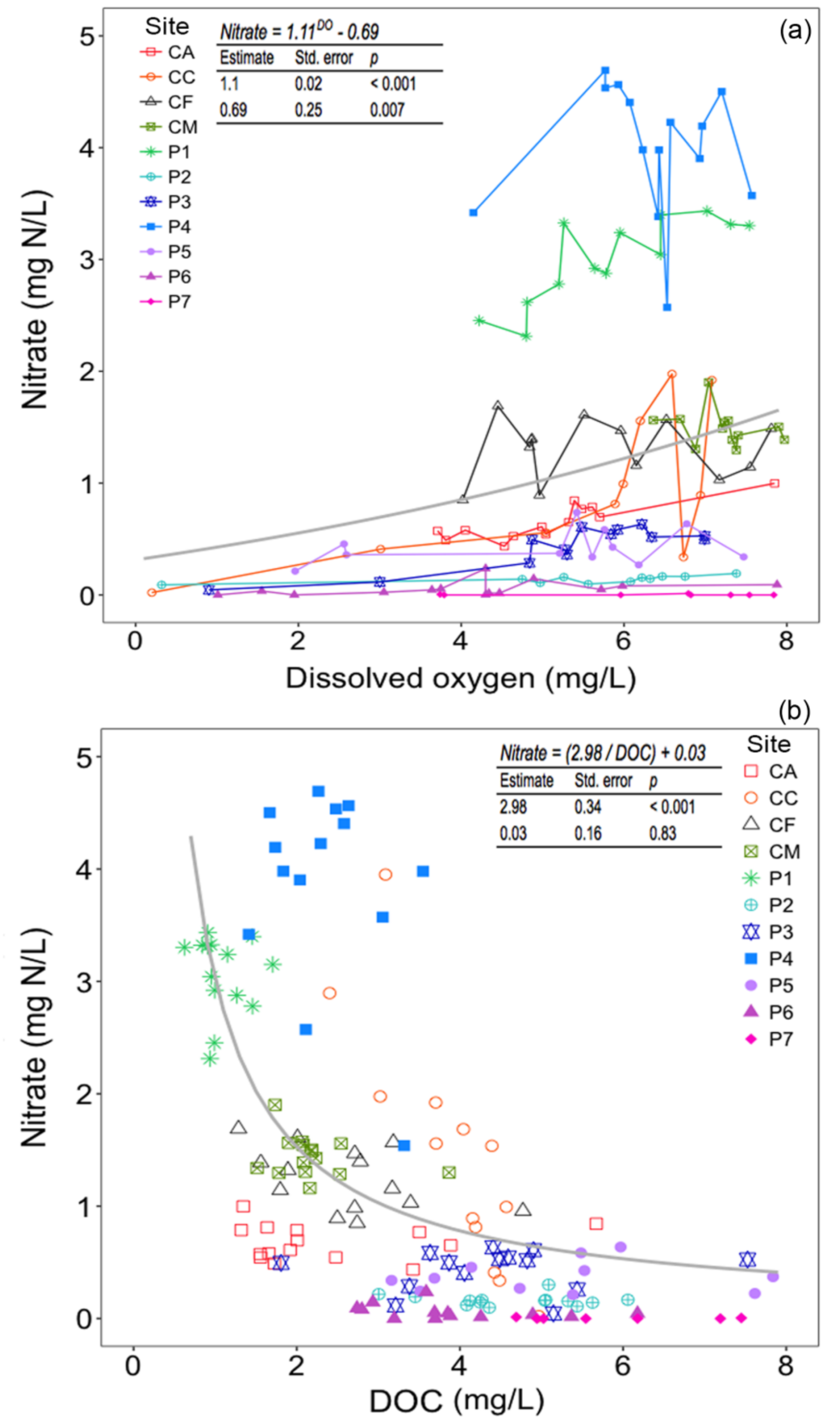

Figure 3.5. Relationship between (a) nitrate concentrations and dissolved oxygen and (b) nitrate and dissolved organic carbon (DOC) concentrations; data from all 11 study sites used. Grey trend lines represent best fit non-linear model; statistics are provided

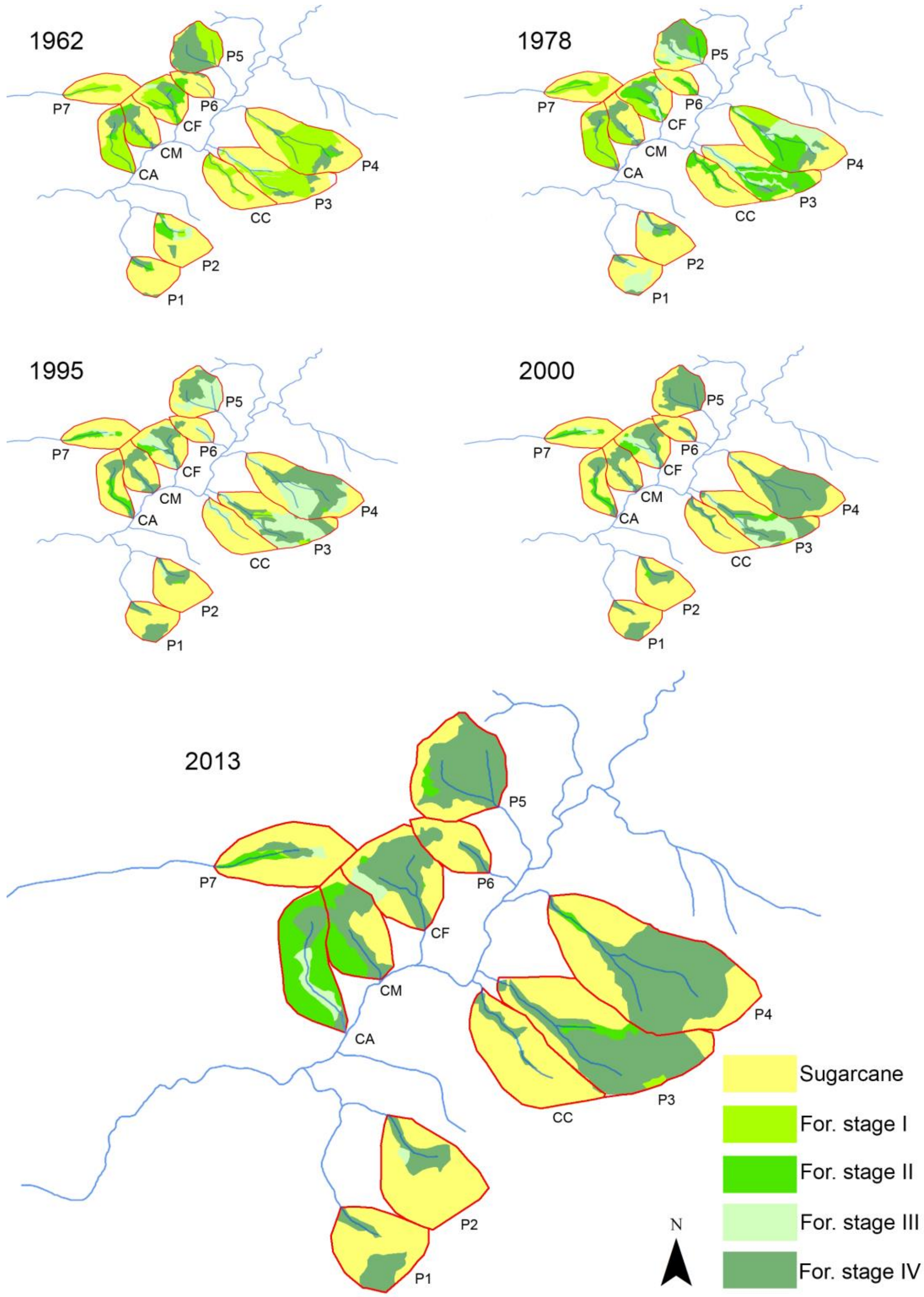

Figure 3.6. Changes in the vegetation cover within each study catchments from 1962 to 2013. Blues lines represent streams

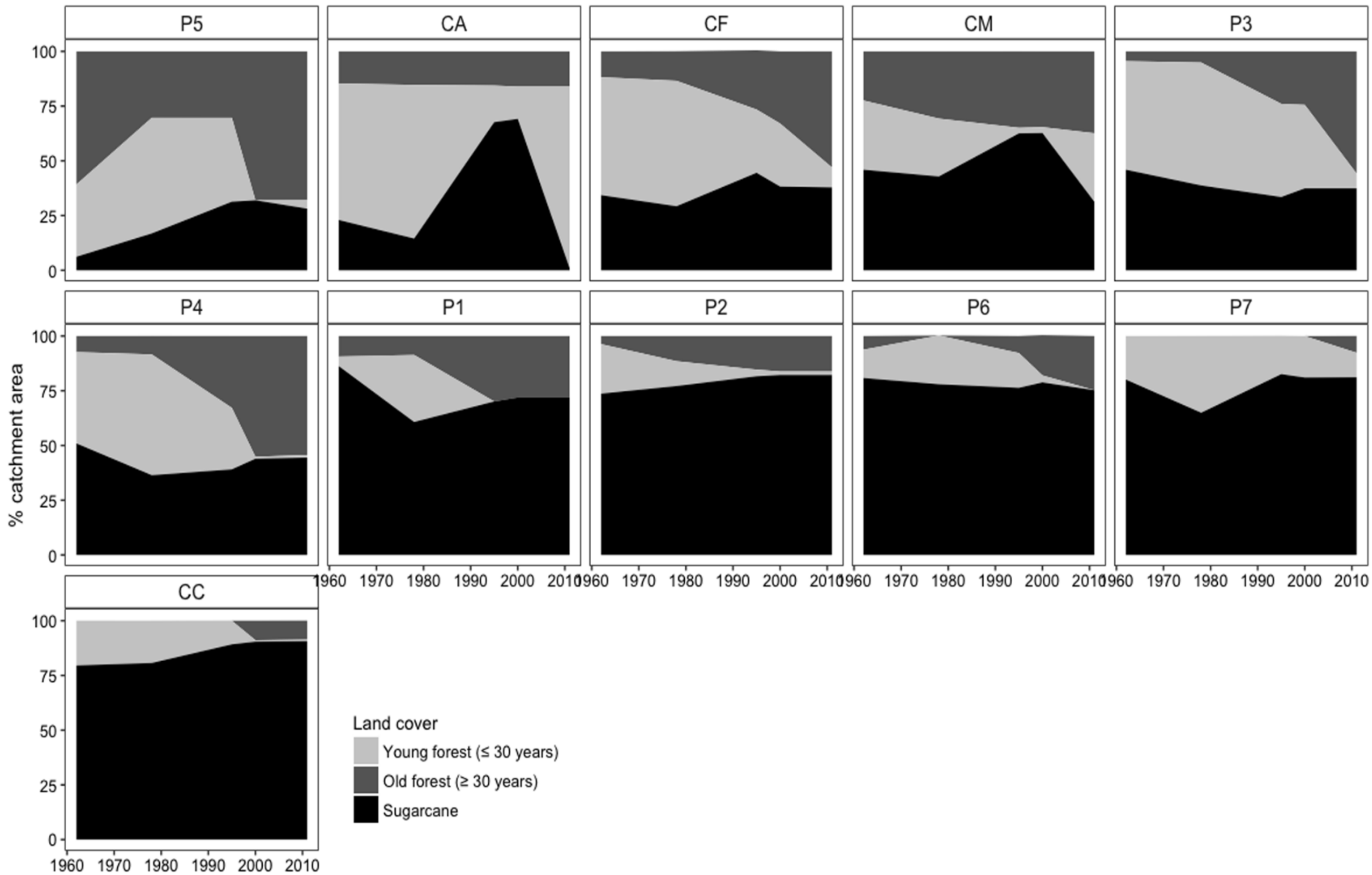

Figure 3.7. Changes in the vegetation cover at the catchment scale across all study catchments from 1962 to 2013

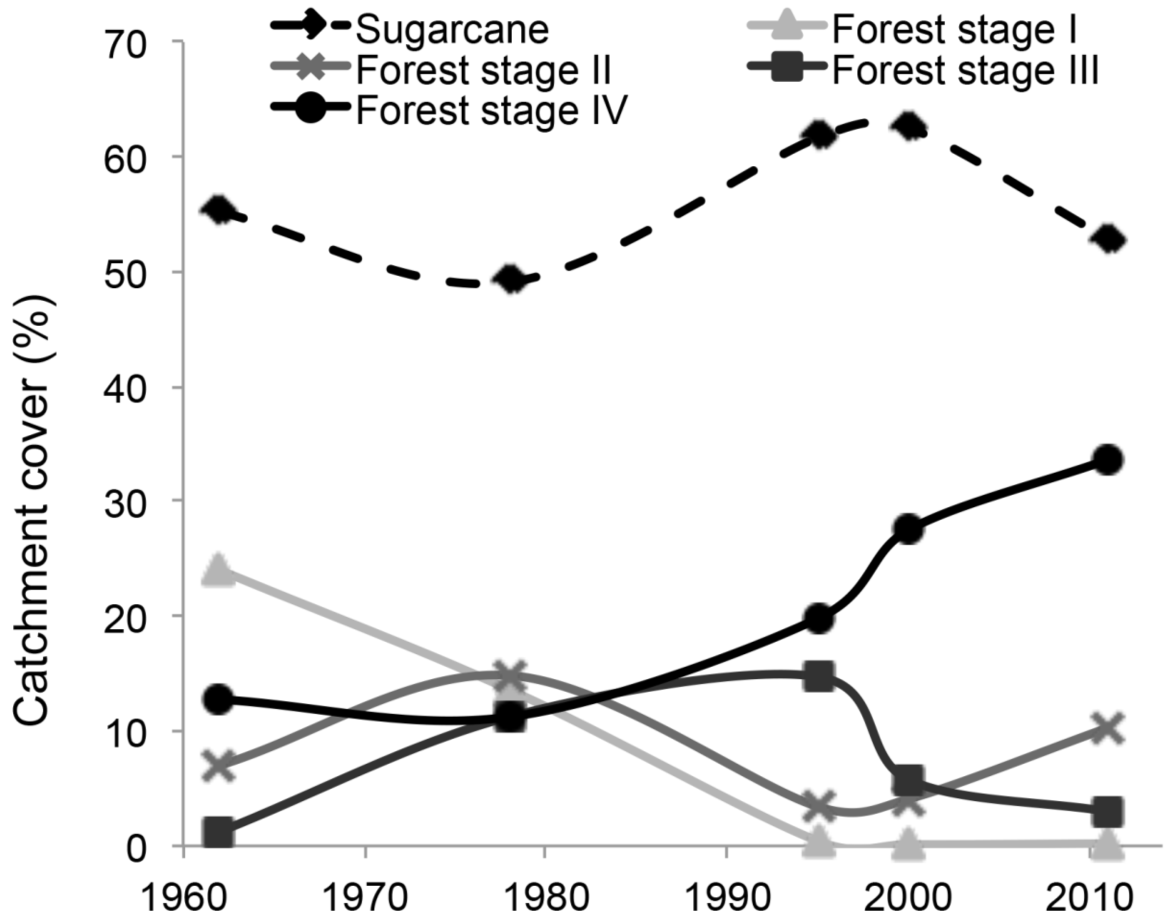

Figure 3.8. Average change in sugarcane cover and in different stages of forest succession across the study catchments from 1962 to 2013

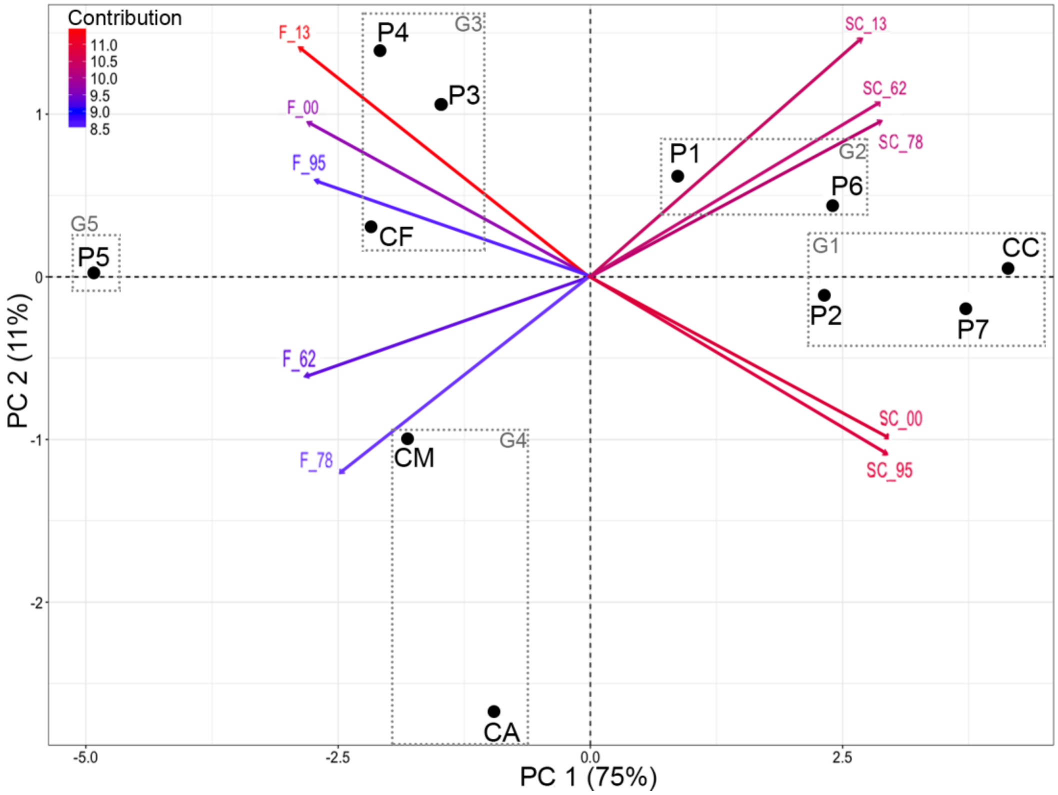

Figure 3.9. Principal component analysis (PCA) biplot. The variance explained by each component is shown in parentheses. Arrows indicate the land cover variables (forest cover (F) and sugarcane cover (SC) in each year 1962 (62), 1978 (78), 1995 (95), 2000 (00), and 2013 (13) used in the analysis and are colored based on their contribution

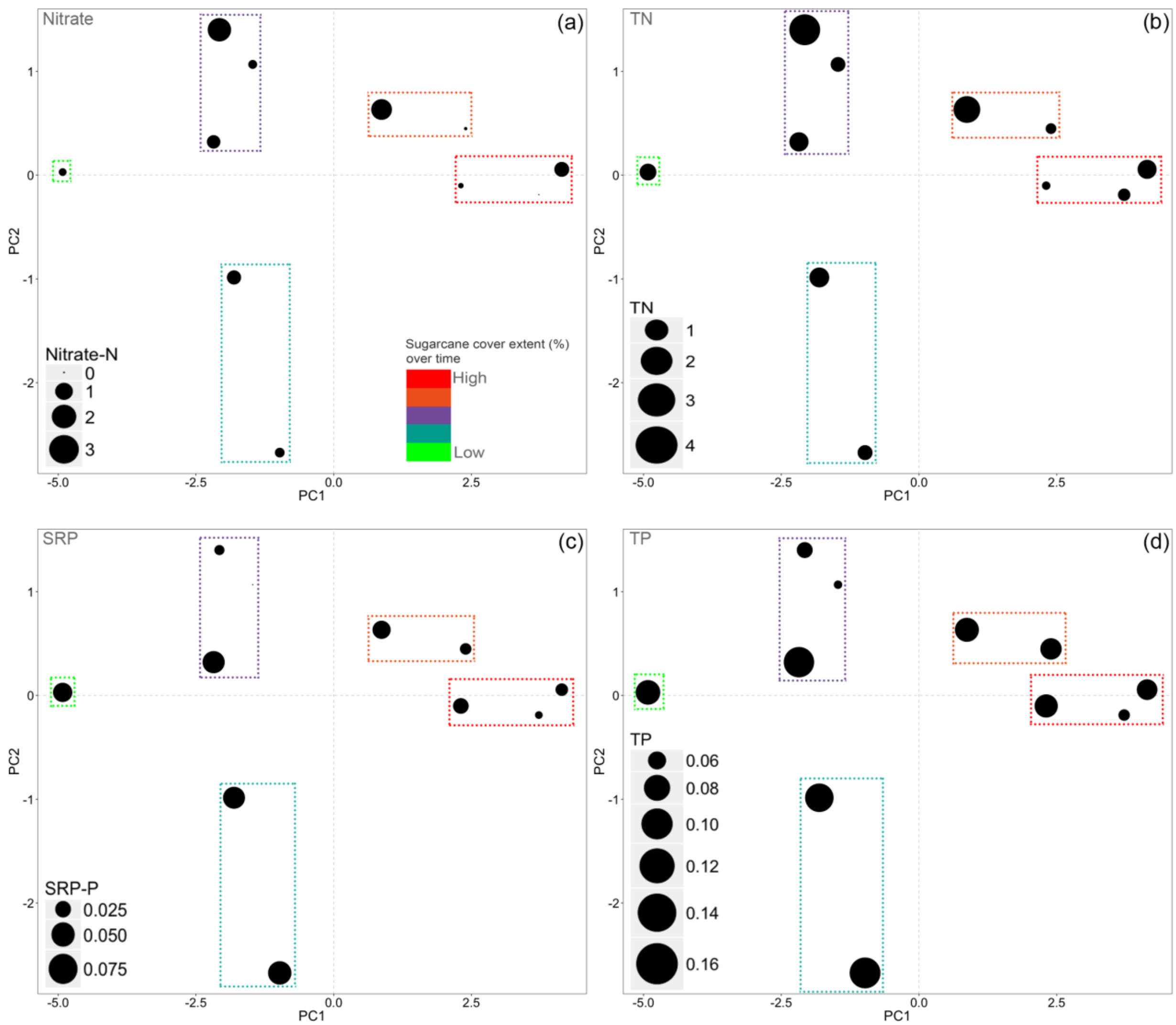

Figure 3.10. PCA ordinations labeled by medians of nutrient concentrations for each study catchments. (a) nitrate; (b) TN; (c) SRP; and (d) TP. Rectangles are colored based on the grouping presented in Figure 9

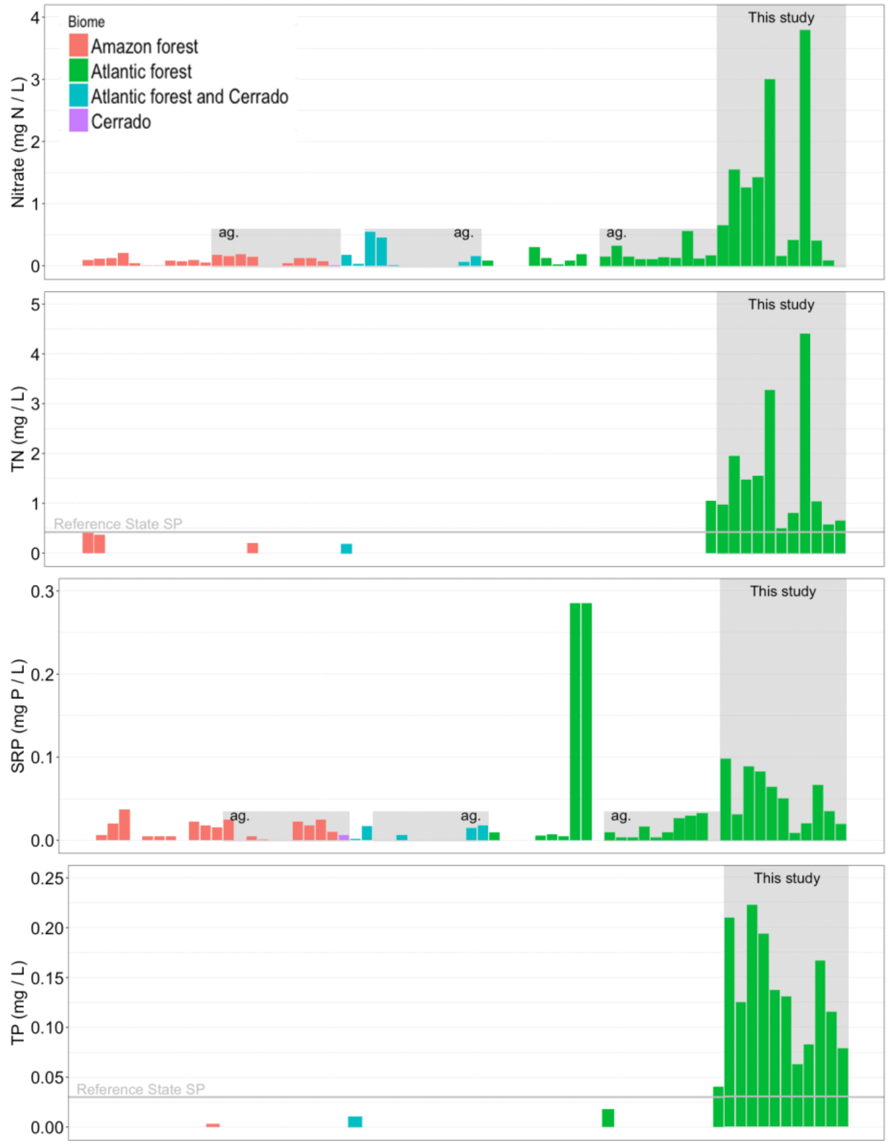

Figure 3.11. Comparisons between nutrient concentrations in this study with those found in the literature survey and found in Cunha et al. (2011)

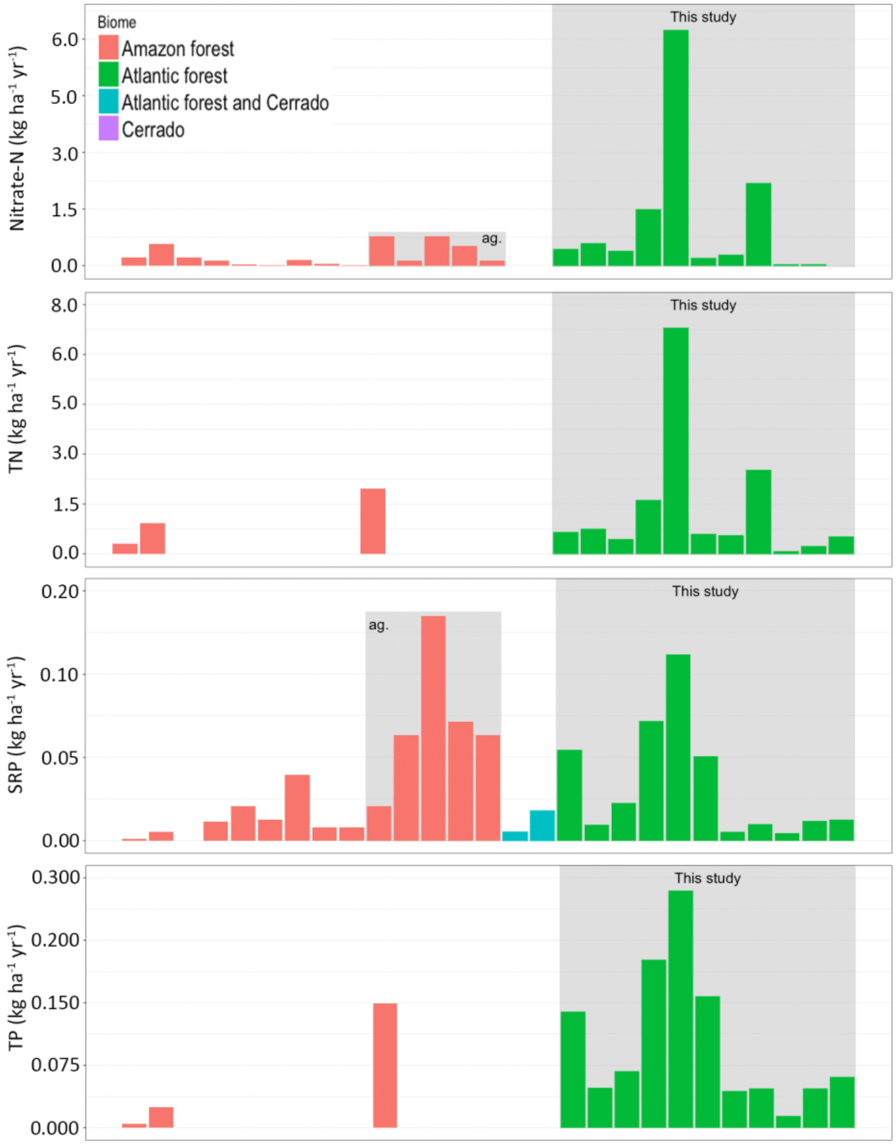

Figure 3.12. Comparisons between nutrient yields in this study with those found in the literature survey

Supplemental material

Table S3.1. Concentrations of nutrients (mg/L) as a function of catchment. SD = standard Deviation; MD = median; MIN = minimum; Max = maximum

	Nitrate						Ammonium					
Site	obs	M	SD	MD	MIN	MAX	obs	M	SD	MD	MIN	MAX
CA	17	0.647	0.168	0.610	0.351	0.998	13	0.017	0.014	0.013	0.003	0.054
CC	15	1.547	1.187	1.537	0.021	3.951	14	0.027	0.014	0.029	0.004	0.063
CF	16	1.254	0.271	1.239	0.849	1.689	14	0.014	0.010	0.013	0.001	0.034
CM	17	1.422	0.182	1.388	1.151	1.901	15	0.014	0.011	0.013	0.001	0.033
P1	16	2.995	0.378	3.097	2.313	3.434	15	0.035	0.032	0.023	0.012	0.140
P2	15	0.159	0.052	0.158	0.090	0.301	14	0.038	0.015	0.034	0.020	0.071
P3	16	0.414	0.181	0.497	0.045	0.633	14	0.064	0.053	0.050	0.010	0.218
P4	16	3.792	0.838	3.981	1.539	4.692	14	0.038	0.031	0.028	0.007	0.125
P5	14	0.401	0.158	0.366	0.213	0.738	14	0.088	0.084	0.056	0.008	0.304
P6	16	0.084	0.127	0.044	0.000	0.500	14	0.021	0.019	0.019	0.002	0.072
P7	9	0.002	0.004	0.000	0.000	0.013	8	0.050	0.035	0.051	0.008	0.103
	DON						TDN					
Site	obs	M	SD	MD	MIN	MAX	obs	M	SD	MD	MIN	MAX
CA	17	0.200	0.230	0.088	0.007	0.901	17	0.859	0.299	0.786	0.577	1.799
CC	14	0.379	0.291	0.300	0.020	0.977	15	1.901	1.386	1.357	0.448	4.736
CF	16	0.148	0.083	0.141	0.009	0.280	16	1.414	0.250	1.395	1.037	1.897
CM	15	0.118	0.106	0.128	0.005	0.378	17	1.514	0.120	1.535	1.289	1.732
P1	11	0.392	0.272	0.308	0.015	0.976	16	3.238	0.387	3.200	2.236	4.000
P2	15	0.269	0.087	0.277	0.149	0.463	15	0.463	0.090	0.470	0.327	0.637
P3	16	0.296	0.101	0.278	0.161	0.496	16	0.765	0.186	0.793	0.369	1.239
P4	15	0.586	0.449	0.432	0.038	1.391	16	4.368	1.004	4.602	1.686	5.880
P5	14	0.389	0.104	0.383	0.226	0.604	14	0.877	0.206	0.929	0.478	1.269
P6	16	0.359	0.158	0.335	0.150	0.730	16	0.461	0.196	0.380	0.241	0.883
P7	9	0.507	0.086	0.523	0.341	0.595	9	0.554	0.077	0.594	0.442	0.639

Table S3.1. *continue*

	PN						TN					
Site	obs	M	SD	MD	MIN	MAX	obs	M	SD	MD	MIN	MAX
CA	14	0.141	0.353	0.042	0.021	1.360	17	0.975	0.468	0.838	0.627	2.369
CC	12	0.061	0.053	0.048	0.017	0.223	15	1.950	1.420	1.417	0.500	4.959
CF	14	0.075	0.067	0.045	0.025	0.274	16	1.480	0.242	1.446	1.072	1.897
CM	15	0.041	0.026	0.033	0.020	0.125	17	1.551	0.119	1.557	1.289	1.753
P1	12	0.047	0.039	0.033	0.017	0.152	16	3.273	0.392	3.249	2.268	4.080
P2	13	0.045	0.025	0.036	0.019	0.091	15	0.502	0.095	0.491	0.355	0.673
P3	12	0.052	0.055	0.025	0.012	0.172	16	0.804	0.192	0.818	0.390	1.268
P4	15	0.043	0.029	0.031	0.019	0.128	16	4.408	1.005	4.632	1.717	5.906
P5	14	0.155	0.186	0.096	0.036	0.772	14	1.032	0.185	1.070	0.697	1.331
P6	15	0.113	0.114	0.069	0.024	0.425	16	0.567	0.207	0.534	0.319	0.955
P7	8	0.114	0.113	0.064	0.031	0.343	9	0.655	0.151	0.622	0.478	0.952
	SRP						DOP					
Site	obs	M	SD	MD	MIN	MAX	obs	M	SD	MD	MIN	MAX
CA	15	0.098	0.031	0.096	0.042	0.144	15	0.110	0.122	0.076	0.015	0.459
CC	13	0.031	0.013	0.030	0.014	0.053	13	0.092	0.098	0.059	0.026	0.389
CF	14	0.089	0.031	0.087	0.034	0.148	14	0.132	0.171	0.064	0.019	0.567
CM	15	0.083	0.015	0.085	0.046	0.105	15	0.109	0.142	0.045	0.005	0.478
P1	15	0.064	0.023	0.059	0.047	0.144	15	0.071	0.066	0.053	0.010	0.223
P2	14	0.050	0.020	0.045	0.020	0.086	14	0.079	0.069	0.057	0.025	0.256
P3	15	0.009	0.008	0.006	0.001	0.032	15	0.052	0.020	0.050	0.028	0.097
P4	15	0.021	0.005	0.021	0.013	0.030	15	0.060	0.044	0.046	0.025	0.191
P5	13	0.067	0.024	0.066	0.019	0.113	13	0.098	0.153	0.036	0.003	0.464
P6	15	0.035	0.029	0.026	0.015	0.132	14	0.085	0.068	0.055	0.030	0.243
P7	9	0.020	0.015	0.014	0.008	0.057	9	0.053	0.038	0.036	0.029	0.150

Table S3.1. *continue*

Site	PP obs	M	SD	MD	MIN	MAX	TP obs	M	SD	MD	MIN	MAX
CA	17	0.001	0.001	0.001	0.001	0.002	15	0.209	0.123	0.163	0.085	0.546
CC	15	0.002	0.001	0.002	0.000	0.003	13	0.125	0.095	0.087	0.051	0.409
CF	16	0.002	0.002	0.002	0.000	0.006	14	0.222	0.177	0.159	0.091	0.673
CM	16	0.001	0.001	0.001	0.000	0.002	14	0.194	0.149	0.142	0.083	0.568
P1	16	0.002	0.002	0.001	0.000	0.007	15	0.137	0.072	0.107	0.071	0.274
P2	15	0.002	0.001	0.001	0.000	0.004	14	0.131	0.073	0.102	0.058	0.300
P3	16	0.001	0.001	0.001	0.000	0.004	15	0.062	0.021	0.055	0.038	0.102
P4	16	0.002	0.001	0.001	0.000	0.004	15	0.082	0.046	0.067	0.050	0.222
P5	14	0.002	0.001	0.002	0.001	0.006	13	0.167	0.153	0.111	0.069	0.529
P6	16	0.002	0.001	0.002	0.001	0.006	15	0.115	0.067	0.091	0.060	0.274
P7	9	0.006	0.006	0.003	0.001	0.019	9	0.078	0.056	0.057	0.039	0.218

Table S3.2. Catchment cover in percentages for all catchments from 1962 to 2013. Catchment areas are in hectares shown in parenthesis

	CA	CC	CF	CM	P1	P2	P3	P4	P5	P6	P7
1962	(5.9)	(7.2)	(6.3)	(5.1)	(5.6)	(7.6)	(12)	(16.5)	(7.4)	(2.9)	(6.1)
Cane	23	80	34	46	86	74	46	51	6	81	80
Forest stage I	54	20	28	25	0	2	41	40	33	0	20
Forest stage II	8	0	22	7	4	11	9	2	0	13	0
Forest stage III	0	0	3	0	0	10	0	0	0	0	0
Forest stage IV	15	0	12	22	9	4	4	7	61	6	0
1978											
Cane	14	81	29	43	61	77	39	36	17	78	65
Forest stage I	70	0	17	24	0	0	0	11	0	0	28
Forest stage II	0	19	28	0	0	3	37	25	27	18	7
Forest stage III	0	0	13	3	31	9	19	20	26	4	0
Forest stage IV	15	0	14	31	9	12	5	8	30	0	0
1995											
Cane	68	89	45	63	70	82	33	39	31	76	83
Forest stage I	0	0	0	0	0	0	5	0	0	0	0
Forest stage II	17	0	7	0	0	1	0	0	0	0	12
Forest stage III	0	11	22	3	0	2	38	28	38	16	5
Forest stage IV	16	0	27	35	30	15	24	33	30	8	0
2000											
Cane	69	90	38	63	72	82	37	44	32	79	81
Forest stage I	0	0	0	0	0	0	1	0	0	0	0
Forest stage II	15	1	10	0	0	2	6	0	0	0	12
Forest stage III	0	0	19	3	0	0	31	1	0	3	7
Forest stage IV	16	9	33	35	28	16	24	55	68	18	0
2013											
Cane	1	91	38	31	72	82	37	44	28	75	81
Forest stage I	0	0	0	0	0	0	1	0	0	0	1
Forest stage II	68	0	1	31	0	0	0	1	4	0	8
Forest stage III	15	1	8	0	0	2	5	0	0	0	2
Forest stage IV	16	9	53	37	28	16	56	54	68	25	8

Table S3.3. Summary of peer-reviewed journal articles included in this research

Site name	*n*	Stream Order	LU category /	Biome	Reference
Lake Calado	1	1	Forest	Amazon forest	Lesack (1993)
CP	1	1	Forest	Amazon forest	McClain et al. (1997)
BB	1	1	Forest	Amazon forest	McClain et al. (1997)
Igarapé de	1	1	Forest	Amazon forest	Williams and Melack
Braço do	1	1	Agriculture / mixed	Amazon forest	Williams and Melack
Forest 1	1	2	Forest	Amazon forest	Neill et al. (2001)
Forest 2	1	2	Forest	Amazon forest	Neill et al. (2001)
1	1	1	Forest	Atlantic forest	Primavesi et al. (2002)
Pedra Branca	1	na	Forest	Atlantic forest	Vieira and Esteves (2002)
P3	1	1	Agriculture / cane	Atlantic forest and Cerrado	Silva et al. (2007)
P4	1	1	Agriculture / cane	Atlantic forest and Cerrado	Silva et al. (2007)
IG54	1	na	Forest	Amazon forest	Figueiredo et al. (2010)
IG7	1	na	Forest	Amazon forest	Figueiredo et al. (2010)
IGP	1	na	Forest	Amazon forest	Figueiredo et al. (2010)
CP	1	na	Forest	Amazon forest	Figueiredo et al. (2010)
Rural	3	mix	Agriculture / maize and soy	Cerrado	Silva et al. (2010)
Site 2	1	1	Forest	Atlantic forest and Cerrado	Bere and Tundisi (2011)
no name	6	mix	Forest	Amazon forest	Deegan et al. (2011)
4	1	unclear	Forest	Atlantic forest	Silva et al. (2012)
5	1	unclear	Forest	Atlantic forest	Silva et al. (2012)
no name	3	na	Forest	Amazon forest	Neill et al. (2013)
no name	4	na	Agriculture / soy	Amazon forest	Neill et al. (2013)
Many	15	mix	Agriculture / unclear	Atlantic forest	Sousa et al. (2013)
Córrego da	1	1	Agriculture / cane	Atlantic forest	Suga and Tanaka (2013)
Ib	1	na	Agriculture / unclear	Atlantic forest and Cerrado	Silva-Junior et al. (2014)
Ma	1	na	Forest	Atlantic forest	Silva-Junior et al. (2014)
Many	77	mix	Agriculture / mixed	Atlantic forest	Casatti et al. (2015)
E1	1	1	Agriculture / cane	Atlantic forest	Ferreira et al. (2015)
E4	1	3	Agriculture / cane	Atlantic forest	Ferreira et al. (2015)
I1	1	2	Agriculture / cane	Atlantic forest	Ferreira et al. (2015)
I2	1	3	Agriculture / cane	Atlantic forest	Ferreira et al. (2015)
I3	1	3	Agriculture / citrus	Atlantic forest	Ferreira et al. (2015)
I4	1	2	Agriculture / citrus	Atlantic forest	Ferreira et al. (2015)
Mãe D'Água	1	na	Forest	Atlantic forest	Moulton et al. (2015)
Correias	1	1	Forest	Atlantic forest	Gucker et al. (2016)
Complexo	1	1	Forest	Atlantic forest	Gucker et al. (2016)
Aguas	1	1	Forest	Atlantic forest	Gucker et al. (2016)
Sao Caetano	1	1	Agriculture / unclear	Atlantic forest and Cerrado	Gucker et al. (2016)
Carandaí	1	1	Agriculture / unclear	Atlantic forest and Cerrado	Gucker et al. (2016)
Capitão	1	1	Agriculture / unclear	Atlantic forest and Cerrado	Gucker et al. (2016)
Mexerica	1	1	Agriculture / unclear	Atlantic forest and Cerrado	Gucker et al. (2016)
Nelson	1	1	Agriculture / unclear	Atlantic forest and Cerrado	Gucker et al. (2016)

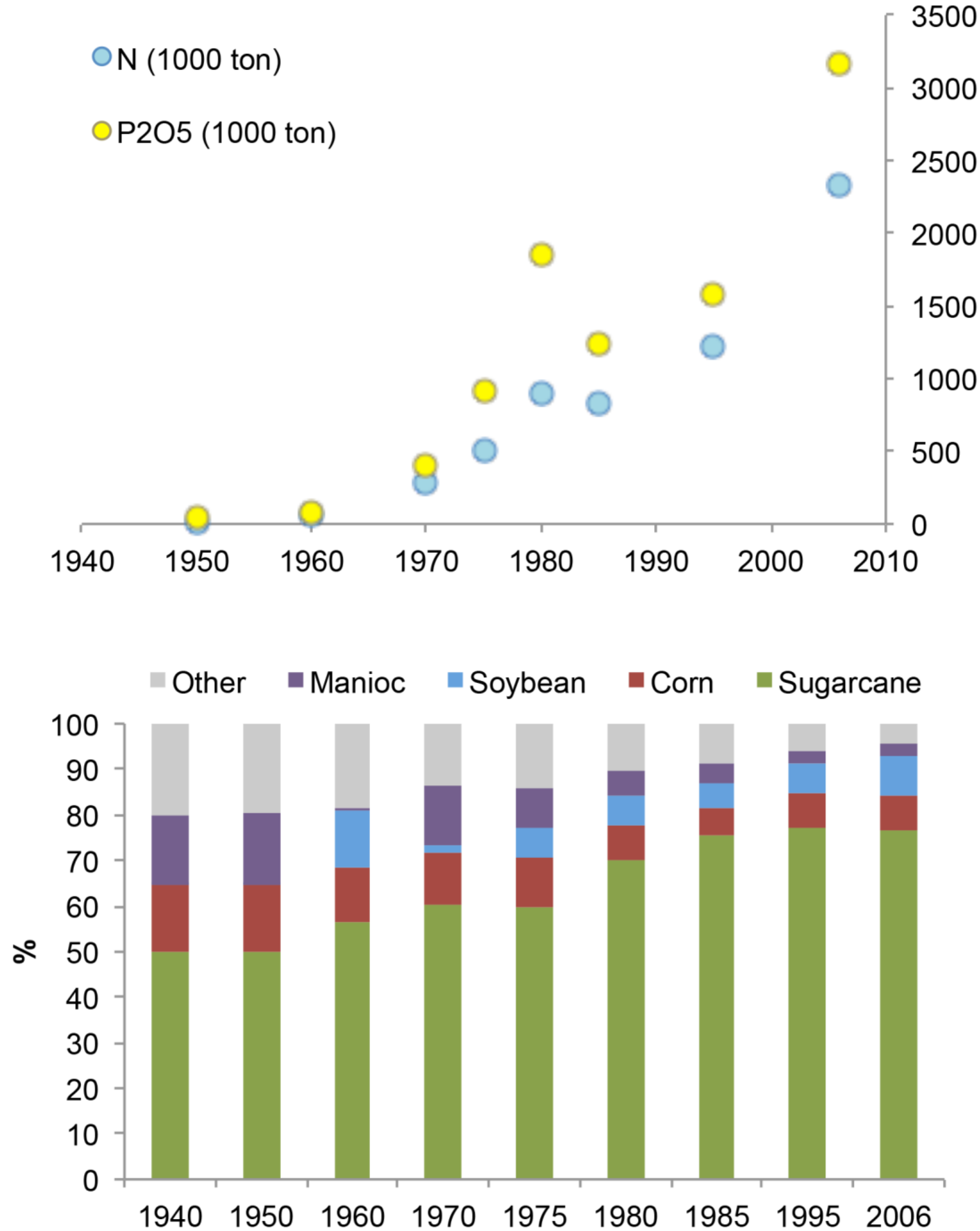

Figure S3.1. (top) Consumption of mineral fertilizer from 1950 until 2006. Source of data "Brazilian Association of Fertilizers" (ANDA 2015). (bottom) Proportion of total agricultural production (tons) in Brazil from 1940 until 2006. Source of data Brazilian Institute of Geography and Statistics (IBGE 2006a, b)

Summary

The objective of this dissertation was to investigate the effects of sugarcane agriculture on catchment geomorphology and headwater stream ecosystems in Brazil. To accomplish this, I first investigated whether sugarcane agriculture has been an important agent of geomorphological change via gully formation [Chapter 1]. Secondly, I assessed whether gully formation effectively direct concentrated flow from sugarcane fields while influencing the effectiveness of riparian buffers [Chapter 2]. In chapter 2, I also examined whether gully formation was an important factor controlling the stream's response to storm events, and the amount of sediment being transported in high flows. Finally [Chapter 3], I investigated whether land cover history in terms of sugarcane and forest cover could explain the variability in nutrient concentrations, while asking how the nutrient levels found by this research compared to levels found throughout Brazil where headwater catchments are impacted by newer, and other forms of intensive agriculture or are in natural vegetation.

In Chapter 1, I evaluated whether the sugarcane intensification process has become an agent of geomorphic disequilibrium by analyzing patterns of channel heads within geomorphic process domains. Process domains where described in terms of slope-specific contributing area (S-SCA relationship) for the study area. Then, I compared the location of the channel heads from two time periods within the process domains. Information on channel heads was from (1) official records prior to sugarcane intensification (1970's); and (2) recent field surveys. The results indicated that sugarcane intensification has been a key driver of gully formation. Additionally, the distribution of gullies within sugarcane fields as well as channel initiation thresholds has decreased

relative to geomorphic process domains over time. From a theoretical standpoint, the comparative analysis of S-SCA distributions of channel heads before and after sugarcane intensification revealed channel initiation thresholds that appeared less and less dependent on slope for a given contributing area through time. Such patterns may have resulted from management practices associated with modern sugarcane agriculture including unpaved pathways, and contour terracing with the potential to alter water routing, soil erosivity, and terrain slope to such an extent as to alter the entire catchment's geomorphic configuration.

In Chapter 2, I described the flow accumulation pattern within the study catchments using geographic-information system-methods, and quantified (1) the potential extent to which permanent gullies directed concentrated surface runoff from sugarcane fields and transportation land use to streams, and (2) the potential extent to which concentrated flow in permanent gullies affected the interception capacity of riparian buffers. Then, using metrics describing gully formation and other landscape characteristics together with hydrologic and sedimentological data, I developed a multi-catchment comparative study of the factors influencing the stream response to storm events, and the amount of sediment being transported during high flows in the headwater streams draining sugarcane fields. It was apparent from the flow map that the pattern of the hydrologic pathways across all study catchments was similar: surface runoff from sugarcane fields and dirt roads was being transmitted to the stream channels predominantly via concentrated flows, entering the channels in very specific locations. When concentrated flow was intercepted by gullies cutting through riparian buffers, the results indicated that it could be effectively directed to the existing stream channels.

Consequently, gully formation was shown to overwhelm any riparian buffer interception capacity of excess runoff and sediment from upslope source areas. This was confirmed with the results from the relationships between landscape variables, and the patterns of the streams' flow regime, and amount of sediment in high flows. I showed that catchments with high proportion of the upslope source areas flowing through gullies displayed greater response to storm events and transported more sediment during storms. These results contribute with much needed information about how intensive agricultural practices in certain regions of Brazil may be undermining the ecological function of riparian buffers because of gully formation.

Finally, in Chapter 3, to understand whether land use history in the study region was important in explaining contemporary stream nutrient concentrations, I (1) quantified the contemporary concentration of nutrients in streams draining catchments that have a long history of sugarcane agriculture, (2) determined if variability in these concentrations could be explained by the amount of sugarcane and forested land in the catchments over the prior 50 years, and (3) compared the nutrient levels found in this research to levels found throughout Brazil. The results suggested that N and P concentrations in streams draining sugarcane agriculture were much higher than previously reported. Different factors that might explain the magnified concentrations found for the study streams in relation to those in other regions of Brazil include the historical patterns of fertilization. While concentrations of N and P are high, amount or age of land cover in sugarcane was not a good predictor of N. Yet it was a statistically significant predictor for P but in a way that was not expected. This is in contrast to what have been extensively reported in the literature indicating that N and P concentrations increase consistently with increasing agricultural cover. Current data suggested that the geomorphological alterations of the catchments could be an important factor determining the observed patterns. Collectively, the results highlighted that the assessment of the influence of agricultural cover on stream N and P concentrations with traditional statistical approaches does not follow most of the previous literature.

One of the many motivations of this dissertation was to better inform watershed managers investing in riparian forest restoration in Brazil. This is due to the existence of an advanced environmental law in Brazil, the Forest Code. This law regulates the amount of forest that must be protected, and restored within private lands with the aim to conserve natural resources. Despite being probably the main legal mechanism requiring management strategies to protect streams within farmlands in that country, scientific information on its effectiveness to guarantee adequate water quality and quantity is rare. Nonetheless, revisions of the Code in recent years are taking place with serious consequences to the sustainability of water resources in the country.

In all three chapters, I documented the shortcomings of intensive sugarcane agriculture to headwater catchments and stream ecosystems. Although the concept behind restoring riparian buffers is promising to protect stream from non-point source pollution associated with agriculture, in reality, there are severe limitations of these forests when gully formation is common. These limitations are particularly associated with changes in stream hydrology, and high sediment transport associated with gullying; which are detrimental to streams, and may overcome any benefits of the riparian forest in terms of intercepting and processing excess runoff and sediment from upslope source areas. Geomorphic changes associated with gully formation may also significantly change the delivery of excess nutrient to streams, and the stream's capacity to process high nutrient concentrations. All these findings imply in greater complexity to not only assess the effectiveness of riparian buffers to protect streams from diffuse pollution, but, more importantly, indicate that there must be a shift in the discourse on the best strategies to protect streams in such highly geomorphic altered catchments.

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