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Modelling the effect of riparian vegetation restoration on sediment transport in a human-impacted Brazilian catchment

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ABSTRACT

Soil erosion threatens both soil and water resources and has increased globally because of the removal of natural vegetation and the intensification of existing agriculture. Brazil is privileged by a large proportion of natural vegetation and abundant freshwater. Recently, modifications of the Brazilian Forest Act (BFA) have been approved, which offer landowners that had committed illegal riparian deforestation in the past amnesty from reforestation, and further reductions of riparian protected areas are currently discussed. Here, we used the Soil and Water Assessment Tool to simulate river discharge and sediment exports in a typical human-impacted Brazilian catchment, the Rio das Mortes catchment. By restoring the riparian vegetation according to the BFA and ignoring amnesties to land owners, the current annual sediment export of the catchment of 0·830 t ha^{-1} was reduced by 29·4% according to our model. Further, simulated reforestation twice the size demanded by the BFA resulted in a 31·4% reduction of the current sediment export. However, reforestation of a 5-m homogeneous riparian corridor only, as currently discussed in the Federal Brazilian State of São Paulo, reduced sediment exports by only 23·8%, not considering expected additional erosion due to deforestation outside the simulated reforested 5-m corridor. Our study is the first catchment-wide assessment of the role of riparian vegetation in preventing soil erosion in Brazil. Its results support intensive reforestation efforts of the riparian zone and point to substantial negative effects of further reductions of the protected riparian corridor width and amnesties from reforestation to land owners. Copyright © 2016 John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

KEY WORDS Brazilian Forest Act; Catchment Modelling; erosion; riparian reforestation; riparian restoration; riparian vegetation; SWAT; SWAT-CUP; sediment export; Watershed Modelling

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INTRODUCTION

Brazil is among the countries with the highest diversity of biomes and proportion of natural land cover, with 5·4 million km^2 of natural vegetation of a total of 8·5 million km^2 However, this vegetation cover is largely not completely pristine and managed for human use (Sparovek *et al*., 2012). The conservation state of the Brazilian biomes is heterogeneous: In 2011, there was only 28% of the original Atlantic Rainforest cover left, whereas 77% of Amazonian Forest was intact (Sparovek *et al*., 2011). Despite its good conservation state, the Amazonian region has the fastest deforestation rate in the country, and an area as large as Belgium is deforested annually (30 500 km^2; Fearnside, 2005). The 'arc of deforestation' extends along the southern and eastern limits of the Brazilian Amazon, and usually, pasture is the result of this land conversion. However, there is a positive correlation between the average annual price of soybeans and the area converted directly to soy cropland in Mato Grosso, the Amazonian State with the highest deforestation rate (Morton *et al*., 2006). The second largest Brazilian biome, the Cerrado savannah, is a biodiversity and endemism hot spot and has one of the world's species richest savannah floras (>7000 plant species). Nevertheless, the Cerrado is also the most impacted Brazilian biome, and more than half of its 2 million km^2 has been converted to pasture or crop plantations (1970–2005; Klink and Machado, 2005).

The riparian zone is an ecotone between terrestrial and aquatic ecosystems and has important roles in maintaining water quality and aquatic ecosystems services (Sweeney *et al*., 2004). The effect of land use – in general, or specifically in the riparian zone – on soil erosion has not been studied yet in these Neotropical biomes at the catchment level, albeit it represents

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an important issue for land use planning and the protection of natural resources, such as soil, water and vegetation. The sole presence of riparian vegetation decreases the speed of the superficial run-off and in combination with root structures, stabilizes the soil of riverbanks, preserving water quality and contributing to soil protection (Allan *et al.*, 1997; Tabacchi *et al.*, 2000). Rivers draining agricultural areas have generally a high sediment yield, especially when the riparian buffer is narrow or absent (Allan *et al.*, 1997; Broadmeadow and Nisbet, 2004). Some of the basic positive effects of riparian buffers do not depend on buffers consisting of natural vegetation but are also exerted by buffers established as a means of environmental management (Barling and Moore, 1994; Simon and Collison, 2002). The riparian zone traps nutrients exported from surrounding crop plantations, reducing the omnipresent diffuse pollution from agricultural fields (Gücker *et al.*, 2009), a process that can occur likewise below-ground (Jordan *et al.*, 1993) or above-ground (Lee *et al.*, 2000). Pastoral streams have narrower channels, probably resulting from the denser root system of graminoids that prevent against stream-bank erosion and also from artificial stream narrowing for drainage purposes (Davies-Colley, 1997; Gücker *et al.*, 2009). Further, trampling by cows compacts the soil, decreasing infiltration and increasing erosion and sediment export to streams (Trimble and Mendel, 1995). The riparian vegetation has also indirect effects on the hydrologic cycle. Roots have high hydraulic conductivity compared with dry soils. When soil water content is low, the water absorbed by deep roots is lost to the superficial soil at night while trees have closed stomata, a process known as hydraulic lift (Caldwell and Richards, 1989; Jackson *et al.*, 1999). Additionally, the vertical redistribution of water within the soil through the roots occurs likewise in the opposite direction (i.e. downwards) when the superficial layers have more moisture than the deeper soil (Burgess *et al.*, 1998) If this inverse hydraulic lift occurs in the riparian zone after precipitation, the presence of trees would increase water infiltration and percolation, potentially decreasing the run-off.

Since colonial times, Brazil has benefited from strict regulations for the exploitation of natural resources (Sparovek *et al.*, 2011). For instance, the extraction of *Caesalpinia echinata*, which had highly priced wood, was only allowed by a written permit. However, this regulation did not aim at the conservation of the nature, but at providing the Portuguese Crown with the monopoly of the exploitation of this resource. Currently, the use of the land and the definition of permanent protection zones are regulated by the Brazilian Forest Act (BFA). Although dating back from 1965, the Brazilian Forest Act has had several appendices added to it along the years. In July 2010, the Brazilian parliament started an initiative to revise the Forest Act (Soares-Filho *et al.*, 2010), because it was seen as an obstacle to the further development of the agrarian sector and to be ineffective to protect natural areas. Albeit the need for revision was evident, there was no consistent scientific basis for this revision (Sparovek *et al.*, 2012). In the BFA, riparian zones are classified as Permanent Preservation Areas because of their importance for water and soil protection. The new Forest Act (Brazilian Federal Law 12.727, 2012) remained almost unchanged regarding the size for the riparian legal reserve, defined by the width of the channel. However, small landowners that had illegally expanded land use within the riparian zone received amnesty from legal penalty, and even worse, from the restoration of these areas. Moreover, riparian vegetation around water springs was formerly protected within a radius of 50 m, but this 50 m now apply only to areas where the original vegetation is still present; otherwise, reforestation must only cover a maximum of 15 m or even only 5 m in small rural properties. In December 2014, São Paulo State representatives approved a State law even more permissive regarding riparian zone protection (São Paulo State Law Project 219, 2014). In this State law, the specifications of the riparian zone Permanent Protection Area are proportional to the size of the rural property and not to the river width and can be as narrow as 5 m from the border of the channel. This law project waits now for the final approval by São Paulo's governor.

The Soil and Water Assessment Tool (SWAT; Arnold *et al.*, 2012) is a time-continuous, semi-distributed, process-based river catchment model developed to assess the impact of land use and land management on soil and streams. SWAT uses maps of topography, land use and soil type in combination with meteorological data to simulate diverse hydrological processes on the landscape scale. Processes are divided into land phase and channel routing. The land phase controls amounts of water, sediments, nutrients and pesticides transferred from sub-catchments to main channels, and the channel routing determines the flow of these components through the channel network towards the main outlet of the catchment. Since its description (Arnold *et al.*, 1998; Srinivasan *et al.*, 1998), the usage of the model has increased in number and diversity of applications, and the suitability of scale ranges from small-scale lysimeter observations (Pohlert *et al.*, 2007) to continent-wide studies (Schuol *et al.*, 2008). Recently, SWAT has been successfully used to estimate the efficiency of natural and diverse riparian buffers or single-species filter strips in management practices to reduce exports of eroded sediments to streams (Moriasi *et al.*, 2011; Rousseau *et al.*, 2013).

The objective of our study was to set up a hydrological model for discharge and sediment exports for an exemplary Brazilian river catchment affected by land use and riparian deforestation and apply the model to quantitatively estimate the potential decrease in erosive processes and riverine sediment transport for a scenario of complete restoration of the legal riparian buffer according to

Brazilian legislation, but ignoring the recent amnesty from reforestation. Additionally, we evaluated the benefits for a doubling of the permanently protected riparian area. We hypothesized a reduction of annual sediment exports to streams of at least 20% for the full restoration of the riparian buffer (44·8% of the 200-km^2 riparian buffer – defined as a continuous 30- to 50-m-wide riparian corridor according to the BFA – is currently deforested). Our study is a pioneer effort to assess the potential efficiency of the riparian legal reserve sizes established by the BFA for catchment soil and water quality protection.

METHODS

Study area

Total catchment area of the studied river, the Rio das Mortes, is ~6500 km^2 (Figure 1). The Rio das Mortes is a fifth-order river (Strahler stream order) with a total length of 278 km. Its headwaters are located in the rural zone of the town Barbacena, and its mouth is close to the town Ibituruna, where the Rio das Mortes joins the Rio Grande (upper Paraná basin). The only meteorological station from the Brazilian National Institute of Meteorology in the catchment is in Barbacena (21·25°S, 43·76°W, 1126 m above sea level). According to this station, the climate of the region is Cwb (Köppen–Geiger classification): mesothermal climate with dry winters, warmest month average temperature of below 22 °C, but at least 4 months with average temperature above 10 °C. Precipitation occurs mainly during the mild austral summer months and averages 1414 mm a^{-1}. The moderate winters are dry and free of frost (Figure 2).

The predominant original vegetation in the State of Minas Gerais is Cerrado savannah followed by Atlantic Forest (IBGE, 2004), and the long historical record of land use is dominated by the extensive cattle pasture. Since the colonial period, Minas Gerais had intensive mining activity with a focus on gold, iron and bauxite mining (Varejão *et al*., 2011). Rural activities such as cattle husbandry,

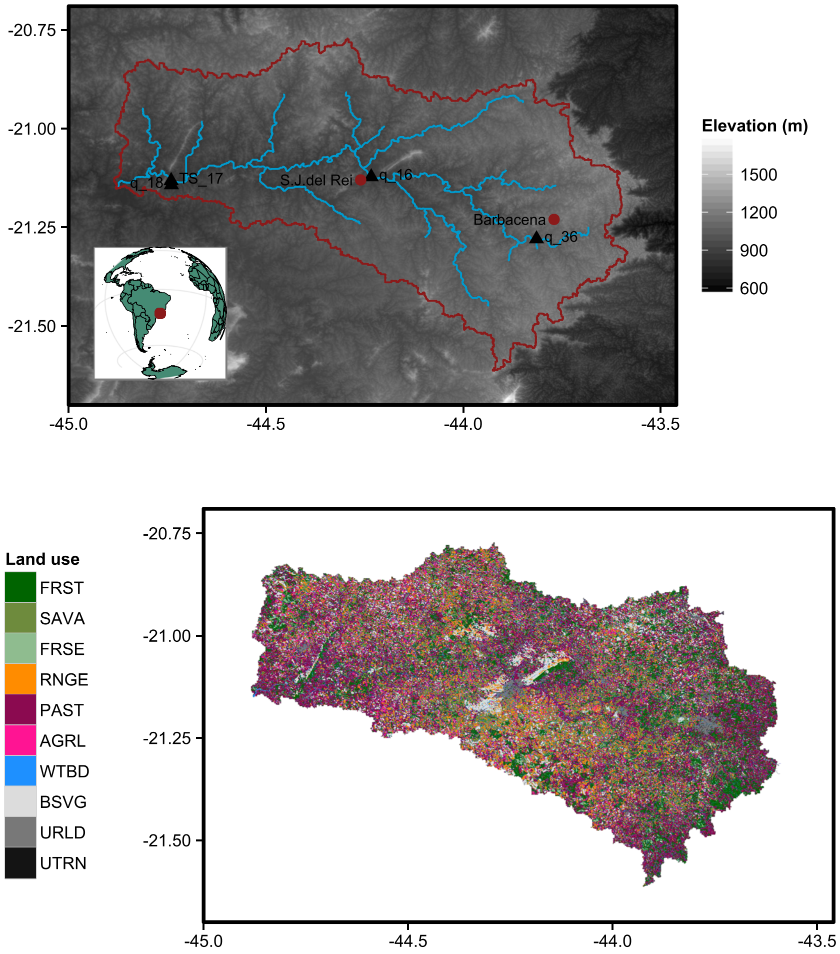

Figure 1. Top: Rio das Mortes catchment, located in Minas Gerais, Brazil. The border of the catchment is represented in red and the main streams in blue. The digital elevation model (90-m resolution) is represented in greyscale. Bottom: Land use distribution in the Rio das Mortes catchment according to the classification used in the Soil and Water Assessment Tool model.

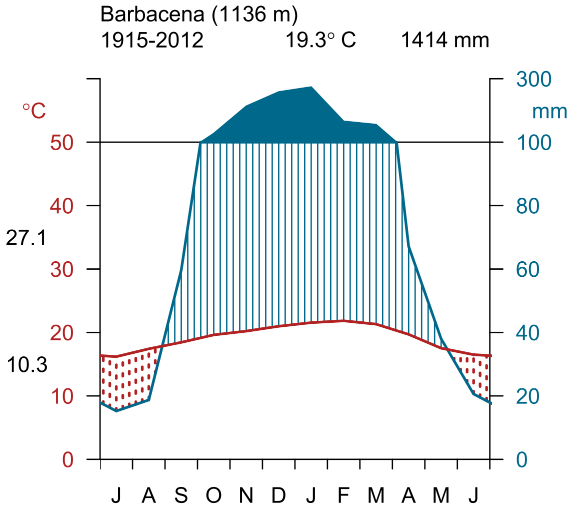

Figure 2. Walter and Lieth (1960) climate diagram for Barbacena. At the top of the panel, from left to right: period assessed, mean annual temperature and mean annual precipitation; the red line stands for mean monthly temperature (left axis), and the black numbers beside the axis are the mean daily maximum and mean daily minimum temperatures of the warmest and coldest months, respectively. Blue line represents precipitation, and the right axis shows precipitation at the ratio of 2 mm C^{-1} up to 100 mm and 20 mm C^{-1} from 100 mm on (left vs right axes). Dashed area indicates months with water stress and striped, and full areas indicate moist months. Note: For the southern hemisphere, the diagram starts on July to have the summer at the central zone.

small-scale agriculture and fish farms have negative impacts on water quality, increasing pollutant and nutrient exports to the running waters (Gücker *et al.*, 2009; Rosa *et al.*, 2013; Silva-Junior *et al.*, 2014). Pastures occupy almost 30% of the catchment, albeit another 9·2%, consisting of natural rangeland, is also extensively used for husbandry. Crop production is not a main activity in the region (5·7%). The largest natural vegetation biome is the Cerrado savannah that covers approximately 17·6% of the area, followed by the Atlantic Forest (15%; Figure 1 and Table I).

Set-up of the SWAT model

The Rio das Mortes catchment was divided into 39 subcatchments not larger than 130 km^2 (Figure SI1) and 752 hydrological response units (HRUs). The model was set up using the interface ArcSWAT 2012.10.12 for ArcGIS 10.2. from the following digital maps:

- digital elevation model: Shuttle Radar Topography Mission 90-m digital elevation data from the Consultative Group on International Agricultural Research Consortium for Spatial Information;
- soil map: the soil global map developed by the Unite Nations Food and Agriculture Organization with 9-km resolution; and
- land use and vegetation map with 30-m resolution (Silva-Junior *et al.*, 2014).

As meteorological input, we used maximum and minimum daily temperature and precipitation from the Climatic Research Unit, University of West Anglia, converting the monthly to daily values (Schuol and Abbaspour, 2007). From the global data set with spatial resolution of 0·5°, we selected five Climatic Research Unit stations inside or close to our study area.

The different land use categories of the catchment were classified into 10 categories present in the SWAT database

Table I. Soil and Water Assessment Test abbreviation, description, land area and percentage of catchment area for land use, soil and slope categories used in the Rio das Mortes model.

	Abbreviation	Description	Area (km^2)	%
Land use	PAST	Pasture	1953	30·0
	FRST	Forest – mixed	979	15·0
	SAVA	Savannah	1145	17·6
	FRSE	Forest – evergreen (*Eucalyptus*)	87	1·3
	AGRL	Agricultural land – generic	370	5·7
	BSVG	Barren or sparsely vegetated	573	8·8
	RNGE	Range – grasses	597	9·2
	WATR	Water	585	9·0
	URLD	Residential – low density	77	1·2
	UTRN	Transportation	142	2·1
Soil	Bd1-3b-5401	Ferralic Cambisols	5924	91·0
	Lf5-2b-5608	Ferric Luvisols	583	9·0
	Fo4-3b-5463	Orthic Ferralsols	5	<0·1
Slope	0–10		3571	54·9
	10–20		2780	42·7
	20–30		153	2·4
	>30		4	<0·1

(Table I and Figure 1). Primary forest (including riparian vegetation) and secondary forest were classified as mixed forest, *Eucalyptus* plantations were classified as evergreen forests, and the remaining categories correspond to the description in Table I. Soil, according to FAO, was classified into three soil types (Ferralic Cambisols, Ferric Luvisols and Orthic Ferralsols). The used soil map had a course resolution that affected the variability in the calculation of erosivity by SWAT. However, the three soil types present in the catchment are rather similar in terms of erosivity, and our main objective of quantifying the effect of land use on erosion mainly relied on a detailed land use map. Topography was summarized into four slope categories: 0–10°, 10–20°, 20–30° and >30°. HRUs were created by grouping unique combinations of land use, soil and slope conditions with the respective thresholds of 0%, 20% and 20%.

Calibration and validation

We used the semi-automatic calibration in SWAT-CUP with the Sequential Uncertainty Fitting Procedure (SUFI-2; Abbaspour *et al.*, 2007). The SUFI-2 algorithm for calibration maps uncertainties on the combined parameter ranges with the purpose of capturing most of the observations within the 95% prediction uncertainty (95 PPU). This way, the overall output uncertainty is represented within the 2·5–97·5% interval of cumulative distribution of an output variable obtained through simulations using parameters set by Latin hypercube sampling. We selected bR^2 (Krause *et al.*, 2005) as objective function to compare the performance of individual simulations, using the observations as reference. The statistics bR^2 is calculated by multiplying the coefficient of determination R^2 of the linear regression between simulation and observation by the slope of the regression b. The values of bR^2 range from 0 to 1, where 1 represents a perfect match between simulation and observation. The best solution of the model was considered the simulation with the highest bR^2, for which we also present the coefficient of determination (R^2), Nash–Sutcliffe coefficient (NS; Nash and Sutcliffe, 1970) and the percentage of bias (Pbias).

To assess the goodness of fit and the degree to which the calibrated model accounts for the uncertainties, we used the statistics *p*-factor and *r*-factor. The *p*-factor represents the fraction of observed data within the 95 PPU interval and varies from 0 to 1. The *r*-factor is obtained dividing the average width of the 95 PPU interval by the standard deviation of the observations, and values close to 1 are considered optimal (Abbaspour *et al.*, 2009). These two indices can be used to judge the quality of the calibration. A larger *p*-factor can be achieved at the expense of a larger *r*-factor. Hence, often, a balance must be reached between the two. When acceptable values of *r*-factor and *p*-factor are reached, then the parameter ranges are the desired parameter distributions representing model uncertainty.

For the calibration and validation of the model, we used monthly averages of three river discharge stations (Brazilian National Water Agency) and one trimonthly total sediment concentration series (Minas Gerais Institute for Water Management; Table II). The trimonthly total sediment concentration data were transformed into a monthly series of sediment load before entering into SWAT-CUP. We used the package *rloadest* (Lorenz *et al.*, 2013) that integrates the functions of the software LOADEST (Runkel *et al.*, 2004) into the R environment. The best model selected to predict sediment concentration in function of river discharge was the model 4 in LOADEST (AIC = 136·2; Pbias = −5·1%) described by the following general equation:

$$\begin{aligned} Variable = {} & a_0 + a_1 \times \ln_Q \\ & + a_2 \times \sin(2\pi \times decimal\ date) \\ & + a_3 \times \cos(2\pi \times decimal\ date) \end{aligned} \tag{1}$$

where a_{0-3} are fitted coefficients (Table III) and $\ln_Q$ is the $-\ln_{(stream\ flow)}$ − centre of $\ln_{(stream\ flow)}$.

Estimates, standard errors of estimates, *z*-scores and *p*-values and the statistical summary of the model are summarized in Tables III and IV.

Subsequently, we used the selected model to generate a daily series of sediment concentration based on daily discharge, which was converted to monthly sediment load

Table II. Station code, code used in the Soil and Water Assessment Tool (SWAT) referring to variable and sub-catchment, city, decimal latitude and longitude and length of the time series for discharge and sediment concentration stations used in the SWAT model for Rio das Mortes catchment.

Station	Code used	City	Latitude	Longitude	Data availability	Variable
61085000	Q_36	Campolide	−21·27940	−43·81440	1973–2006	Discharge
61107000	Q_16	Tiradentes	−21·12220	−44·23330	1973–2002	Discharge
61135000	Q_18	Ibituruna	−21·14250	−44·73970	1973–2006	Discharge
BG017[a]	TS_17	Ibituruna	−21·13194	−44·74028	1988–2006	Sediment

[a] The series for BG017 were completed with sediment data from station 61135000 collected with the same periodicity (four observations per year).

Table III. Estimated coefficients ($a_{0–3}$), standard errors, z-score and p-values for the fitted model to predict sediment concentrations in function of river discharge.

Coefficients	Estimate	SE	z-score	p-value
a_0	4·98531	0·08719	57·1763	<0·001
a_1	0·57521	0·23088	2·4914	0·0121
a_2	−0·03212	0·13615	−0·2359	0·8081
a_3	0·8521	0·14009	6·0824	<0·001

and used as observational data for the calibration in SWAT-CUP. We skipped 3 years as a warm-up period (1970–1972), calibrated the model over 25 years (1973–1997) and reserved 9 years for the model validation (1998–2006). We adjusted the average slope steepness (HRU_SLP.hru) and the average slope length (SLSUBBSN.hru) in SWAT manually to cope with general agricultural practices. A point source of water was added after Barbacena City to cope with the high use of underground water in the city (12% of the water consumption = 354 240 $\mathrm{m}^3\,\mathrm{month}^{-1}$). We also changed the channel resistance to erosion (CH_EROD.rte), setting it to 0 for the dry season and 0·6 for the rainy season, and we used the simplified Bagnold equation as a sediment routing method (CH_EQN.rte). The river discharge calibration was performed first and for each gauge separately, from the uppermost station downwards, substituting the final calibrated parameters for the respective dependent sub-catchments before proceeding to the next gauge (Table V). Finally, parameters related to sediment transport were calibrated by the same procedure for the entire catchment.

Scenarios of riparian vegetation recovery

We used the ‘automatic watershed delineation’ in SWAT 2012 to create a stream network with high spatial accuracy. The accuracy of the network was verified by a field survey of selected first-order streams. To identify the riparian legal reserve according to the BFA, we combined the digital stream network with survey data of river width in the catchment (Boëchat *et al.*, 2013), attributing a 30-m riparian buffer to first-order to third-order Strahler streams and a 50 m to fourth-order to fifth-order Strahler streams (Brazilian Federal Law 12.727, 2012). The condition of degradation of the riparian buffer was estimated based on the vegetation map. We considered the presence of pasture or crop instead of natural vegetation as degradation. Urban areas were not considered as degradation because their superficial run-off is channelized, and the presence or absence of riparian vegetation in urban areas has thus no filtering effect on the water flow entering streams.

Table IV. Summary statistics for the LOADEST model to predict sediment concentration in function of discharge for the Rio das Mortes catchment.

Period	p-factor	r-factor	R^2	NS	bR^2	Pbias
Total ($n = 70$)	0·010	2·10	0·33	0·332	0·182	−5·1

Measurements belong to the Ibituruna station.

The filter strip function of SWAT was used to simulate the recovery of the degraded riparian zone into natural vegetation. The filter strip is set up as a ratio of field area to filter strip area. Because this function is applied at the HRU level, we used the area of pasture or crop in each sub-catchment as field area, and the filter strip area was the fraction of the riparian legal reserve in the same sub-catchment classified as crop or pasture. We created three scenarios of recovery for the riparian zone. In the first scenario, the reforestation was realized in the complete riparian buffer, defined by the BFA (30- or 50-m buffer width, depending on river width). The second scenario consisted of a riparian buffer zone twice as large as defined by the BFA (60- or 100-m buffer width). Additionally, we explored a worst-case scenario based on the minimum riparian buffer width suggested by a new State law project (São Paulo State Law Project 219, 2014) and simulated reforestation only along a 5-m buffer along the streams.

Statistical analysis

To test for differences in sediment exports (annual rate of sediment transported from each sub-catchment to the main channel divided by its area) between the current scenario and three scenarios of simulated riparian vegetation reforestation, we used a mixed-effect model. The response variable sediment export was analysed as a function of the fixed factor scenario, and we included sub-catchment as random factor. The analysis was performed with the function ‘lme’ (package ‘nlme’; Pinheiro *et al.*, 2013) in the software R (R Development Core Team, 2013). The model was tested for normality and homoscedasticity (Zuur *et al.*, 2009). Further, we performed a multiple comparison Tukey test for differences between the current scenario and the three modelled scenarios.

RESULTS

Hydrologic model calibration and validation

Monthly river discharge calibration for the Rio das Mortes catchment showed generally acceptable results. On the headwater and central catchment, the 95 PPU interval captured respectively 49% and 41% of the observed data, whereas close to the main outlet, the model performed worse, with only 29% of the observations within the 95 PPU interval (p-factors; Table VI). However, for the validation period, p-factors increased for all three gauges

Table V. List of parameters used in the Soil and Water Assessment Tool watershed modelling for the Rio das Mortes catchment.

Parameter name	Sub-catchment/land use	Original value	Modification range	Final modification
r_CN2.mgt	30, 36	Variable	−0·1 to 0·1	0·039667
	12, 16, 20–28, 31–35, 37–39	Variable	−0·15 to 0·0	−0·03975
	1–11, 13–15, 17–19, 29	Variable	−0·15 to 0·0	−0·01325
r_SOL_AWC().sol	30, 36	0·14	−0·05 to 0·05	0·001167
	12, 16, 20–28, 31–35, 37–39	0·14	0·2 to 0·5	0·3945
	1–11, 13–15, 17–19, 29	Variable	0·2 to 0·5	0·3925
v_ESCO.hru	30, 36	0·95	0·1 to 0·5	0·440667
	12, 16, 20–28, 31–35, 37–39	0·95	0·01 to 0·2	0·16865
	1–11, 13–15, 17–19, 29	0·95	0·01 to 0·2	0·067317
v_CANMX.hru (FRST)	30, 36	0	0 to 40	4
	12, 16, 20–28, 31–35, 37–39	0	10 to 30	16
	1–11, 13–15, 17–19, 29	0	10 to 30	22
v_CANMX.hru (SAVA)	30, 36	0	0 to 40	5
	12, 16, 20–28, 31–35, 37–39	0	10 to 30	10
	1–11, 13–15, 17–19, 29	0	10 to 30	26
v_CANMX.hru (PAST)	30, 36	0	0 to 40	4
	12, 16, 20–28, 31–35, 37–39	0	10 to 30	14
	1–11, 13–15, 17–19, 29	0	10 to 30	11
v_HRU_SLP.hru	AGRL (slope > 10%)	Variable	—	0·02
v_SLSUBBSN.hru	AGRL (slope > 10%)	Variable	—	75
a_GW_DELAY.gw	30, 36	31	−30 to 60	1
	12, 16, 20–28, 31–35, 37–39	31	0 to 80	52
	1–11, 13–15, 17–19, 29	31	0 to 80	79
v_ALPHA_BF.gw	30, 36	0·048	0·0 to 1·0	0·625
	12, 16, 20–28, 31–35, 37–39	0·048	0·0 to 0·5	0·004167
	1–11, 13–15, 17–19, 29	0·048	0·0 to 0·5	0·1125
v_ALPHA_BF_D.gw	12, 16, 20–28, 31–35, 37–39	0·01	0·0 to 1·0	0·248333
	1–11, 13–15, 17–19, 29	0·01	0·0 to 1·0	0·141667
a_GWQMN.gw	30, 36	1000	−1000 to 2000	−835
	12, 16, 20–28, 31–35, 37–39	1000	−1000 to 1000	−837
	1–11, 13–15, 17–19, 29	1000	−1000 to 1000	377
v_GW_REVAP.gw	30, 36	0·02	0·02 to 0·1	0·039333
	12, 16, 20–28, 31–35, 37–39	0·02	0·02 to 0·06	0·041667
	1–11, 13–15, 17–19, 29	0·02	0·02 to 0·06	0·059667
a_REVAPMN.gw	30, 36	750	−1000 to 2000	−495
	12, 16, 20–28, 31–35, 37–39	750	0 to 1000	975
	1–11, 13–15, 17–19, 29	750	0 to 1000	355
v_RCHRG_DP.gw	12, 16, 20–28, 31–35, 37–39	0·05	0·0 to 1·0	0·118333
	1–11, 13–15, 17–19, 29	0·05	0·0 to 1·0	0·591667
v_CH_N2.rte	12, 16, 20–28, 31–35, 37–39	0·014	−0·01 to 0·3	0·157917
	1–11, 13–15, 17–19, 29	0·014	−0·01 to 0·3	0·07215
v_CH_EROD.rte (1–3, 11, 12)	—	0	—	0·6
v_CH_EQN.rte	—	0	—	1
v_CH_N1.sub	12, 16, 20–28, 31–35, 37–39	0·014	0·01 to 30	17·954018
	1–11, 13–15, 17–19, 29	0·014	0·01 to 30	4·758417
v_SPCON().bsn	—	0·0001	0·0014 to 0·0018	0·001498
v_SPEXP().bsn	—	1·0	0·5 to 2·0	1·8325

Original values, range for the 95 PPU and final calibrated value. Parameters are abbreviated as follows: CN2, SCS run-off curve number; SOL_AWC, soil available water storage capacity; ESCO, soil evaporation compensation factor; CANMX, maximum canopy water storage (mm); HRU_SLP, average slope steepness ($\mathrm{m\,m^{-1}}$); SLSUBBSN, average slope length (m); GW_DELAY, groundwater delay time (days); ALPHA_BF, baseflow alpha factor ($\mathrm{day^{-1}}$); ALPHA_BF_D, groundwater alpha factor ($\mathrm{day^{-1}}$); GWQMN, threshold depth of water in the shallow aquifer required for return flow to occur (mm); GW_REVAP, groundwater revap (water in shallow aquifer returning to root zone) coefficient; REVAPMN, threshold depth of water in the shallow aquifer for revap or percolation to the deep aquifer; RCHRG_DP, deep aquifer percolation fraction; CH_N2, Manning's *n* value for the main channel; CH_EROD, channel erosivity; CH_EQN, sediment routing method; CH_N1, Manning's *n* value for tributary channels; SPCON, linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing; SPEXP, exponent parameter for calculating sediment re-entrained in channel sediment routing.

Table VI. Summary statistics for calibration and validation periods of the Soil and Water Assessment Tool catchment modelling for the Rio das Mortes catchment.

Variable	Period	p-factor	r-factor	R^2	NS	bR^2	Pbias
Q_36	Calibration ($n = 296$)	0·49	0·76	0·70	0·57	0·68	−3·7
	Validation ($n = 97$)	0·59	0·78	0·77	0·59	0·69	11·5
Q_16	Calibration ($n = 295$)	0·41	0·94	0·72	0·56	0·65	15·8
	Validation ($n = 60$)	0·57	1·28	0·82	0·12	0·60	41·2
Q_18	Calibration ($n = 299$)	0·29	0·52	0·75	0·66	0·72	−6·2
	Validation ($n = 104$)	0·41	0·68	0·86	0·44	0·72	13·0
TS_17	Calibration ($n = 119$)	0·24	0·39	0·63	0·62	0·43	2·8
	Validation ($n = 105$)	0·28	0·69	0·73	0·37	0·59	35·6

and was never <0·4. Further, the width of the 95 PPU was not excessively large, with values always <1, except for the validation of q_16, with r-factor = 1·28. The correlation between simulations and observations was good for calibration and validation ($R^2 > 0·7$ and $bR^2 > 0·6$). Model efficiency was considered good, with most values of NS close to 0·6, with the exception of the validations of q_16 (NS = 0·12) and q_18 (NS = 44). Further, the percentage of bias was overall small (Pbias < 16%), with the exception of q_16, where bias for validation was >40%. The hydrographs for studied gauges are represented in Figure 3.

River discharge, sediment exports and the effect of simulated reforestation of riparian vegetation on sediment exports

The river discharge at the main outlet of the catchment had a 6·5-fold seasonal variation. January showed the highest monthly average of 307 ± 111 $m^3 s^{-1}$ ($n = 34$ years), while the lowest monthly average discharge of 48 ± 9 $m^3 s^{-1}$

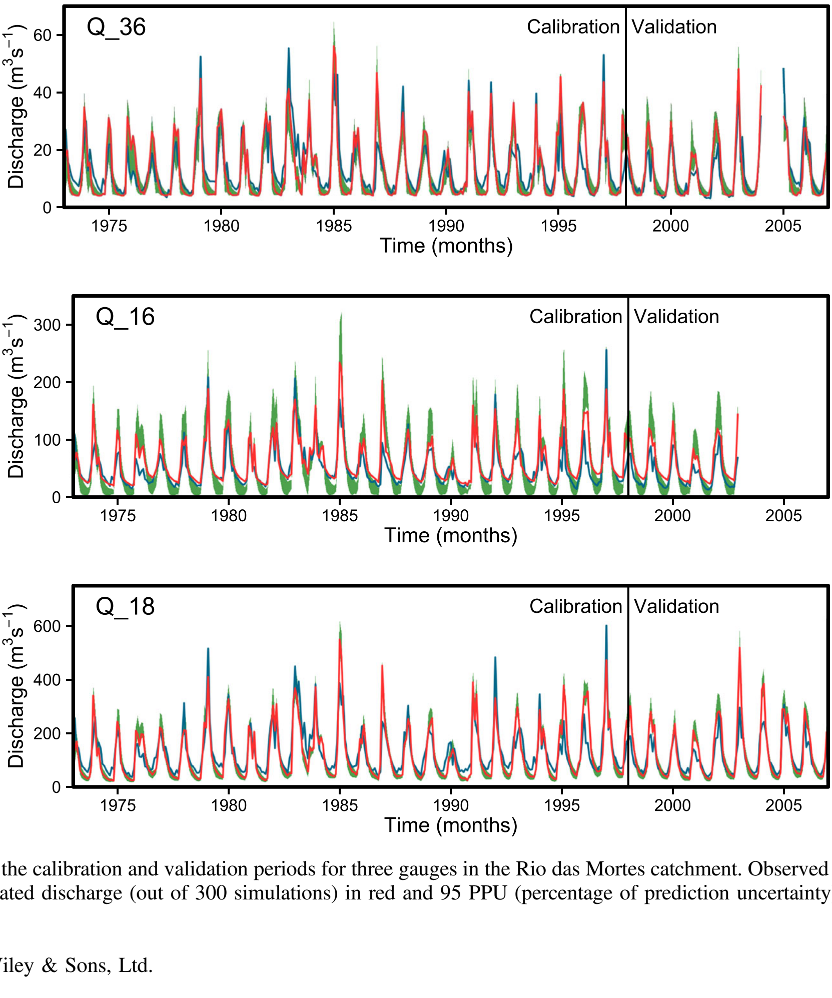

Figure 3. Hydrographs for the calibration and validation periods for three gauges in the Rio das Mortes catchment. Observed monthly mean discharge is in blue, best simulated discharge (out of 300 simulations) in red and 95 PPU (percentage of prediction uncertainty) interval in green.

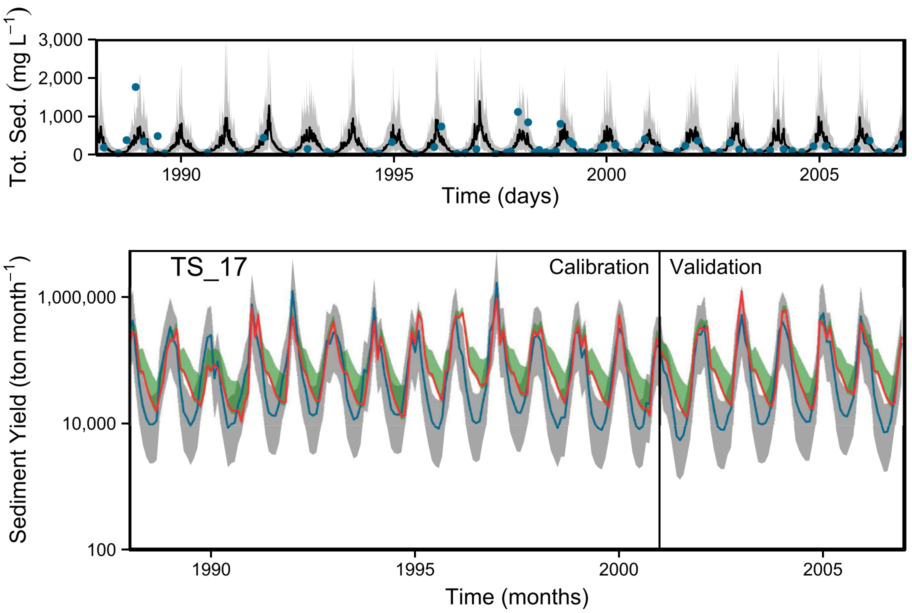

Figure 4. Upper panel – Daily concentration of total sediments obtained from model 4 of LOADEST (black line; Runkel *et al.*, 2004) and 95% confidence interval (grey area) for the 1988–2006 period. Observations that formed the basis for model calibration and validation are plotted as blue circles. Lower panel – Calibration and validation of sediment load for the Rio das Mortes catchment. Observed monthly sediment yield in blue, best simulated discharge (out of 300 simulations) in red and 95 PPU (percentage of prediction uncertainty) interval in green and 95% confidence interval for sediment load generated with the LOADEST model (grey area).

occurred in August (monthly means and SDs). In the whole period, the highest absolute monthly discharge was registered for January 1985 (606 m^3 s^{-1}), and the lowest absolute monthly discharge was 29 m^3 s^{-1} in September 1975, roughly twice and one-quarter of the highest and lowest monthly averages across the time series, respectively.

Our model divided the Rio das Mortes catchment into 39 sub-catchments with average areas of 167 km^2 (smallest and largest sub-catchments were 0·8 and 658·5 km^2, respectively; Figure SI1). The analysis of the high-resolution stream map resulted in a total legal riparian area of 200·0 km^2, roughly 3% of the 6508·5 km^2 of the catchment (Figure SI2). We estimated the degradation of the riparian zone (i.e. the part of the riparian zone converted to agricultural crop fields or pasture) to amount to 44·8%. The degradation in the riparian zone was higher compared with the fraction of the whole catchment occupied by agricultural activities, which summed up to 35·7% of the whole catchment.

The daily sediment concentration predicted by Loadest is illustrated in Figure 4 (top panel). We used the final model selected by Loadest to generate a daily sediment concentration series based on daily discharge. Daily sediment load was calculated by multiplying daily sediment concentration with daily discharge. Further, daily sediment load was converted to a monthly sediment load series by integrating daily values to monthly, and the monthly series was used in the calibration with SWAT-CUP. The 95 PPU for sediment load bracketed 24% of the observations within a thinner interval (*r*-factor = 0·39). Nevertheless, correlation of simulation and observation (R^2 = 0·63 and bR^2 = 0·43) and model efficiency (NS = 0·62) were considered good, and the percentage bias was the smallest obtained in this study (2·8%). Model statistics for validation was overall better than calibration, with the exception of NS and Pbias (Table VI).

Under current conditions, the sediment export averaged by year was 0·830 t ha^{-1} (minimum and maximum rates for sub-catchments were 0·27 and 2·06 t ha^{-1}; Figure 5). Most erosion occurred during the rainy season (October–March; 0·80 t ha^{-1}), and only a small part during the dry season (April–September; 0·03 t ha^{-1}; data not shown). The simulated reforestation of the entire riparian legal buffer area according to BFA, despite amounting to less than 1·4% of the total catchment area, resulted in a significant decrease in sediment export of 29·4% ($p < 0·001$; Tables VII and VIII). The reduction in sediment yield in the scenario of reforestation of a riparian area twice as wide as the legal riparian buffer zone resulted in an average annual reduction of 31·4% ($p < 0·001$) of the sediment export, representing only an additional 2·0% reduction compared with the first scenario (restoration of the riparian buffer according to the BFA). Further, the reforestation of degraded riparian vegetation within a 5-m-wide buffer only, i.e. our worst-case reforestation scenario, resulted in a 23·8% annual sediment export reduction ($p < 0·001$; Table VIII).

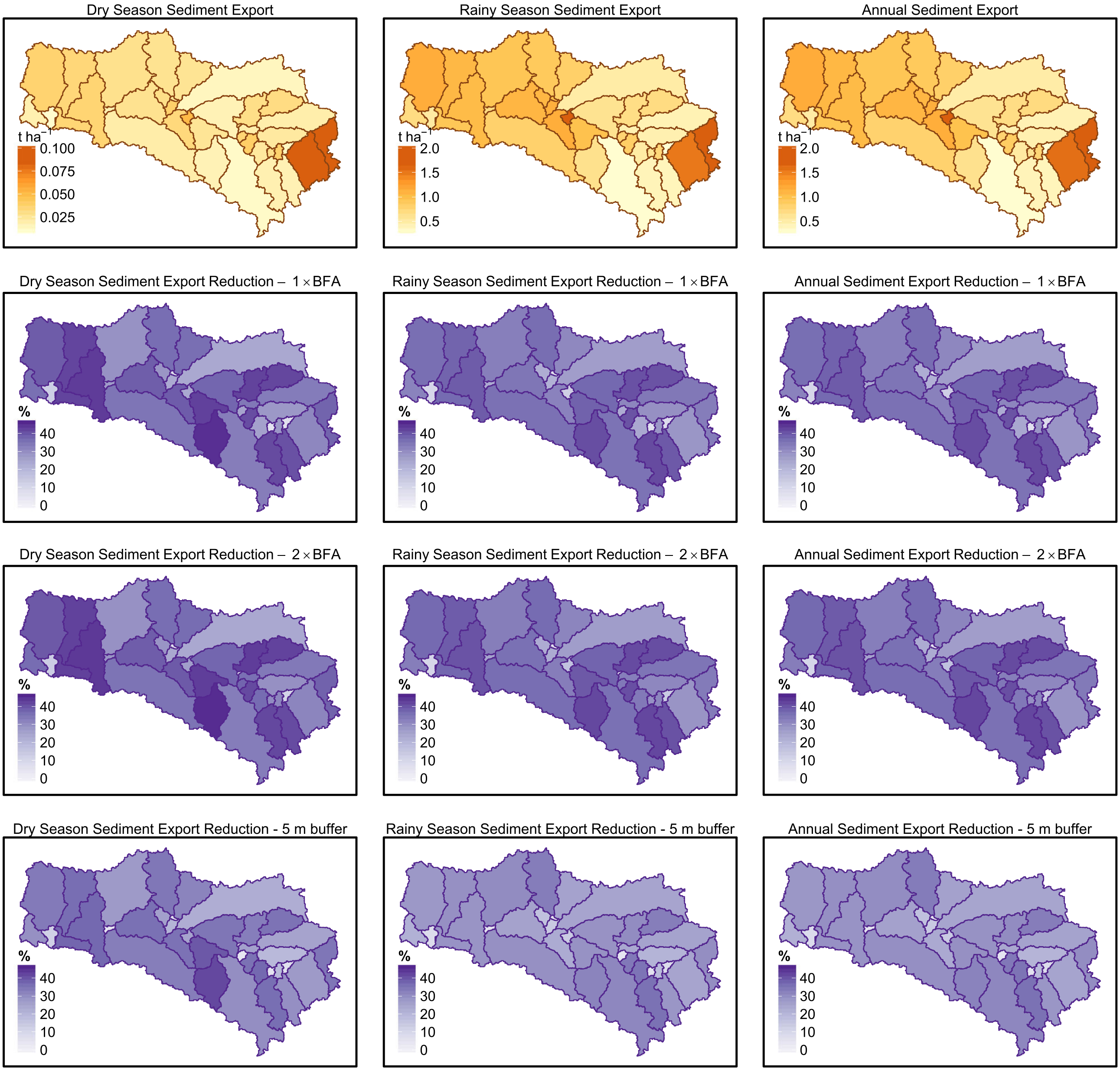

Figure 5. Average sediment export (t ha^{-1} a^{-1}; first row) and percentage of sediment reduction in simulated riparian reforestation according to Brazilian Forest Act (1 × BFA; second row), according to twice the width predicted by Brazilian Forest Act (2 × BFA; third row) and according to a 5-m riparian area reforestation (5-m buffer; bottom row). The left column shows results for the dry season according to Köppen classification (April–September), the middle column for the rainy season (October–March) and the right column shows annual results.

DISCUSSION

Our study is the first to use a semi-distributed catchment-scale model to assess the role of the restoration of the riparian vegetation in decreasing sediment exports from tropical catchments. Our simulation of riparian vegetation reforestation was carried out using the vegetative filter strip (VFS) module in SWAT (White and Arnold, 2009). The VFS was conceived by combining literature data for grassy filter strips with simulations of the process-based model VFSMOD (Muñoz-Carpena *et al*., 1999; Muñoz-Carpena and Parsons, 2005) into a sub-model for SWAT. The riparian vegetation in the tropics is usually composed of woody species (Tabacchi *et al*., 2000). Therefore, the used filter strip module for grassy vegetation may appear inappropriate for modelling woody tropical riparian vegetation. Grassy and woody vegetation differ in many physical and ecological aspects in their interaction with streams. Grasslands tend to have a denser root system, increasing the stability of the channel and generally producing narrower, deeper channels compared with woody riparian areas (Davies-Colley, 1997). While grassy

Table VII. Mixed-effect model and Tukey test comparing the effect of different scenarios of different riparian vegetation reforestations in 39 sub-catchments of the Rio das Mortes catchment in South-east Brazil.

Variable	numDF	denDF	F-value	p-value
Scenario	3	114	66·8	<0·001
Linear hypothesis	**Estimate**	**SD**	**z-value**	**p-value**
5 m − current = 0	−0·0160887	0·0018286	−8·798	<0·001
1 × BFA − current = 0	−0·0201158	0·0017669	−11·385	<0·001
2 × BFA − current = 0	−0·0214139	0·0017836	−12·006	<0·001
1 × BFA − 5 m = 0	−0·0040271	0·0005602	−7·189	<0·001
2 × BFA − 5 m = 0	−0·0053252	0·0006110	−8·716	<0·001
2 × BFA − 1 × BFA = 0	−0·0012981	0·0003891	−3·336	<0·001

riparian vegetation exhibits, in general, larger phosphorus assimilation, woody riparian vegetation assimilates nitrogen better than grassy riparian vegetation when the first is not composed of nitrogen-fixing species, such as *Alnus* spp. (Lyons *et al.*, 2000). Nevertheless, despite their different effects on dissolved nutrient trapping, sediment-filtering capacities seem to be remarkably similar in woody or grassy vegetation (Daniels and Gilliam, 1996; Lyons *et al.*, 2000; Yuan *et al.*, 2009).

To complete the daily sediment concentration time series, for which there were only trimonthly measurements ($n = 70$), the best model selected by LOADEST had an NS that could be considered satisfactory and very good Pbias, because the prediction was at a daily time step (Moriasi *et al.*, 2007). Nevertheless, the prediction uncertainty of sediment load was relatively high as indicated by low p-factor, high r-factor and low R^2, resulting in a wide confidence interval (Figure 4). This uncertainty must be taken into account when interpreting our sediment export results. However, our scenarios of riparian reforestation were calculated in SWAT models with the same calibrated parameters as the original model, and therefore, all models had similar uncertainty; thus, the relative differences between scenarios and the original model should be more reliable model results than the absolute export values.

Running waters deliver annually 16 Gt of sediments to the ocean (Ludwig and Probst, 1998). Nevertheless, the transport of sediments in streams is a slow process, and because of the combination of erosion and sedimentation, the residence time of sediment particles in streams is long. The sediment export from terrestrial systems to freshwater streams is estimated to range from 0·04 to 18·25 $\mathrm{t\,ha^{-1}\,a^{-1}}$, assessed from 60 worldwide distributed stations (Meybeck *et al.*, 2003). Studies reporting sediment export on the catchment level in Brazil are still scarce, and many of them refer to experimental catchments. An intensely managed catchment (<7% natural vegetation, >69% crops and husbandry) in a tropical humid region in the Paraíba State in North-east Brazil produced a sediment export of 0·17 $\mathrm{t\,ha^{-1}\,a^{-1}}$ (modelled with Erosion Potential Method (EPM); da Silva *et al.*, 2014). In recent years, the use of SWAT in Brazil has increased considerably; however, only two-thirds of the published studies present results for calibration, and only one-quarter present results for model validation (Bressiani *et al.*, 2015). In a large-scale application in the Rio São Francisco basin (630 000 $\mathrm{km^2}$) in East Brazil, sediment in-stream deposition increased from 7 to 27 $\mathrm{Mt\,a^{-1}}$, comparing pre-European settlement to present conditions (Creech *et al.*, 2015). In this study, the main model changes considered estimate pre-European settlement conditions involved the substitution of anthropic land uses by natural vegetation and removal of dams. Further, in the North-east Brazil region, sub-catchment sediment exports for the small catchment of Mamuaba (60·9 $\mathrm{km^2}$) ranged between 0·66 and 25·62 $\mathrm{t\,ha^{-1}\,a^{-1}}$ (average = 9·4 $\mathrm{t\,ha^{-1}\,a^{-1}}$; da Silva *et al.*, 2013). However, more than half of the sub-catchments had sediment export rates lower than 5 $\mathrm{t\,ha^{-1}\,a^{-1}}$, and rates larger than 20 $\mathrm{t\,ha^{-1}\,a^{-1}}$ mainly occurred in headwater sub-catchments that accounted for less than one-sixth of the catchment area. Our findings were close to the lowest range of the former study, but its result must be considered with care because, owing to the lack of sediment data, the SWAT model for the Mamuaba catchment was only calibrated for river discharge. In South Brazil, tobacco crops are important for the local economy, but represent a large source of sediment as they usually occupy hill slopes and have a demand for intensive drainage realized by tilling the soil in the direction of the slope. In the Arvorezinha catchment (1·19 $\mathrm{km^2}$), a South Brazilian catchment with tobacco plantations, sediment export rates of 1·47 $\mathrm{t\,ha^{-1}\,a^{-1}}$ (5-year observation average) were poorly simulated by SWAT, and overprediction of sediment exports was 474% (Uzeika *et al.*, 2012). These results were not validated, but authors report statistical metrics for model simulations year by year and with NS worse than

Table VIII. Annual sediment export (sed. exp.) by sub-catchment for the Rio das Mortes catchment, Minas Gerais, Brazil, for the current scenario of land use (current), and simulations of riparian vegetation reforestation according to the Brazilian Forest Act (1 × BFA), to twice the Brazilian Forest Act (2 × BFA) and to a fixed width of 5 m.

	Area (km^2)				Sed. exp. current (t ha^{-1})				Sed. exp. 1 × BFA (t ha^{-1})				Sed. exp. 2 × BFA (t ha^{-1})				Sed. exp. 5 m (t ha^{-1})				Sed. exp. reduction (%)		
No.	Sub-catchment	RA 1 × BFA	RA 2 × BFA	RA 5 m	1Qu.	$\tilde{x}$	$\bar{x}$	3Qu.	1Qu.	$\tilde{x}$	$\bar{x}$	3Qu.	1Qu.	$\tilde{x}$	$\bar{x}$	3Qu.	1Qu.	$\tilde{x}$	$\bar{x}$	3Qu.	1 × BFA	2 × BFA	5 m
1	302·9 (9; 25)	8·3 (52)	16·48 (50)	1·23 (52)	0·674	0·836	0·920	0·153	0·419	0·538	0·586	0·686	0·418	0·536	0·584	0·684	0·434	0·569	0·613	0·721	36·6	36·8	33·9
2	198·5 (5; 36)	5·82 (54)	11·53 (54)	0·88 (53)	0·610	0·783	0·848	0·145	0·413	0·541	0·583	0·650	0·409	0·534	0·579	0·645	0·444	0·586	0·631	0·705	31·9	32·4	26·7
3	4·5 (1; 29)	0·16 (20)	0·32 (20)	0·03 (22)	0·732	0·962	1·027	0·288	0·684	0·900	0·972	1·108	0·684	0·899	0·972	1·108	0·686	0·902	0·974	1·110	5·3	5·4	5·2
4	34 (4; 30)	1·15 (44)	2·29 (43)	0·17 (47)	0·824	1·015	1·092	0·245	0·628	0·774	0·844	0·977	0·621	0·766	0·839	0·972	0·677	0·831	0·904	1·037	23·3	23·8	18·1
5	506·6 (10; 24)	14·51 (43)	28·76 (42)	2·13 (42)	0·704	0·890	0·954	0·170	0·466	0·596	0·642	0·756	0·466	0·593	0·640	0·753	0·484	0·622	0·666	0·792	33·0	33·2	30·6
6	10·7 (2; 42)	0·53 (39)	1·05 (38)	0·05 (41)	0·538	0·682	0·697	0·162	0·408	0·520	0·534	0·636	0·400	0·501	0·520	0·622	0·512	0·640	0·655	0·795	23·9	25·9	5·9
7	25·6 (3; 29)	0·69 (38)	1·36 (37)	0·11 (35)	0·864	1·068	1·163	0·292	0·668	0·830	0·911	1·041	0·664	0·802	0·894	1·025	0·724	0·914	0·992	1·132	22·3	23·7	15·6
8	658·5 (5; 29)	19·69 (43)	38·97 (43)	2·79 (43)	0·359	0·473	0·506	0·112	0·252	0·346	0·371	0·416	0·252	0·346	0·370	0·416	0·259	0·352	0·381	0·428	27·0	27·1	25·2
9	416·7 (8; 33)	13·33 (45)	26·37 (44)	1·87 (44)	0·867	1·102	1·185	0·228	0·544	0·703	0·757	0·922	0·540	0·694	0·747	0·908	0·609	0·788	0·850	1·050	36·5	37·4	29·1
10	232·8 (6; 25)	6·9 (43)	13·66 (43)	1·04 (43)	0·828	1·030	1·097	0·216	0·530	0·667	0·716	0·864	0·523	0·658	0·706	0·852	0·586	0·756	0·814	0·984	35·3	36·2	27·0
11	116·8 (6; 12)	3·75 (28)	7·44 (28)	0·5 (28)	0·897	1·114	1·173	0·238	0·596	0·761	0·793	0·942	0·586	0·745	0·782	0·930	0·660	0·856	0·897	1·062	33·1	34·0	24·7
12	140·8 (5; 27)	4·35 (46)	8·64 (45)	0·61 (46)	0·521	0·687	0·718	0·103	0·308	0·402	0·429	0·514	0·306	0·398	0·424	0·510	0·335	0·454	0·480	0·574	40·6	41·2	34·0
13	39 (0; 46)	1·13 (46)	2·25 (44)	0·15 (46)	0·389	0·484	0·522	0·114	0·351	0·432	0·468	0·550	0·351	0·431	0·467	0·548	0·357	0·440	0·477	0·562	10·6	10·8	8·9
14	261·9 (8; 34)	7·9 (55)	15·39 (55)	1·17 (54)	0·803	1·014	1·088	0·192	0·484	0·624	0·675	0·817	0·477	0·614	0·664	0·802	0·543	0·707	0·765	0·942	38·5	39·4	30·7
15	300·8 (7; 36)	9·42 (53)	18·7 (54)	1·31 (53)	0·808	1·042	1·062	0·229	0·490	0·623	0·648	0·776	0·482	0·611	0·635	0·754	0·563	0·738	0·754	0·956	39·4	40·5	29·7
16	21·1 (5; 27)	0·54 (65)	1·1 (64)	0·09 (65)	1·504	1·864	2·059	0·535	1·306	1·634	1·794	2·109	1·228	1·589	1·708	1·992	1·286	1·616	1·766	2·072	14·0	18·1	15·4
17	0·8 (0; 56)	0·05 (60)	0·11 (66)	0·01 (56)	0·297	0·394	0·422	0·083	0·258	0·335	0·365	0·426	0·258	0·334	0·365	0·426	0·258	0·336	0·367	0·429	13·9	14·0	13·5
18	79·7 (4; 46)	2·42 (53)	4·81 (53)	0·36 (52)	0·756	0·938	0·952	0·218	0·472	0·572	0·601	0·727	0·468	0·567	0·594	0·715	0·520	0·664	0·674	0·823	37·3	37·9	29·9
19	84·3 (2; 56)	2·56 (55)	5·07 (56)	0·35 (54)	0·546	0·694	0·704	0·153	0·371	0·464	0·477	0·589	0·366	0·458	0·471	0·584	0·427	0·550	0·550	0·652	32·7	33·5	22·6
20	252·9 (3; 33)	8·67 (41)	17·17 (40)	1·13 (42)	0·316	0·419	0·438	0·072	0·207	0·274	0·289	0·346	0·206	0·272	0·286	0·343	0·228	0·311	0·327	0·394	34·5	35·1	26·2
21	118·9 (5; 25)	3·87 (33)	7·72 (32)	0·49 (34)	0·503	0·666	0·692	0·092	0·293	0·388	0·412	0·493	0·290	0·382	0·406	0·486	0·337	0·462	0·482	0·582	41·0	41·7	31·4
22	240·7 (5; 30)	9·01 (50)	17·78 (49)	1·14 (49)	0·477	0·600	0·622	0·113	0·300	0·369	0·392	0·479	0·297	0·366	0·388	0·473	0·323	0·418	0·441	0·562	37·4	38·0	30·1
23	2·1 (2; 41)	0·07 (55)	0·15 (54)	0·01 (52)	0·428	0·608	0·608	0·131	0·395	0·554	0·555	0·680	0·395	0·554	0·555	0·680	0·396	0·554	0·556	0·682	8·5	8·5	8·3
24	27·7 (2; 37)	0·93 (46)	1·85 (48)	0·14 (45)	0·320	0·440	0·461	0·065	0·212	0·294	0·315	0·392	0·210	0·286	0·309	0·383	0·235	0·330	0·349	0·439	32·2	33·5	25·2
25	130·5 (8; 20)	4·74 (54)	9·46 (52)	0·59 (56)	0·761	0·955	0·994	0·169	0·462	0·578	0·614	0·769	0·456	0·564	0·601	0·746	0·506	0·661	0·701	0·889	38·7	39·9	30·6
26	15·1 (3; 31)	0·44 (38)	0·89 (38)	0·06 (38)	0·563	0·756	0·805	0·120	0·422	0·568	0·619	0·773	0·356	0·476	0·529	0·654	0·539	0·710	0·766	0·936	24·3	35·0	4·8
27	42 (6; 35)	1·26 (54)	2·51 (53)	0·19 (52)	0·632	0·864	0·878	0·121	0·373	0·512	0·525	0·630	0·371	0·508	0·520	0·626	0·403	0·568	0·578	0·698	40·6	41·0	35·0
28	132·7 (2; 25)	3·91 (31)	7·76 (30)	0·57 (31)	0·332	0·432	0·461	0·090	0·231	0·300	0·326	0·396	0·227	0·293	0·318	0·387	0·259	0·341	0·366	0·453	29·8	31·4	21·4
29	549·5 (8; 19)	15·61 (35)	30·87 (34)	2·33 (34)	0·636	0·778	0·824	0·161	0·404	0·509	0·531	0·628	0·402	0·502	0·526	0·620	0·443	0·554	0·580	0·700	35·8	36·4	30·2
30	130·1 (0; 52)	3·65 (53)	7·22 (55)	0·54 (52)	1·394	1·800	1·864	0·324	0·909	1·172	1·239	1·533	0·906	1·164	1·232	1·526	0·950	1·235	1·302	1·614	33·8	34·0	30·5
31	211·9 (5; 27)	6·01 (43)	11·92 (43)	0·92 (43)	0·490	0·616	0·642	0·103	0·284	0·368	0·379	0·474	0·282	0·361	0·374	0·463	0·312	0·417	0·436	0·555	41·4	42·1	33·2
32	54·9 (3; 28)	2·05 (36)	4·06 (37)	0·28 (36)	0·380	0·506	0·530	0·079	0·282	0·386	0·403	0·498	0·242	0·327	0·349	0·424	0·239	0·322	0·344	0·417	25·2	34·8	35·7
33	16·7 (0; 36)	0·54 (53)	1·05 (55)	0·08 (57)	0·188	0·248	0·267	0·070	0·170	0·224	0·244	0·308	0·159	0·210	0·230	0·291	0·170	0·224	0·244	0·308	8·3	13·7	8·2
34	11·9 (2; 25)	0·34 (24)	0·69 (26)	0·03 (20)	0·443	0·614	0·626	0·138	0·418	0·569	0·586	0·716	0·306	0·428	0·442	0·542	0·419	0·570	0·588	0·718	6·2	29·9	5·9
35	21·1 (3; 27)	0·7 (39)	1·39 (37)	0·08 (39)	0·556	0·729	0·775	0·137	0·386	0·508	0·556	0·686	0·368	0·483	0·530	0·652	0·444	0·584	0·627	0·784	28·9	32·1	20·0
36	268·7 (1; 36)	8·02 (49)	15·74 (49)	1·15 (50)	1·184	1·543	1·602	0·350	0·824	1·081	1·145	1·459	0·820	1·079	1·140	1·454	0·855	1·125	1·201	1·524	28·9	29·2	25·5
37	142 (3; 34)	4·63 (40)	9·15 (40)	0·65 (40)	0·286	0·389	0·399	0·055	0·170	0·232	0·242	0·290	0·168	0·228	0·238	0·285	0·198	0·278	0·286	0·349	39·7	40·7	29·6
38	183·5 (4; 32)	5·35 (42)	10·62 (42)	0·85 (44)	0·298	0·406	0·412	0·055	0·172	0·236	0·242	0·295	0·171	0·235	0·240	0·293	0·187	0·262	0·266	0·325	41·6	42·1	36·2
39	519·5 (5; 34)	16·98 (46)	33·55 (46)	2·45 (47)	0·210	0·278	0·287	0·047	0·136	0·178	0·186	0·220	0·135	0·176	0·185	0·220	0·142	0·189	0·198	0·233	35·4	35·7	31·7
Total	6508·5	200·0 (44·8)	395·8 (44·4)	28·53 (44·8)	0·526	0·775	0·830	1·044	0·386	0·555	0·589	0·661	0·372	0·526	0·573	0·652	0·408	0·588	0·637	0·766	29·4	31·4	23·8

Columns show sub-catchment number (No.); sub-catchment area (in parenthesis, percentage occupied by agricultural crops and pastures); area of riparian buffer (RA) for scenarios 1 × BAF, 2 × BAF and 5 m (in parenthesis, the percentage of riparian degradation, pasture + agricultural crops); grouped by scenario, first quantile, median ($\tilde{x}$), mean ($\bar{x}$) and third quantile of annual sediment export. Following, the percentage reduction in sediment export for all three scenarios of riparian reforestation.

ours ($\text{NS} < -7{\cdot}0$). Again in South Brazil, in the catchment drained by the Arroio Lino stream where tobacco crop was even more abundant (90% of the catchment area, in comparison with ~55% in the Arvorezinha catchment), sediment export was estimated to be 14·5 t ha^{-1} a^{-1} (Bonumá *et al.*, 2013, 2015). Our study area showed much lower sediment export rates, probably resulting from the prevalence of pastures instead of crop fields. An assessment of erosivity using the Universal Soil Loss Equation in the Rio Grande catchment, the greater catchment in which our study catchment is nested, found that >53% of the catchment had potential soil loss larger than 5 t ha^{-1} a^{-1} (Beskow *et al.*, 2009). Our studied region had most likely forms of land management not as impacting as the tobacco crops of South Brazil mentioned before. Nevertheless, it is a gully erosion-prone region, which can contribute substantially to the catchment's sediment export to the streams (Thomaz, 2012).

Although there is still much uncertainty regarding the optimum width of riparian buffers for water quality management (Lee *et al.*, 2004; Richardson *et al.*, 2012), a general rule of thumb is that an 11- to 22-m buffer strip (on either side of the streams) should be effective for maintaining water quality standards, but up to 20–30 m should be necessary to protect the stream ecosystem (Barling and Moore, 1994). However, the literature lacks studies evaluating buffers narrower than 10 m, restricting conclusions on the filtering capacity of vegetated buffers relative to its width (Hickey and Doran, 2004).

The reforestation of riparian areas formerly used as pastures in Australia reduced the soil bulk density 1·4-fold, increasing infiltration rate 60-fold and (Gageler *et al.*, 2014), thereby decreasing run-off, which should in turn increase riverine sediment deposition. Regardless of filtering properties, natural riparian zones showed 30 times less erosivity than intensive sugar cane crops in South-east Brazil, as assessed by the Universal Soil Loss Equation method, resulting in estimated exports of 2 versus 58 t ha^{-1} a^{-1} (Weill and Sparovek, 2008). In an assessment of the benefits of using several best-practice managements in a Texan highly impacted catchment, filter strips simulated in SWAT to cover 12% of the catchment area resulted in 16·8% sediment export reduction at the sub-catchment level and 9·4% lower sediment load at the catchment outlet (Tuppad *et al.*, 2010). In a much larger catchment, the Upper Blue Nile catchment (~185 000 km^2), a 1-m filter strip simulated on the border of the agricultural fields (23% of the catchment area) reduced the sediment export by 29–68% at the sub-catchment level (Betrie *et al.*, 2011). To our best knowledge, a catchment-wide simulation of riparian reforestation using hydro-sedimentologic models in Brazil is still missing. However, a theoretical work by Sparovek *et al.* (2002) assessed the filtering effect of the riparian vegetation. The conceptual model was based on topography, land use and soil maps and aimed to calculate the optimal width of the riparian buffer based on defined maximum sediment yield threshold, using the Water Erosion Prediction Project to assess the efficiency of the riparian buffer to filter sediments (Flanagan and Nearing, 1995). For South-eastern Brazilian scenarios of sugar cane production (70% of the area occupied by this crop in a 77-ha catchment), a buffer of 52 m was necessary to reduce the sediment export from 15 to 12 t ha^{-1} a^{-1}, which represented an increase of 73% of the legal riparian reserve. In our study, substituting agricultural and pasture areas equivalent to <1·5% of the catchment by riparian filter strips resulted in a 29·4% reduction of sediment export. The riparian area had an average level of degradation of almost 45%, which represents a smaller restoration area, compared with the difference between optimum width and current legal width (52 m at 70% degradation) assessed by Flanagan and Nearing (1995). Moreover, despite a smaller reforested area, the reduction in sediment export in our study was larger.

Besides the influence on water quality for human use, sediment exports to streams have several ecological effects. Increased sediment concentrations in freshwaters increase turbidity and reduce light transmission, with consequent decreases in primary production (Van Nieuwenhuyse and LaPerriere, 1986; Davies-Colley *et al.*, 1992; Parkhill and Gulliver, 2002), with a potential subsequent effect on consumers. Elevated silt concentrations also have negative impacts on invertebrate communities of the hyporheic zone, the ecotone between streams and groundwater, by reducing hydraulic connectivity and thus oxygen and organic matter supply. Invertebrate hyporheic communities play an important role in maintaining the porosity of this ecotone, contributing to water exchange between groundwater and channel (Brunke and Gonser, 1997). Sedimentation also alters fish communities towards a smaller fraction of fishes that spawn preferably in cobble and gravel substrates and a larger fraction of mound-building and sub-tract excavators (Walser and Bart, 1999; Sutherland *et al.*, 2002).

Our results stress the importance of the riparian vegetation for maintaining adequate levels of water quality. The riparian corridor width currently protected by the BFA seems sufficient for the range of river widths studied. Nevertheless, the recent amnesty from reforestation granted to land owners that have illegally expanded their crop fields and pastures into protected riparian areas in the past negatively affects the water quality in our study catchment. Further, it is estimated that the recent changes in the BFA reduced the protected riparian area because of the changes in the definitions of the riparian buffers of small rivers and springs (Sparovek *et al.*, 2012). The State of São Paulo has recently approved a law project to reduce the protected riparian area, depending on the size of the property, in contrast to the river width-based protected riparian areas of the BFA. According to our model, restoring the riparian vegetation to the minimum riparian corridor width (5 m) in this law project – and ignoring the recent amnesty from reforestation – would decrease sediment exports from the Rio das Mortes catchment by only 23·8%, compared with a 29·4% reduction in the scenario with the restoration of the riparian corridor demanded by the BFA. Despite still sounding slightly positive, our model does not predict additional erosion effects of the highly probable deforestation that would occur outside the 5-m protected riparian corridor in this scenario. Our study demonstrated the benefits of the complete restoration of the protected riparian corridor according to the BFA in a representative human-impacted the Brazilian catchment and points to substantial negative effects of further reductions of the protected corridor width and amnesties from reforestation to land owners.

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