Tropical montane forest conversion is a critical driver for sediment supply in East African catchments

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Key Points:

- Agricultural catchments generated six times more suspended sediment yield than a forested catchment.
- Land use change towards agriculture shifted the dominant water pathways from deep subsurface to shallow subsurface flow and surface runoff.
- Delayed sediment responses were observed in a smallholder agriculture catchment, in contrast to fast responses in a forested catchment.

Abstract

Land use change is known to affect suspended sediment fluxes in headwater catchments. There is however limited empirical evidence of the magnitude of these effects for montane catchments in East Africa. We collected a unique four-year high frequency dataset and assessed seasonal sediment variation, water pathways and sediment response to hydrology in three catchments under contrasting land use in the Mau Forest Complex, Kenya's largest tropical montane forest. Annual suspended sediment yield was significantly higher in a smallholder agriculture-dominated catchment (131.5±90.6 t km^{-2} yr^{-1}) than in a tea-tree plantation catchment (42.0±21.0 t km^{-2} yr^{-1}) and a natural forest catchment (21.5±11.1 t km^{-2} yr^{-1}) ($p<0.05$). Transfer function models showed that in the natural forest and the tea-tree plantations subsurface flow pathways delivered water to the stream, while in the smallholder agriculture shallow subsurface and surface runoff were dominant. There was a delayed sediment response to rainfall for the smallholder agriculture and the tea-tree plantations. A slow depletion in sediment supply suggests that the wider catchment area supplies sediment, especially in the catchment dominated by smallholder farming. In contrast, a fast sediment response and depletion in sediment supply in the natural forest suggests a dominance of temporarily stored and nearby sediment sources. This study shows that the vegetation cover of a forest ecosystem is very effective in conserving soil, whereas catchments with more bare soil and poor soil conservation practices generated six times more suspended sediment yield. Catchment connectivity through unpaved tracks is thought to be the main explanation for the difference in sediment yield.

Keywords: Land use, temporal and spatial variability, suspended sediment, water pathways, tropical montane forests, Lake Victoria basin

1 Introduction

The conversion of native ecosystems to agriculture leads to the degradation of soil properties (Morgan 2005; Githui *et al.* 2009; Owuor *et al.* 2018), which can increase soil erosion rates (Bruijnzeel 2004). Soil erosion does not only deplete fertile topsoil from agricultural land, but also leads to water quality deterioration caused by an increase in fine suspended sediments (Brown *et al.* 1996; Quinton *et al.* 2001; Horowitz 2008). Hence, suspended sediment physically affects the fluvial network, (Owens *et al.* 2005) polluting drinking water for communities,

livestock and wildlife, and impacting downstream water reservoirs and hydropower generation because of the accumulation of the sediments (Mogaka *et al.* 2006; Foster *et al.* 2012; Wangechi *et al.* 2015). Additionally, pollutants such as pesticides (Brown *et al.* 1996) and nutrients (phosphorus or nitrogen) (Fraser *et al.* 1999; Quinton *et al.* 2001; Horowitz 2008) can be attached to sediments and can harm aquatic biota (Owens *et al.* 2005; Kemp *et al.* 2011; Gellis & Mukundan 2013). The increase in nutrient concentrations can result in eutrophication of water bodies (Foy & Bailey-Watts 1998; Hilton *et al.* 2006; Mogaka *et al.* 2006).

Land use change in catchments with strong connectivity between sediment sources and streams can abruptly increase sediment supply to the fluvial system (Fryirs 2013). There may be multiple sediment source areas, such as hillslope soils (Minella *et al.* 2008; Didoné *et al.* 2014), gullies (Poesen *et al.* 2003; Minella *et al.* 2008; Fan *et al.* 2012), riverbanks (Trimble & Mendel 1995; Lefrançois *et al.* 2007) and unpaved tracks (Ziegler *et al.* 2001; Minella *et al.* 2008; Ramos-Scharrón & Thomaz 2016). Unravelling sediment dynamics is complex and requires continuous high-frequency monitoring because suspended sediment concentrations change rapidly throughout individual storms (De Girolamo *et al.* 2015; Sun *et al.* 2016; Vercruysse *et al.* 2017). Alternatively, turbidity observations can be used as a surrogate to determine in-stream suspended sediment concentrations, which allow for establishing continuous *in situ* suspended sediment datasets, even for remote sites (Lewis 1996; Ziegler *et al.* 2014; Minella *et al.* 2018).

Streams in montane headwaters are major contributors to suspended sediment yield because of the steep terrain that leads to a strong hillslope to channel connectivity (Wohl 2006; Grangeon *et al.* 2012; Morris 2014). Significant increases in suspended sediment yield can be expected from tropical montane headwater catchments, which are heavily affected by deforestation followed by cultivation of erosion prone areas, often without soil conservation measures (Ramos-Scharrón & Thomaz, 2016; Wohl, 2006). Land use change may impact catchment hydrology and runoff mechanisms in the tropics (Muñoz-Villers & McDonnell 2013; Ogden *et al.* 2013), which are key processes determining sediment yields.

In East-Africa, land use change in tropical montane forests are mainly driven by scarcity of arable land (Pellikka *et al.* 2004) with the most fertile lands located in the proximity of natural ecosystems (Krhoda 1988). The Mau Forest Complex exemplifies this case, with one quarter of

the forest converted to agricultural land over the last four decades (Brandt *et al.* 2018), in addition to the clearances at the beginning of the 20th century to establish commercial tea plantations (Binge 1962). Due to its location in the highlands of Kenya, the Mau forest is a critical catchment area for the country; it is the headwater to twelve rivers, one of which is the Sondu River, a tributary of Lake Victoria (UNEP *et al.* 2005; Mogaka *et al.* 2006).

Eutrophication and sedimentation are major environmental problems affecting Lake Victoria, where sediments are estimated to accumulate at a rate of 2.3 mm yr^{-1} (Verschuren *et al.* 2002). Although authorities in Kenya acknowledge the need to reduce sediment pollution, the linkages between land use change and changes in sediment dynamics in the headwater catchments are not well quantified (Nyssen *et al.* 2004; Vanmaercke *et al.* 2010, 2014). There is limited data on sediment export for montane catchments in Sub-Saharan Africa in general, and in East Africa in particular (Walling & Webb 1996; Ntiba *et al.* 2001). Clearly, this is a significant gap in our knowledge of these environments that requires empirical measurements to address it. Not only will these measurements improve our understanding of these under-researched environments, but they will also assist in the development of targeted soil and water conservation strategies to disconnect sediment source areas in the upper catchments of the Mau Forest from the fluvial system and downstream environments, including Lake Victoria.

The overall aim of this study was to elucidate the spatial and temporal dynamics of suspended sediment and to quantify suspended sediment loads in tropical montane streams under contrasting land uses using a four year high-temporal resolution dataset. The main objectives were: (a) to quantify rainfall, streamflow and suspended sediment transport dynamics, (b) to compare the seasonal responses in suspended sediment yield, (c) to assess the timing of the response of suspended sediment to rainfall and discharge and (d) to improve our understanding of the dominant water flow pathways.

2 Materials and Methods

2.1 Catchment characteristics and site description

The three catchments studied are located in the headwaters of the Sondu River basin (3,470 km^2) in the Western Highlands of Kenya (Figure 1). Each catchment is dominated by a distinct land use: (1) natural forest (NF; 35.9 km^2), (2) smallholder agriculture (SHA; 27.2 km^2) and (3)

tea-tree plantations (TTP; 33.3 km^2). The Sondu River drains into Lake Victoria, which is the second largest fresh water lake in the world, an important water and economic resource for five countries and one source of the Nile River.

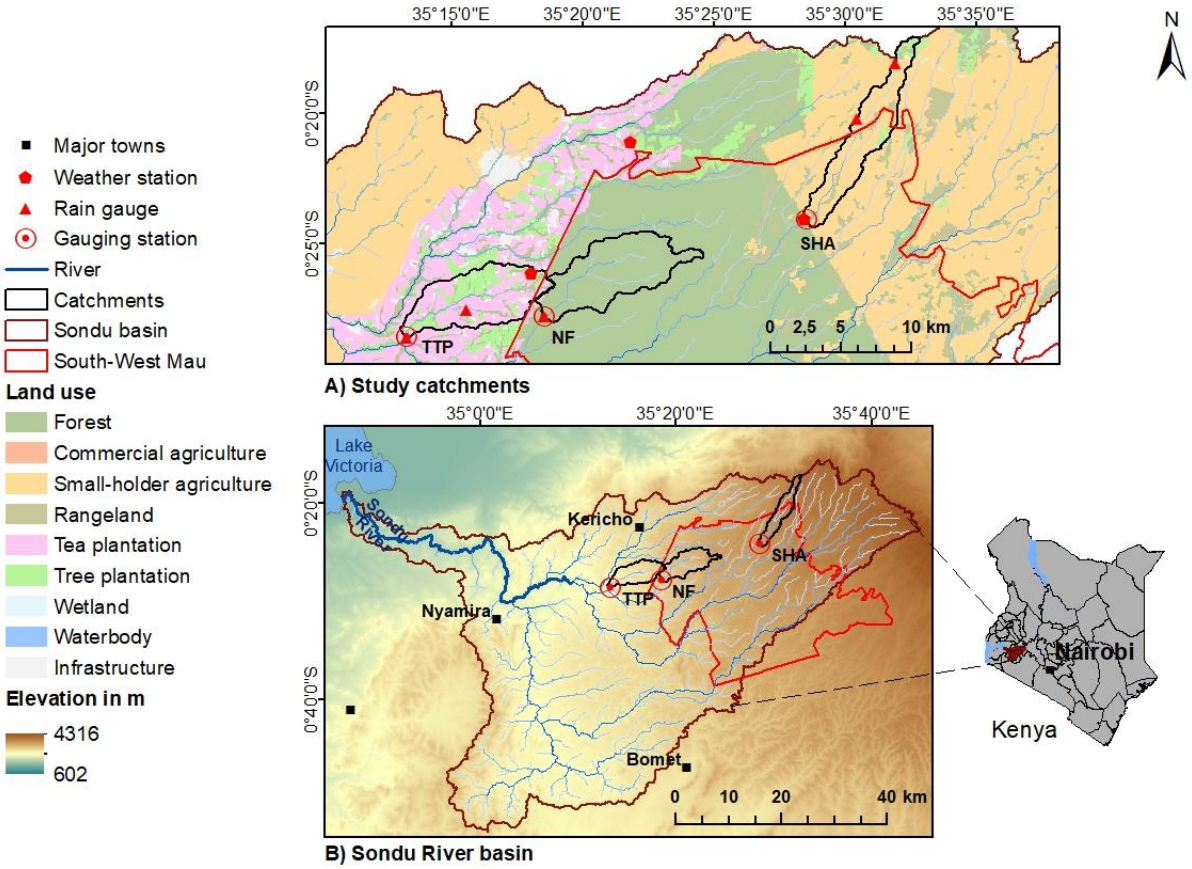

Figure 1 Overview of the A) study catchments: tea-tree plantations (TTP), natural forest (NF) and the smallholder agriculture (SHA), showing locations of gauging and weather stations, tipping bucket rain gauges and land use in the B) Sondu River basin and its outlet to Lake Victoria (SRTM digital elevation model 30 m resolution; USGS, 2000) in Western Kenya.

The three catchments (Table 1) are characterized by steep hillslopes with a maximum slope gradient of 72% in the natural forest catchment. The streams are mostly first- and second-order perennial streams that merge together to form the River Sondu (a sixth-order stream). The rainy seasons are bimodal with a long rainy season between March and June, and a short rainy season between October and December with a continued intermediate rainy season between the two wet seasons. Mean annual precipitation is 1,988 ± 328 mm (period 1905-2014) with rainfall peaks in

April and May (>260 mm month^{-1}). January and February (<95 mm month^{-1}) are the driest months.

Table 1 Physical characteristics of the three catchments under different land use natural forest, tea-tree plantations and smallholder agriculture in the South-West Mau, Kenya.

	Natural forest	Tea-tree plantations	Smallholder agriculture
Outlet coordinates[a]	35°18'32.0472"E 0°27'47.592"S	35°13'17.22"E 0°28'34.9176"S	35°28'31.7316"E 0°24'4.0248"S
Area (km^2)	35.9	33.3	27.2
Elevation range (m a.s.l.)	1,968-2,385	1,788-2,141	2,389-2,691
Mean slope ± SD (%)	15.7±8.4	12.4±7.6	11.6±6.7
Basin order (Strahler)	2	2	2
Drainage density (km km$^{-2)}$	0.48	0.42	0.64
Soil infiltration rate (mm hr^{-1})[b]	760±500	430±290	401±211
Geology[c]	Igneous rock (Volcanic) (100%)	Igneous rock (Volcanic) (100%)	Igneous rock (Volcanic) (72%) & Pyroclastic (28%)
Dominant soils[c]	Humic Nitisols (100%)	Humic Nitisols (100%),	Humic Nitisols (72%) & mollic Andosols (28%)
Vegetation	Afromontane mixed forest, grassland, bamboo, broad-leafed evergreen trees and shrubs	Tea plantations with woodlots of *Eucalyptus* spp., *Cypress* spp. and *Pinus* spp.	Perennial & annual crops (maize interspersed with beans, potatoes, millet, cabbage and onions), woodlots, grassland
Riparian vegetation	Forest vegetation	>30 m buffer with indigenous vegetation	Degraded riparian vegetation, Eucalyptus woodlots

[a]WGS 1984 UTM Zone 36S
[b]Owuor et al. 2018
[c]KENSOTER Geology data from the Soil and Terrain database for Kenya (KENSOTER) version 2.0

The natural forest catchment is located in the South-West Mau block of the Mau Forest Complex. The Mau Forest is an afromontane mixed forest dominated by indigenous broad-leafed evergreen trees and shrubs with a complex vegetation pattern. Riparian forests with a mixture of indigenous vegetation are present throughout the catchment. The natural forest catchment is characterized by high infiltration rates with the occurrence of shallow to deeper subsurface water pathways, whereas the tea-tree plantation and the smallholder agriculture catchments have lower infiltration rates with a dominance of surface runoff (Jacobs *et al.* 2018a; Owuor *et al.* 2018) (Table 1).

In the smallholder agriculture catchment, subsistence farmers grow maize interspersed with beans, potatoes, millet and cabbage on small farms (circa 1 ha). Small-scale tea plantations, eucalyptus (*Eucalyptus* spp.), cypress (*Cypressus* spp.) and pine (*Pinus* spp.) woodlots are interspersed with crop fields and grazing land (Table 1). A combination of hand weeding, hoeing and herbicides is used for weed control. Bamboo (*Bambusa* spp.) is generally found around natural springs. The whole catchment is connected by a dense network of unpaved tracks either bare or sparsely covered by grass; stream crossings rarely have bridges. The heavily travelled unpaved tracks have commonly become eroded gullies (Figure 2a-b), that run down the slope to rivers, connecting surface runoff from surrounding fields with the stream network (Figure 2c-e). Cattle entrance points to the stream are generally highly disturbed and have degraded riverbanks (Figure 2d-f). The natural riparian vegetation is in many areas replaced by Eucalyptus woodlots or small bushes. In some places, riparian wetlands are found.

Figure 2 a-c) Incised and unpaved tracks provide a direct connection with the stream, d-e) degraded and disturbed riverbank from livestock entering the streams and f) eroded suspended sediments in streams within the smallholder agriculture catchment.

The tea-tree plantation catchment has tea fields alternated with *Eucalyptus* spp. and *Cypress* spp. woodlots that are used for fuelwood at the tea factories. Some of the tea companies use mulch and rows of oat grass between rows of tea to control soil erosion during the establishment of new tea bushes. Herbicides are commonly used to control weeds. Cover crops with mature tea trees during the establishment of a new tea crop, terracing and sited cut-off drains are also used within the catchment to control soil erosion. The catchment is covered by a network of well-maintained paved and unpaved roads, linked to drainage systems, such as open culverts along the roads that connect them to the streams. The riparian vegetation includes a mix of indigenous tree species that cover densely the ground and form a buffer of approximately 30 m (Table 1).

The study area is composed of folded volcanics from the early Miocene times. Porphyritic phonolites, a member of the sequence of basic and intermediate lavas (igneous rocks) are

predominant in the study area (Binge 1962), where pyroclastic rocks cover the upper part of the catchment (ISRIC 2007). The study area comprises well-drained, very deep (>1.8 m) dark-red and dark-brown loamy soils (Sombroek *et al.* 1982), with moderate to high amounts of organic matter under the forest cover (Dunne 1979).

2.2 Automated hydrological and sediment monitoring

This study uses a four year dataset (January 2015 to December 2018) on rainfall, discharge and turbidity with a 10 minute resolution (Figure 1). A radar sensor (VEGAPULS WL61, VEGA Grieshaber KG, Schiltach, Germany) collected continuous water level measurements. Water level ('stage') was used to determine stream discharge based on a site-specific second-order polynomial stage-discharge relationship (Jacobs *et al.* 2018b). The calibration was checked over a wide range of stream flows using salt-dilution gauging (Shaw *et al.* 2011), an Accoustic Doppler Velocimeter (ADV; FlowTracker, SonTek, San Diego CA, USA) or an Acoustic Doppler Current Profiler (ADCP; RiverSurveyor S5, SonTek, San Diego, USA) depending on river size and discharge (Jacobs *et al.* 2018b). Specific discharge [mm day^{-1}] was determined by integrating instantaneous discharge taken at 10 minute intervals over a day and relating it to the catchment area. Precipitation was measured using eight automatic tipping bucket rain gauges calibrated to measure cumulative rainfall every 10 minutes with a 0.2 mm resolution (5 tipping bucket rain gauges: Theodor Friedrichs, Schenefeld, Germany, and 3 weather stations: ECRN-100 high resolution rain gauge). Using Thiessen polygons, we estimated the weighted contribution of rainfall of every tipping bucket in each catchment. A more detailed description of the study sites and instrumentation can be found in Jacobs et al. 2018b. Turbidity was measured *in situ* as a surrogate for suspended sediment concentrations using a UV/Vis spectroscopy sensor (spectro::lyser, s::can Messtechnik GmbH, Vienna, Austria). Turbidity is measured in FTU (formazin turbidity unit) by transmitting a beam of light to an optical receptor. With an increase in water turbidity the transmission of light decreases. To calculate sediment concentrations, a site-specific turbidity-suspended sediment calibration was established (section 2.3.1). Before each turbidity measurement, the window of the sensors was automatically cleaned by compressed air to remove any interfering particles. The sensors were additionally cleaned manually on a weekly basis using a specific cleaning agent recommended by the manufacturer to reduce biofouling on the measurement window and by manually removing debris and sediment.

2.3 Calibration, quality assurance and analysis

2.3.1 Sediment-turbidity rating curve

We used a site-specific, *ex situ* incremental suspension calibration to convert long-term turbidity records into an estimate of instantaneous suspended sediment concentrations (mg l^{-1}). A river water-sediment suspension with 16 to 18 concentration increments was established to simulate changing stream water suspended sediment concentrations occurring from low flow conditions (minimum 0 mg l^{-1}) to storm events (maximum 4,607 mg l^{-1}). The sediment suspension consisted of fine suspended sediment collected from sediment traps (time-integrated Phillips samplers) and fine soil material mixed with turbid river water collected during storm events. To ensure that only the clay size fraction remained in the suspension, the sediment suspension was decanted twice after the settling time for coarse particles (particle size >2 μm) had elapsed (Stokes law: 98 sec). The spectro::lyser probes from each monitoring station measured each concentration increment starting with river water representing low flow conditions (0 to 8 FTU). Small quantities of the synthetic sediment suspension were added at each concentration increment until the maximum measurable turbidity of 1,500 FTU was reached. The exact concentration was then determined gravimetrically from a 250 ml sub-sample at each increment. Total suspended sediment load was determined by multiplying suspended sediment concentration by discharge. Suspended sediment yield was calculated by integrating the sediment load over time and relating it to the catchment area. The sediment mass is reported in tonnes (t=megagrams) to conform with other published values.

2.3.2 Data quality assurance

Quality assurance of the turbidity, discharge and precipitation dataset was performed in two different ways. First, during equipment maintenance and manually downloading of the data any observed anomalities were recorded in a log book. Potential causes of anomalous values included (i) sensor above water level, (ii) turbidity sensor completely buried by deposited sediment during storm periods, (iii) biofilm or other phenomena on the measurement window due to malfunctioning of automatic cleaning with compressed air, (iv) measurement gaps due to incidents of power supply failure or (v) counting of number of tips by the rain gauges restricted by blocked funnel or spiderwebs. The readings for these periods were flagged with Not-a-Number (NaN).

After anomalous values were replaced by NaN, the median absolute deviation (MAD) was used to detect local outliers. The MAD has the following form:

$$MAD_i = b\, M_{i2}(|x_i - M_{i1}(x_i)|) \quad (1)$$

where x_i is the whole dataset, M_{i1} is the median of the dataset and M_{i2} is the median of the absolute deviation from the dataset from its median. The constant b estimates the standard deviation and was set to 1.4826 for normal distribution (Leys *et al.* 2013).

A moving window of k measurements around observation x_i at time t_i was used to detect local outliers with $x_j = (x_{i-k/2} \dots x_{i-1}, x_{i+1} \dots x_{i+k/2})$:

$$\frac{x_i - M_{j,i}}{MAD_{j,i}} > a \quad (2)$$

where a=6 is the threshold for outlier selection, $M_{j,i}$ is the median and the $MAD_{j,i}$ is the MAD for x_j, while the moving window k was set to 16. Missing sediment data was interpolated using a linear function.

2.3.3 Data analysis

All data were tested for normality with the Shapiro-Wilk test. We tested significant differences on suspended sediment, rainfall and discharge values among the different land uses using Kruskal-Wallis test for analyses of variances. To detect the significance of the effect of land use on the hydrological and sedimentological parameters, and within and among seasons on suspended sediment load we used the pairwise Wilcoxon rank sum test.

Five seasons, dry season, start of long rains, long rains (long rainy season), intermediate rains (season between the long and short rainy season) and short rains (short rainy season), were identified to calculate their contribution to annual suspended sediment yield (Jacobs *et al.* 2018b). The periods were chosen based on exceeding a threshold of monthly specific discharge for each catchment. The seasons for each year vary in length and timing due to variations in the onset of the rains and monthly streamflow (Figure 3).

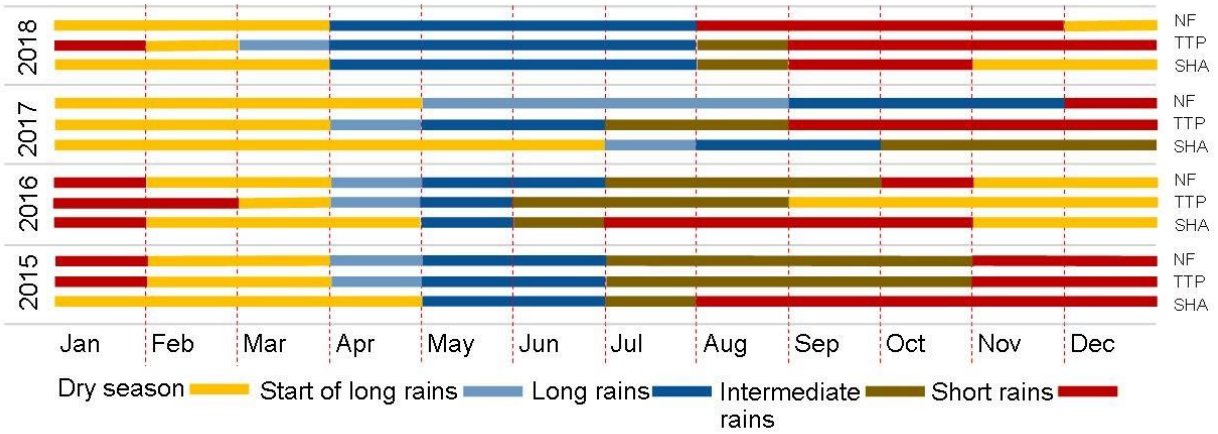

Figure 3 Timing of the five hydrological seasons for the natural forest (NF), tea-tree plantation (TTP) and smallholder agriculture (SHA) catchment during the observation period January 2015-December 2018.

2.3.4 Modelling flow pathways

A linear continuous-time (CT) transfer function (TF) model with rainfall-runoff non-linearity was used to identify the dynamics that explain the response of water flow pathways to rainfall within a catchment by conceptualising a *Single-Input, Single-Output* (SISO) system (Young & Garnier, 2006). These types of models are equivalent to systems of linear differential equations and can be applied in numerous mass and energy transport as well as chemical or biochemical proccess applications, including flow and sediment delivery models (Chappell *et al.* 2006). The

transfer function modelling process follows the *Data-Based Mechanistic* (DBM) modelling philosophy, searching through a range of model structures, ordering them according to statistical criteria, then retaining models that have a physical explanation (Young & Beven 1994). The DBM approach produces parsimonious models describing rainfall-runoff relationships, that include very few tuneable parameters (Lees 2000). Hourly time series of rainfall [mm hr^{-1}] was used as input, and the corresponding hourly time series of discharge [m^3 sec^{-1}] as output (the units conversion is absorbed into the model coefficients, in case of Eq. 6 – into coefficient b_0). These parameters have hydrological interpretation, describing hydrological pathways, so while these are not strictly hydrological models derived from the process models, they still apply to hydrological systems (Beven 2012).

Hydrological processes are known to be non-linear (Beven 2012), with the effectiveness of rainfall (amount of rainfall converted into discharge) dependent upon the state of saturation of the catchment. Therefore, the rainfall-runoff non-linearity is modelled using the Hammerstein model structure, with the input (rainfall) transformed using a non-linear function into what is termed 'effective rainfall', which then drives the linear dynamics of the transport process model. This study uses a power law relationship between measured rainfall and effective rainfall as surrogate for soil moisture to translate rainfall to effective rainfall (See text S1 for more details). Effective rainfall is the dynamically changing proportion of rainfall representing the volume of streamflow generated after soil moisture storage is deducted from the total rainfall (Beven 2012). The RIVCBJ (Refined Instrumental Variable Continuous Time Box-Jenkins Identification, for continuous models, Young and Garnier, 2006) algorithm was used to estimate model parameters. RIVCBJ is a component of the CAPTAIN toolbox which runs within MATLAB® (Taylor *et al.* 2007). The linear CT transfer function model has the following form:

$$Y(s) = \frac{B(s)}{A(s)} U(s) e^{-s\tau} + E(s) \qquad (3)$$

$A(s)$ and $B(s)$ characterise the dynamic relationship between the input and the output signals in the Laplace operator domain. The Laplace operator is the Laplace frequency domain equivalent of the time derivative operator $s \sim \frac{d}{dt}$. Functions $A(s)$ and $B(s)$ are constructed as polynomials in the s domain as follows, with m and n being the respective orders of the numerator and denominator polynomials:

$$A(s) = s^n + a_1 s^{n-1} + \cdots + a_n s^0 \quad (4)$$

$$B(s) = b_0 s^{m-1} + b_1 s^{m-2} + \cdots + b_m s^0 \quad (5)$$

In Eq. (3) $Y(s)$ denotes the Laplace transform of the output signal as hourly streamflow [m^3 sec^{-1}], $U(s)$ is the Laplace transform of the input signal hourly rainfall [mm hr^{-1}], $E(s)$ are the model residuals and $e^{-s\tau}$ is the Laplace transform of time delay τ representing the pure time delay (as opposed to the dynamic lag resulting from the system's dynamics) in time units between the input and output signals.

In this study, up to third order models were tested for all the sites and model fit was evaluated according to the coefficient of determination (R_t^2) (also known as the Nash-Sutcliffe efficiency) (see text S2) and the Young Identification Criterion (YIC) (see text S3 and S4). First order transfer function models were selected for the three catchments, where each system has a different depletion time, determined by its time constant. A first order continuous time transfer function model is written as:

$$Y = \left(\frac{b_0}{s+a_1}\right) e^{-s\tau} U = \left(\frac{SSG}{sTC+1}\right) e^{-s\tau} U \quad (6)$$

where $1/a_1$ is the time constant and the parameter b_0/a_1 represent the Steady State Gain (SSG) of the hypothetical pathway of rainfall through the catchment with a and b as the dynamic response characteristics. The time constant (TC) reflects the response between the input (rainfall) and the output (runoff or streamflow) (Young & Garnier 2006). Linear CT transfer function models were identified for each year between 2015 and 2018 for all three catchments.

2.3.5 Sediment response to hydrological variables

We used the cross-correlation function (CCF) to identify the statistical correlation between two sets of time series at different time lags (Lee *et al.* 2006; Mayaud *et al.* 2014). Rainfall and discharge time series were cross-correlated with the suspended sediment concentration time series. The peak response time between either precipitation or discharge to sediment concentrations was calculated as the delay time in time lags together with its correlation strength between these variables. Cross-correlation functions were calculated as:

$$CCC(\tau) = \frac{\frac{1}{n}\sum(x_i - \bar{x})(y_{i-\tau} - \bar{y})}{\sigma_x \sigma_y} \quad (7)$$

where $CCC(\tau)$ is the cross-correlation coefficient at time lag $\tau, \tau = 0, \pm 1 \pm 2 \ldots \pm m$ between the two time series (sampled every 10 minutes), where x_i is observed rainfall or positive derivative of discharge at sample number i and $y_{i-\tau}$ is the suspended sediment concentration at sample number $i - \tau$, $\bar{x}$ is the mean rainfall or positive derivative of discharge, $\bar{y}$ is the mean suspended sediment concentration, σ_x is the standard deviation of rainfall or estimated positive derivative of discharge and σ_y is the standard deviation of suspended sediment and n is the number of data points. At the 95%-confidence interval, lag-time correlations are significant when $CCC(\tau)$ exceeds the standard error of $2/\sqrt{N}$, where N is the length of the dataset (Diggle 1990). The positive derivative of discharge, i.e. the estimated rate of change on the rising limb of the hydrograph, was selected because the main sediment pulses are mostly generated during the rising limb (Alexandrov *et al.* 2003; De Girolamo *et al.* 2015). A similar derivative effect has been observed in dynamic sediment load models by Walsh et al. (2011). The CCF analysis was carried out for each year between 2015 and 2018 for all three catchments.

3 Results

3.1 Hydrological response of the three catchments

Mean annual rainfall for the study period was 1,842, 1,730 and 1,554 mm yr^{-1} with maximum hourly rainfall over the whole observation period of 37.4, 33.1 and 27.5 mm hr^{-1} for the natural forest, tea-tree plantations and smallholder agriculture catchments, respectively. The wettest year for the smallholder agriculture catchment was 2018 with 1,823 mm yr^{-1} of rainfall, while for the natural forest and tea-tree plantations precipitation was highest in 2015 with 1,986 and 1,928 mm yr^{-1}, respectively. The annual mean specific discharge was 632±157, 610±153 and 621±224 mm yr^{-1} for the natural forest, tea-tree plantations and smallholder agriculture catchments, respectively. The catchment runoff coefficient was similar for the natural forest and the tea-tree plantations with a mean of 0.34 and 0.35, respectively, and 0.39 for the smallholder agriculture (Table 2).

339 Table 2 Hydrological characteristics and total suspended sediment (and 95%-confidence interval) for the
340 three catchments under different land use natural forest (NF; 35.9 km^2), tea-tree plantations (TTP;
341 33.3 km^2) and smallholder agriculture (SHA; 35.9 km^2) in the South-West Mau, Kenya. Different capital
342 letters indicate significant differences between the different land uses ($p<0.05$).

Site	Year	Annual rainfall (mm yr^{-1})	Annual specific discharge (mm yr^{-1})	Runoff coefficient [a]	Total suspended sediment load (t yr^{-1})	Total suspended sediment yield (t km^{-2} yr^{-1})
NF	2015	1,986	714 (693-738)	0.36 (0.35-0.37)	407 (378-439)	11.3 (10.5-12.2)
	2016	1,846	518 (497-542)	0.28 (0.27-0.29)	667 (615-724)	18.6 (17.1-20.2)
	2017	1,783	483 (466-502)	0.27 (0.26-0.28)	673 (622-729)	18.7 (17.3-20.3)
	2018	1,755	812 (783-844)	0.46 (0.45-0.48)	1,337 (1,228-1,457)	37.2 (34.2-40.6)
Mean		1,842 A	632 (610-656) A	0.34 (0.33-0.36) A	771 (711-837) A	21.5 (19.8-23.2) A
TTP	2015	1,928	768 (730-820)	0.40 (0.38-0.43)	2,376 (2,185-2,603)	71.4 (65.6-78.2)
	2016	1,655	593 (555-642)	0.36 (0.34-0.39)	1,397 (1,277-1,539)	42.0 (38.4-46.2)
	2017	1,478	408 (372-468)	0.28 (0.25-0.32)	780 (701-880)	23.4 (21.0-26.4)
	2018	1,858	673 (634-728)	0.36 (0.34-0.39)	1,042 (952-1,151)	31.3 (28.6-34.5)
Mean		1,730 A	610 (573-665) A	0.35 (0.33-0.38) A	1,399 (1,279-1,543) A	42.0 (38.4-46.3) A
SHA	2015	1,607	561 (539-582)	0.35 (0.34-0.36)	2,324 (2,161-2,494)	85.4 (79.5-91.7)
	2016	1,369	479 (456-503)	0.35 (0.33-0.37)	2,271 (2,088-2,464)	83.5 (76.8-90.6)
	2017	1,416	492 (471-514)	0.35 (0.33-0.36)	2,440 (2,237-2,653)	89.7 (82.2-97.5)
	2018	1,823	953 (920-986)	0.52 (0.50-0.54)	7,273 (6,774-7,790)	267.4 (249.1-286.4)
Mean		1,554 A	621 (596-646) A	0.39 (0.38-0.41) A	3,577 (3,315-3,851) A	131.5 (121.9-141.6) B

343 [a]Annual specific discharge as proportion of annual rainfall

344 Discharge in all catchments was flashy and varied seasonally. Rising limbs were generally steep
345 and had variable falling limbs depending on event size. The highest discharge peaks were
346 measured during the long rainy seasons between April and July in 2015, 2016 and 2018. In
347 contrast, 2017 was the driest year with a late onset of the rains and the highest discharge peaks
348 between August and November for the smallholder agriculture and the natural forest catchments.
349 However, in the tea-tree plantation catchment the rains started in May lasting until November
350 2017, resulting in discharge peaking in May and September 2017. High discharges were also
351 recorded in January 2016 because the 2015 rains continued through November and December
352 and were followed by an unusually wet January (Figure 4).

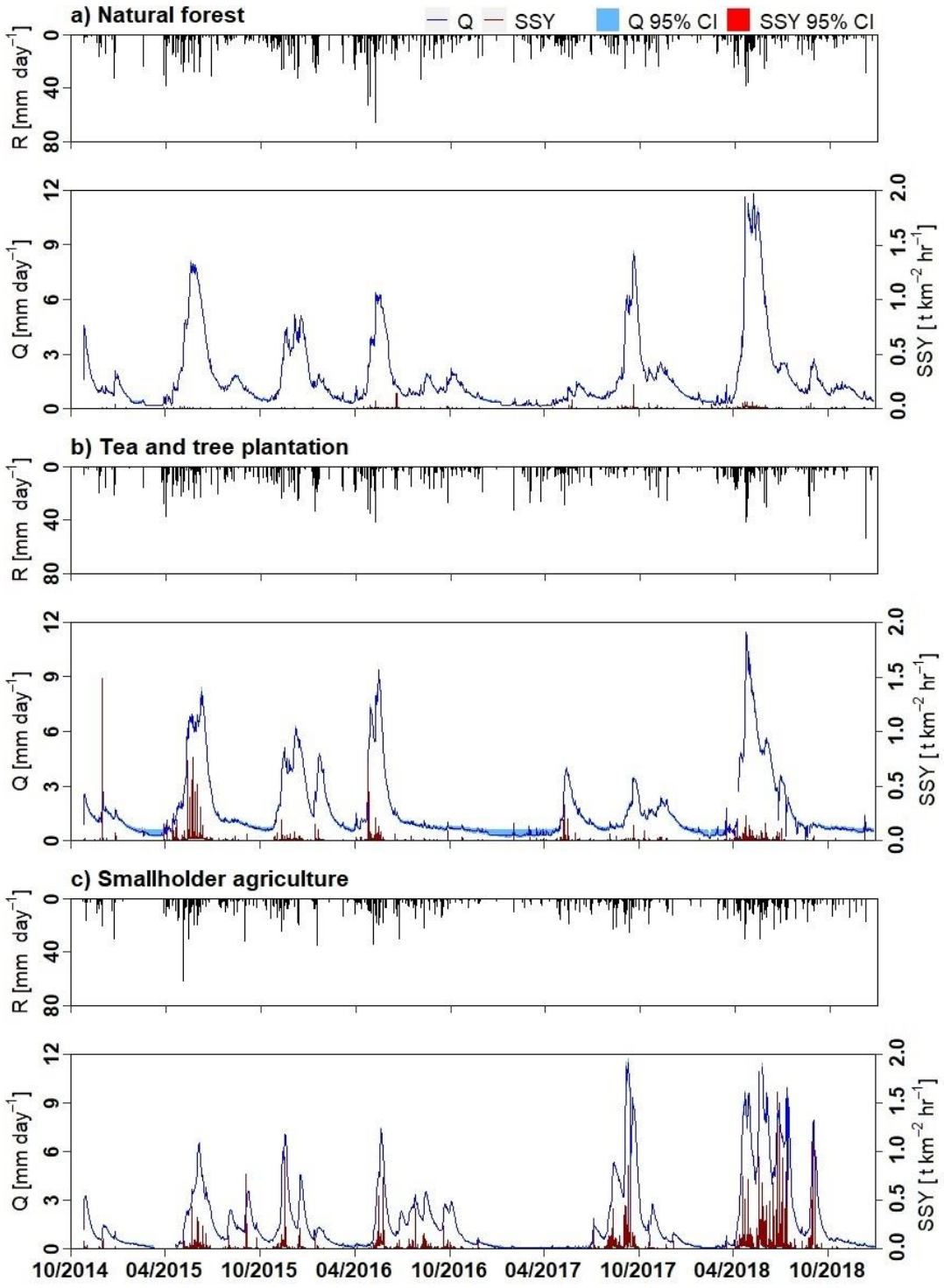

Figure 4 Time series of daily accumulated rainfall (R) [mm day^{-1}], daily specific discharge (Q) [mm day^{-1}] and hourly suspended sediment yield (SSY) [t km^{-2} hr^{-1}] aggregated from 10 minute resolution with 95%-confidence interval of the a) natural forest, b) smallholder agriculture and c) tea-tree plantation catchments in the South-West Mau, Kenya, between October 2014 and December 2018.

3.2 Relationship between turbidity and suspended sediment concentration

We obtained one rating curve for all three catchments to predict suspended sediment concentration from the measured turbidity values. A linear model provided the best fit between the *in situ* turbidity and suspended sediment concentrations, and there was no significant difference between slopes for each site-specific calibration (p-value>0.1). The intercept of the linear model was forced through the origin to prevent negative sediment concentrations at low turbidity, yielding an equation of the form TSS = 2.4*turbidity (R^2=0.98, p-value<0.001, n=50; Figure 5). This equation was used to convert the turbidity data to suspended sediment concentrations.

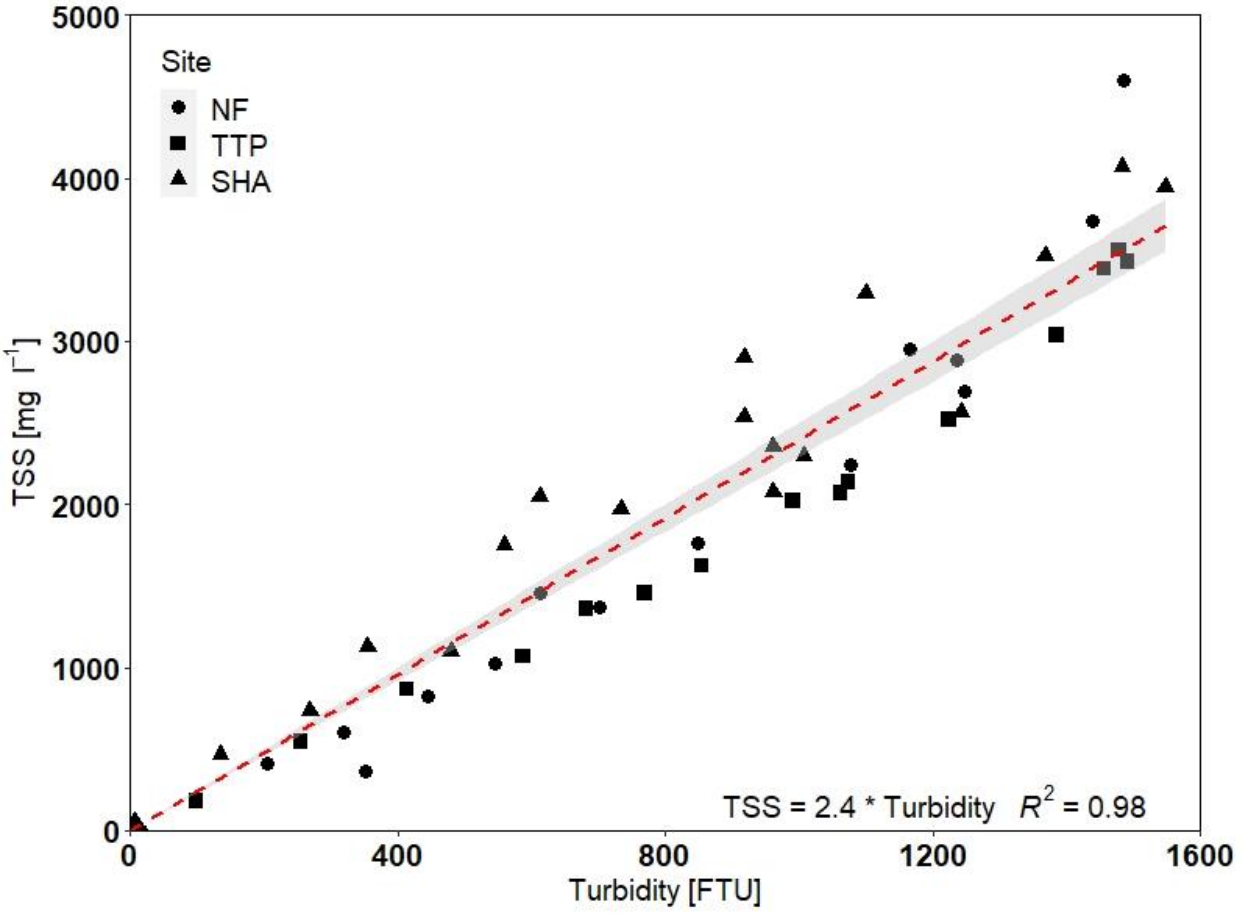

Figure 5 Relation between total suspended sediment concentrations (TSS) [mg l^{-1}] and turbidity [FTU=Formazin Turbidity Unit] measurements for three catchments: natural forest (NF), tea-tree plantations (TTP) and smallholder agriculture (SHA) and the fitted linear model (grey shaded area: 95%-confidence interval).

3.3 Suspended sediment dynamics

Sediment yield for the natural forest was lower than for the other two catchments (Figure 4). The sedigraph of the natural forest had smaller peaks with a short event time, whereas the smallholder agriculture and tea-tree plantations showed a steep increase followed by a flat recession with a long event time. The sedigraph of the smallholder agriculture catchment showed a flashy sediment response to rainfall and increased discharge. The maximum sediment yield in the natural forest catchment was 0.2 t km^{-2} hr^{-1}, followed by the tea-tree plantations with 1.5 t km^{-2} hr^{-1} and the smallholder agriculture with a maximum sediment peak of 1.6 t km^{-2} hr^{-1} (Figure 4). The mean annual suspended sediment yield was significantly higher for the smallholder agriculture catchment (131.5±90.6 t km^{-2} yr^{-1}) than for the tea-tree plantations (42.0±21.0 t km^{-2} yr^{-1}) and the natural forest (21.5±11.1 t km^{-2} yr^{-1}) ($p<0.05$) (Table 2). The lowest mean suspended sediment concentration (33.8±73.8 mg l^{-1}) was also lowest for the natural forest catchment, followed by the tea-tree plantations (47.4±90.7 mg l^{-1}). Concentrations were three to four times higher at the outlet of the smallholder agriculture catchment (128.6±233.4 mg l^{-1}) than at the other catchments ($p=0.04$). The daily mean suspended sediment load from the natural forest was the lowest, followed by the tea-tree plantations and the smallholder agriculture (2.1, 3.9 and 10.0 t day^{-1}, respectively). The total suspended sediment load for the entire study period (2015-2018) for the smallholder agriculture (14,308 t) was four times higher than that of the natural forest (3,083 t), whereas sediment load for the tea-tree plantations (5,595 t) was only twice that of the natural forest. These loads represent a mean of 771, 1,399 and 3,577 t yr^{-1} for the natural forest, tea-tree plantations and smallholder agriculture, respectively. Suspended sediment yield increased from 2015 to 2018 in the natural forest and smallholder agriculture catchments. In the tea-tree plantations, a similar sediment and rainfall pattern was observed with a decline from 2015 to 2017 and then an increase again in 2018 (Table 2). The natural forest had the longest period of missing data lasting for 95 days in November 2015 to February 2016, followed by a shorter gap in the smallholder agriculture of 50 days from March to April 2015 and the tea-tree plantations had the shortest period of missing sediment data of 13 days between March and April 2017. Besides these periods, minor gaps were usually of less than 24 hours with a total of missing sediment data of 7% for the natural forest, 2% for the tea-tree plantations and 4% for the smallholder agriculture catchments between 2015-2018.

3.4 Seasonal variations in suspended sediment

During the study period, suspended sediment yield showed pronounced seasonal variability, with most sediment being transported during the long rains in all catchments, and the highest monthly yields being recorded for the smallholder agriculture catchment (Figure 6). Overall, more than half of the sediment yield (45-52%) was attributed to the long rains, which cover less than one third of the year. The sediment contribution during the long rains, intermediate rains and short rains in the smallholder agriculture was significantly greater than in the natural forest and tea-tree plantations ($p<0.05$). For the natural forest the streams carried significantly more material during the long rains (mean yield of 4.3 ± 1.8 t km^{-2} month^{-1}) than during any other season. In the tea-tree plantations and smallholder agriculture, the sediment yield for the long rains (mean 10.9 ± 6.9 and 30.7 ± 10.6 t km^{-2} month^{-1}, respectively) differed significantly from the dry season (mean 0.4 ± 0.2 and 0.6 ± 0.3 t km^{-2} month^{-1}, respectively), the intermediate rains (mean 1.1 ± 0.6 and 5.4 ± 3.3 t km^{-2} month^{-1}, respectively) and the short rains (mean 3.2 ± 2.2 and 23.9 ± 26.1 t km^{-2} month^{-1}, respectively), while there was no difference between the sediment yield for the start of the long rains (mean 5.7 ± 6.5 and 7.8 t km^{-2} month^{-1}, respectively) and the long rains ($p<0.05$).

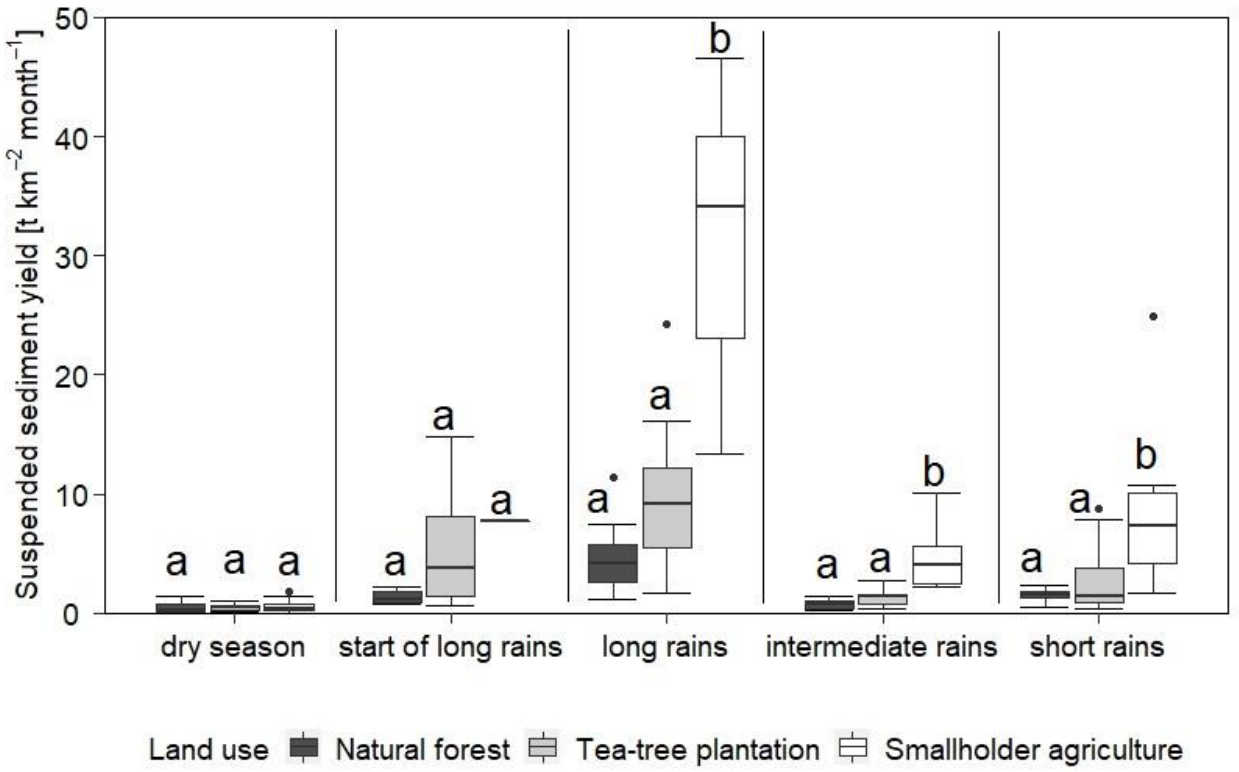

Figure 6 Boxplots of the monthly total suspended sediment yield [t km^{-2} month^{-1}] for different seasons for the natural forest (NF), tea-tree plantations (TTPs) and smallholder agriculture (SHA) catchments in the South-West Mau, Kenya. Seasons: dry season, start of the long rainy season, long rainy season, intermediate rainy season and short rainy season between January 2015 and December 2018. Different letters above the box plot indicate significant differences between the land uses within each season ($p<0.05$).

3.5 Flow pathways and streamflow dynamics

We compared hydrological flow pathways for each catchment as these are key in delivering sediments to the streams. Rainfall-runoff response was modelled over a continuous period of one year for each monitoring year 2015-2018 (see figure S1). In all three catchments, first order linear models (Eq. 6) were selected because these had the highest coefficients of determination (R_t^2) ranging between 86 and 93% and explained the data with the most negative YIC ranging between -12.5 and -10.4. The tea-tree plantations had a lower model performance in 2017 compared to the other years with a R_t^2 value of 54% and a YIC of -8.3, where the first order model was identified as the optimal model (Table 3). A simple first order model was used to derive the time constant to compare the dynamic relationship between rainfall and runoff response among the three catchments. Our interpretation of the continuous time transfer function

model suggests a slower rainfall-runoff catchment response in the natural forest and tea-tree plantation catchments in contrast to the fast flow response to rainfall in the smallholder agriculture catchment. The time constants calculated ranged from 8.4 to 11.5 days in the natural forest catchment and from 9.6 to 13.0 days in the tea-tree plantations. The smallholder agriculture had time constants between 6.2 to 8.6 days (Table 3).

Table 3 Summary of the linear continuous-time transfer function models for the natural forest, tea-tree plantation and smallholder agriculture catchment in the South-West Mau, Kenya for four years (study period 2015-2018). YIC=Young Identification Criterion, R_t^2=coefficient of determination, model structure [n=denominator polynomial, m=numerator polynomial, τ=pure time delay].

Site	Year	Time constant [days]	YIC	$\boldsymbol{R_t^2}$	Model structure [n, m, τ]
Natural forest	2015	11.5	-11.2	0.92	[1 1 2]
	2016	12.6	-11.1	0.92	[1 1 2]
	2017	8.4	-11.2	0.92	[1 1 2]
	2018	9.8	-12.1	0.93	[1 1 2]
Tea-tree plantations	2015	12.1	-10.4	0.86	[1 1 2]
	2016	9.6	-11.5	0.90	[1 1 2]
	2017	13.0	-8.3	0.54	[1 1 2]
	2018	10.5	-11.4	0.92	[1 1 2]
Smallholder agriculture	2015[a]	8.6	-10.7	0.86	[1 1 2]
	2016	8.7	-11.3	0.88	[1 1 3]
	2017	6.2	-12.5	0.96	[1 1 2]
	2018	6.9	-11.4	0.92	[1 1 2]

[a]Data used in the analysis 1May-31Dec2015

3.6 Time lags between rainfall and discharge to sediment concentrations

The analysis using cross-correlation functions (CCF) (Eq. 7) showed statistically significant correlations between rainfall and discharge to suspended sediment exceeding the 95%-confidence interval of 0.001 for a sample size of 61,201 in all three catchments for the four years. The CCF indicates the impulse response time between the peak of rainfall and discharge to the suspended sediment peak (see figure S2). The natural forest had almost instantaneous (<10 minutes) to rapid responses (1.5 hrs) in suspended sediment to both rainfall and discharge in all four years. A period shorter than a year was used for the natural forest in 2015 and 2016 because of missing sediment data (Table 4). The rainfall to sediment cross-correlogram in the tea-tree plantations differed from the other two catchments, with a first fast peak within one hour followed by a delayed second peak after 5 to 8.5 hours. The discharge to sediment response in the tea-tree plantations was similar to that of the smallholder agriculture catchment with a time

lag of around two to three hours. The smallholder agriculture had variable time lags between either rainfall or discharge to sediment ranging between 1.5 to 3.8 hours. The impulse response time between the peaks of discharge and sediment concentration was in general longer compared to the rainfall peak (Table 4).

Table 4 Summary of cross-correlation functions (CCF) between rainfall/ positive derivative of discharge to suspended sediment with time lag (in hours) and peak cross-correlation coefficients reported for the natural forest, tea-tree plantation and smallholder agriculture catchment in the South-West Mau, Kenya over four years (study period 2015-2018).

Site	Year	Discharge to sediment		Rainfall to sediment	
		Time lag [hours]	CCF coefficient	Time lag [hours]	CCF coefficient
Natural forest	2015[a]	1.0	0.10	1.5	0.16
	2016[a]	<0.2	0.03	<0.2	0.05
	2017	0.5	0.07	<0.2	0.12
	2018	0.5	0.10	0.2	0.03
Tea-tree plantations[b]	2015	2.5	0.34	1^{st} 0.5 and 2^{nd} 6.5	1^{st} 0.08 and 2^{nd} 0.17
	2016	2.3	0.18	1^{st} 1.0 and 2^{nd} 7.0	1^{st} 0.08 and 2^{nd} 0.16
	2017	3.2	0.32	1^{st} 0.8 and 2^{nd} 8.5	1^{st} 0.08 and 2^{nd} 0.14
	2018	1^{st} 0.5 and 2^{nd} 2.0	1^{st} 0.17 and 2^{nd} 0.17	1^{st} 0.3 and 2^{nd} 5.0	1^{st} 0.18 and 2^{nd} 0.15
Smallholder agriculture	2015	2.8	0.27	0.7	0.13
	2016	2.2	0.18	1.5	0.08
	2017	3.8	0.17	1.5	0.11
	2018	2.2	0.21	3.5	0.15

[a]Data used in the analysis 1Jan-22Nov2015 and 1Mar-31Dec2016
[b]1^{st} and 2^{nd}: identifies the first and second time lag and CCF coefficient of the CCF in the tea-tree plantations

4 Discussion

4.1 Suspended sediment dynamics

This study shows that the annual suspended sediment yield is around six times greater for the drier smallholder agriculture catchment, and twice greater in the tea-tree plantation catchment compared to the wetter natural forest catchment. The sediment yield difference is likely the result of more vegetation cover and low surface hydrological connectivity in the natural forest, where consequently erosion processes (including mass wasting) are not as active. Similar findings were reported for the neighbouring Mara river basin, where a semi-arid catchment had higher suspended sediment yields (44 t km^{-2} yr^{-1}) with half of the annual rainfall in contrast to a wetter,

but less populated and less disturbed catchment (33 t km^{-2} yr^{-1}) (Dutton et al., 2018) (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

480 Table 5 Overview of different studies reporting annual suspended sediment yields (SSY) in Kenyan headwater streams and tropical montane forest
481 catchments worldwide derived from gauging station measurements.

Montane catchment	Area (km^2)	Land use	Study period (year)	Annual rainfall ($mm\ yr^{-1}$)	SSY ($t\ km^{-2}\ yr^{-1}$)	Reference
Sub-catchments of Sondu basin (West Kenya)	35.9	Natural forest	2014-2018	1,842	21	This study
	33.3	Tea-tree (Eucalyptus) plantations	2014-2018	1,730	42	
	27.2	Smallholder agriculture	2014-2018	1,554	131	
Different catchments throughout southern half of Kenya	n.a.	Natural forest (100%)	1948-1968	n.a.	20-30	Dunne, 1979
	n.a.	Natural forest (>51%)	1948-1968	n.a.	10-100	
	n.a.	Agricultural land (>50%)	1948-1968	n.a.	10-1,500	
	n.a.	Grazing land	1948-1968	n.a.	5,000-20,000	
Athi (Kenya)	510	Agriculture, grazing land and settlements	1985	n.a.	109	Kithiia, 1997
Upper Mara-Emarti (South-West Kenya)	2,450	Smallholder agriculture and urban development	2011-2014 (3-4 months)	1,400	33	Dutton et al., 2018
Middle Mara-Talek (South-West Kenya)	4,050	Grazing land	2011-2014 (3-4 months)	600	44	Dutton et al., 2018
Ruharo (Uganda)	2,121	Grazing land, agriculture, <20% Papyrus wetlands	2009-2010	1,535	106	Ryken et al., 2015
Koga (Uganda)	379	Grazing land, agriculture, >80% Papyrus wetlands	2009-2010	1,330	37	Ryken et al., 2015
Andit Tid (Ethiopia)	4.77	Agriculture (30%)	1989-1996	1,467	522	Guzman et al., 2013
Anjeni (Ethiopia)	1.13	Agriculture (80%)	1989-1996	1,675	2,470	
Maybar (Ethiopia)	1.12	Agriculture (60%)	1989-2001	1,417	740	
May Zegzeg (Ethiopia)	1.87	Agriculture and grazing land	2000	774	850	Nyssen et al., 2009
		Agriculture and grazing land with soil conservation practices	2006	708	190	
Arvorezinha (South Brazil)	1.23	Agriculture with traditional soil management & natural forest	2002-2003	2,051	298	Minella et al., 2018
		Agriculture with soil conservation practices & natural forest	2004-2008	1,655	68	
		Agriculture with traditional soil management & cultivated forest	2009-2016	2,102	163	
Conceição (South Brazil)	800	>85% agriculture (soybean, wheat, oats, ryegrass) with soil management, <15% gallery forest, wetlands and urban areas	2000-2010	1718	140	Didoné et al., 2014
			2011	1,422	242	
			2012	1,463	41	
Guaporé (South Brazil)	2,000	Agriculture (soybean, tobacco, maize, oats, ryegrass), grazing land and cultivated forest	2000-2010	1550	140	Didoné et al., 2014
			2011	1,195	390	
			2012	1,660	158	
Baru (Borneo)	0.44	Disturbed logged natural forest	1989	3,205	1,632	Douglas et al., 1993
		Natural forest immediately after logging	1991	2,609	1,017	Douglas et al., 1993
		Natural forest after logging	1995-1996	2,956	592	Chappell et al., 2004
W8S5 (Borneo)	1.7	Natural forest	1989	3,205	118	Douglas et al., 1993
			1991	2,609	117	
Mae Sa (Thailand)	74.2	Natural forest (62%) and agriculture (>20%)	2006-2008	1,743	323	Ziegler et al., 2014
Basper (Philippines)	0.32	Grassland and shrubs	2013	2,660	2,740	Zhang et al., 2018

482 n.a.=no data available
483

Missing sediment data and linear interpolation to fill these gaps could have increased the uncertainty in the sediment yields calculated. However, data gaps during dry periods, such as those in the sediment data for the natural forest during 2015 and 2016, would not have a large influence on yield calculations because of the small amount of material transported. Gaps during periods of heavy rainfall, which occasionally occurred in the smallholder agriculture catchment due to siltation, could have contributed to underestimation of the sediment yield, as peaks in the sediment concentration could be missing.

For Africa, suspended sediment yield was estimated to be 634 t km^{-2} yr^{-1} at continental scale based on 682 catchments and rivers with larger drainage areas (mean >1,000 km^2) (Vanmaercke *et al.* 2014). Compared to this, and other sediment studies in Kenya with varying catchment sizes of 24-42,000 km^2 and 8.2 to 6,330 t km^{-2} yr^{-1} (Dunne, 1979; Vanmaercke et al., 2014), our annual suspended sediment yields (21-131 t km^{-2} yr^{-1}) are within the lower reported ranges. Suspended sediment yields from the tea-tree plantations and natural forest catchment of our study are comparable to those observed in the neighbouring upper Mara river basin (33 t km^{-2} yr^{-1}; Dutton et al., 2018), which is dominated by small-scale farming and urban development. The smallholder agriculture catchment in our study had slightly higher suspended sediment yields than the Athi catchment in Kenya (109 t km^{-2} yr^{-1}; Kithiia, 1997) and had lower suspended sediment yields than disturbed agricultural catchments in montane headwaters such as the May Zegzeg catchment in Ethiopia (850 t km^{-2} yr^{-1}; Nyssen et al., 2009) or the Arvorezinha, Conceição and Guapore catchments in South Brazil (140-298 t km^{-2} yr^{-1}; Didoné et al., 2014; Minella et al., 2018). Guzman et al. (2013) found that in Ethiopia the highest suspended sediment yields (2,470 t km^{-2} yr^{-1}) in small catchments were in those with the largest proportion of agricultural land. Their reported annual yields were significantly higher than the suspended sediment yields observed in this study with similar annual rainfall. Annual suspended sediment yields of 117 up to 2,740 t km^{-2} yr^{-1} from undisturbed to highly disturbed forest or upland grassland catchments were measured in South-East Asia (Borneo, Thailand and the Philippines) subjected to mass wasting during typhoon or post-typhoon events.

4.2 Factors controlling sediment yield

Vegetation cover

The low annual suspended sediment yield measured in the Mau forest shows that forest vegetation is the most effective surface cover to limit soil erosion despite the steepest slopes of the forested catchment (Table 1). The dense vegetation, diverse strata and complex rooting systems prevent soil detachment and trap potentially erodible material. Similarly, a dense perennial tea vegetation covers the soil surface in the tea-tree plantations, which can buffer erosive rainfall (Edwards & Blackie 1979). Nevertheless, the annual suspended sediment yield for the tea-tree plantation catchment was twice that of the natural forest despite the soil conservation practices applied by tea companies such as mulching, planting of buffer strips (oat grass) between rows of young tea bushes or cover trees on newly planted tea plots. This indicates that high sediment loads originate from unprotected bare surfaces during renovation of tea plantations or logging activities of woodlots. Logging activities trigger overland flow and erosion processes and lead sediments to the streams, when there are no buffer strips (Douglas *et al.* 1993; Chappell *et al.* 2004). The dense vegetation contrasts with the land management in the smallholder agriculture catchment, where steep slopes tend to be bare between crop harvest and the start of the next cropping season. During that period, bare surfaces are prone to soil erosion, although cropland surface erosion was not observed, which may be explained by the high infiltration rates previously measured on these croplands (401 ± 211 mm hr^{-1}) (Owuor *et al.* 2018). The routing of main flow paths was observed on compacted gullied tracks which act as ephemeral channels during a storm event. Based on these observations, we hypothesize that rural unpaved tracks in the smallholder agriculture generate a larger contribution to the total sediment load than agricultural land, but further work is required to confirm this. A potential reason for the annual increase in suspended sediment yield in the smallholder agriculture and the natural forest catchments during the study period could be the reduced tree cover and increasing areas under annual crops and forest disturbance indicated by the study of Brandt et al. (2018).

Connectivity between sediment sources and the streams

The tea-tree plantations and the smallholder agriculture have higher catchment surface connectivity than the natural forest, which may be causing higher sediment transfer by connecting multiple source areas with the streams. Lateral linkages (tracks, gullies or drains) connect sediment source areas at catchment-scale with the stream network (Lane & Richards 1997), which can be an important driving force for the total sediment load into the rivers (Sidle

& Ziegler 2010).

In the smallholder agriculture catchment, unpaved tracks are the main pathways for people and livestock to access streams, thus being frequently used and heavily trafficked also by motorbikes (Figure 2). This activity generates highly compacted surfaces, where soil infiltration is impeded. Ziegler et al. (2001) observed that unpaved rural roads, similar in appearance to the unpaved tracks of our study, generate significantly more overland flow compared to adjacent hillslopes. As a consequence of low infiltration rates and downslope-orientated tracks, surface runoff energy increases generating more volume and velocity of flow that can transport large quantities of soil, eventually eroding tracks into gullies (Svoray & Markovitch 2009; Sidle & Ziegler 2010). Other researchers found a strong influence of subsurface water tables in valleys on gully formation and the development of large scale sediment mobilization (Tebebu *et al.* 2010; Zegeye *et al.* 2018). High sediment loads at the outlet of the smallholder agriculture catchment are thought to originate from the eroded unpaved tracks and its connecting adjacent source areas. Catchment drainage density is higher in the smallholder agriculture (0.64 km km^{-2}) compared to the natural forest and tea-tree plantations (0.48 and 0.42 km km^{-2}, respectively) suggesting a link to increased erosion rates. The tea-tree plantation catchment is hydrologically connected through a network of tracks and well-engineered paved and unpaved drains in between the tea fields. The design of the well-engineered drains took into account the appropriate routing of surface runoff to the riparian zones before entering the streams, suggesting a higher hydrological connectivity than in the smallholder agriculture catchment. However, the drains are well-maintained with a densely forested riparian zone, which reduces sediment export, thereby reducing sediment transport connectivity. The strong hydrological connectivity of the tea-tree plantation catchment could lead to high sediment transport and loads with poor maintenance of the drainage network.

Riparian zones

Dense riparian vegetation can trap sediments before they reach the stream (Pavanelli & Cavazza 2010). An intact forested riparian zone in the natural forest and a riparian buffer of 30 m, as pre-described by the Kenya's Water Act (Republic of Kenya 2012), of mixed indigenous vegetation in the tea-tree plantations seem to be reducing sediment delivery to the streams by trapping eroded soil. In contrast, high sediment loads are expected in the smallholder agriculture

572 catchment, where the riparian vegetation is highly degraded or replaced by crops or woodlots
573 planted on the river banks. Small floodplains in a steep, narrow valley floor provide limited
574 space for sediment storage. In the same river basin, other studies reported that highly degraded
575 riparian zones adjacent to areas cultivated by smallholder agriculture lead to increased suspended
576 sediment concentrations (Masese *et al.* 2012; Njue *et al.* 2016). In the smallholder agriculture
577 catchment, livestock access the streams through the riparian area for watering (Figure 2d-f),
578 which damages the riverbank and the riparian vegetation and further increases sediment supply.

579 4.3 Water pathways are key for sediment production

580 Hydrological pathways such as surface runoff or subsurface flow are key in determining
581 sediment response in catchments. Our analysis showed that the natural forest and tea-tree
582 plantation catchments, with lower suspended sediment yields had the longest streamflow
583 response time to rainfall using the CT transfer function model (Eq. 6). This supports our
584 hypothesis that shorter pathways indicate that surface runoff mobilizes soil particles causing six
585 times more suspended sediment yields.

586 The number of pathways and their response time depend on catchment characteristics (Chappell
587 *et al.* 2006; Ockenden & Chappell 2011). Forest ecosystems are generally characterized by
588 complex catchment behaviour (Chappell *et al.* 1999), where soils with high infiltration rates
589 promote infiltration to deeper subsurfaces. These pathways can be divided into shallow water
590 pathway and deep groundwater pathway (Chappell & Franks 1996). The high infiltration rates
591 (760±500 mm hr^{-1}, Owuor *et al.* 2018) and the long time constants derived through modelling for
592 the natural forest catchment (Table 3) point to subsurface flow pathways. Jacobs et al. (2018a)
593 reported the occurrence of shallow to deeper subsurface flow by using an endmember mixing
594 analysis in the same natural forest catchment. Groundwater seemed to be an important stream
595 water source (Jacobs *et al.*, 2018a), which agrees with the long response time we calculated
596 (Table 3). Our findings corroborate those of other studies in tropical forest catchments, which
597 demonstrated that subsurface flow is the main water pathway of forest ecosystems (Noguchi *et*
598 *al.* 1997; Boy *et al.* 2008; Muñoz-Villers & McDonnell 2013). Consequently, low suspended
599 sediment yields are associated with limited surface erosion and sediment delivery to the streams
600 in the natural forest catchment.

The main pathways in the tea-tree plantations with slightly shorter time constants (Table 3) and almost half the infiltration rate (430±290 mm hr^{-1}, Owuor *et al.* 2018) compared to the natural forest suggest that shallow subsurface flow and surface runoff may dominate. Overland flow was observed to be routed through the well-engineered drainage network along roads and surface water drains between tea plantations to the well buffered fluvial network. Overland flow was also thought to be significant by Jacobs et al. (2018b), where nitrate concentrations in stream water seemed to be diluted by surface runoff. The well-maintained drains explain the lower suspended sediment yields, despite the prevalence of surface runoff observed in the tea-tree plantations.

The analysis of the smallholder agriculture catchment showed a relatively fast pathway. However, Owuor et al. (2018) measured infiltration rates of 401±211 mm hr^{-1} on croplands in the catchment, suggesting that subsurface flow is the most likely pathway. Nevertheless, field observations of runoff along with poorly maintained highly compacted tracks, and the shape of a classification of hysteresis loops by Jacobs et al. (2018b) provides a contrasting insight suggesting that surface runoff in the smallholder agriculture is an important vector for sediment. Our hypothesis is that the tracks act as ephemeral streams and receive water from the surrounding areas as shallow lateral flow, thus explaining the shorter water response times. The natural forest and tea-tree plantation catchment with high tree cover showed similar time constants, whereas the much lower tree cover in the smallholder agriculture catchment lead to faster pathways. The generally slow pathway component in each model can be explained by the presence of deep and well-drained soils in all catchments (Sombroek et al. 1982).

4.4 Sediment response times and event duration

The shorter time lag between the peaks of rainfall to sediment than to discharge can be attributed to exposed and easy erodible material adjacent to the outlet. The almost instantaneous sediment response to rainfall in the natural forest and tea-tree plantations suggest sediment supply from readily available, nearby sediment sources (Francke *et al.* 2014; Tena *et al.* 2014; De Girolamo *et al.* 2015) (Figure 7). Near-channel or in-channel sediment sources can originate from the stream bank or the stream bed (Kronvang *et al.* 1997; Chappell *et al.* 1999; Lenzi & Marchi 2000). Temporarily stored sediment is thought to be mobilized very quickly during the first stages of a storm event (Eder *et al.* 2010). Fast response systems of short duration and low mass

631 magnitude, as those observed in the natural forest catchment, are characterized by rapid sediment
632 flushing and fast depletion of sediment supply (Chappell *et al.* 1999), due to limited availability
633 of eroded material from the protected surface (Fang *et al.* 2008; Fan *et al.* 2012; De Girolamo *et*
634 *al.* 2015). The paved drain network in the tea-tree plantation catchment can act as conduits
635 transporting sediment instantaneously from nearby logged plantations or tracks to the stream.
636 The delayed sediment response after a rainfall event in the smallholder agriculture and the
637 second sediment response in the tea-tree plantation catchment suggest a long travel distance
638 between the sediment source and the catchment outlet. The delayed response can be related to
639 the magnitude of mass, where more distant sediment source areas from the wider catchment
640 accumulate more mass over a longer period. These responses may also indicate the breaching of
641 barriers such as hedges, fences or grazing land, especially in the smallholder agriculture
642 catchment. The long recession limb in the smallholder agriculture and the tea-tree plantation
643 catchments is typically explained as a slow depletion of sediment supply (Francke *et al.* 2014;
644 Tena *et al.* 2014; De Girolamo *et al.* 2015). The more pronounced sedigraph in the smallholder
645 agriculture catchment can be associated with the wide range of accumulated sediment source
646 areas (Figure 7).

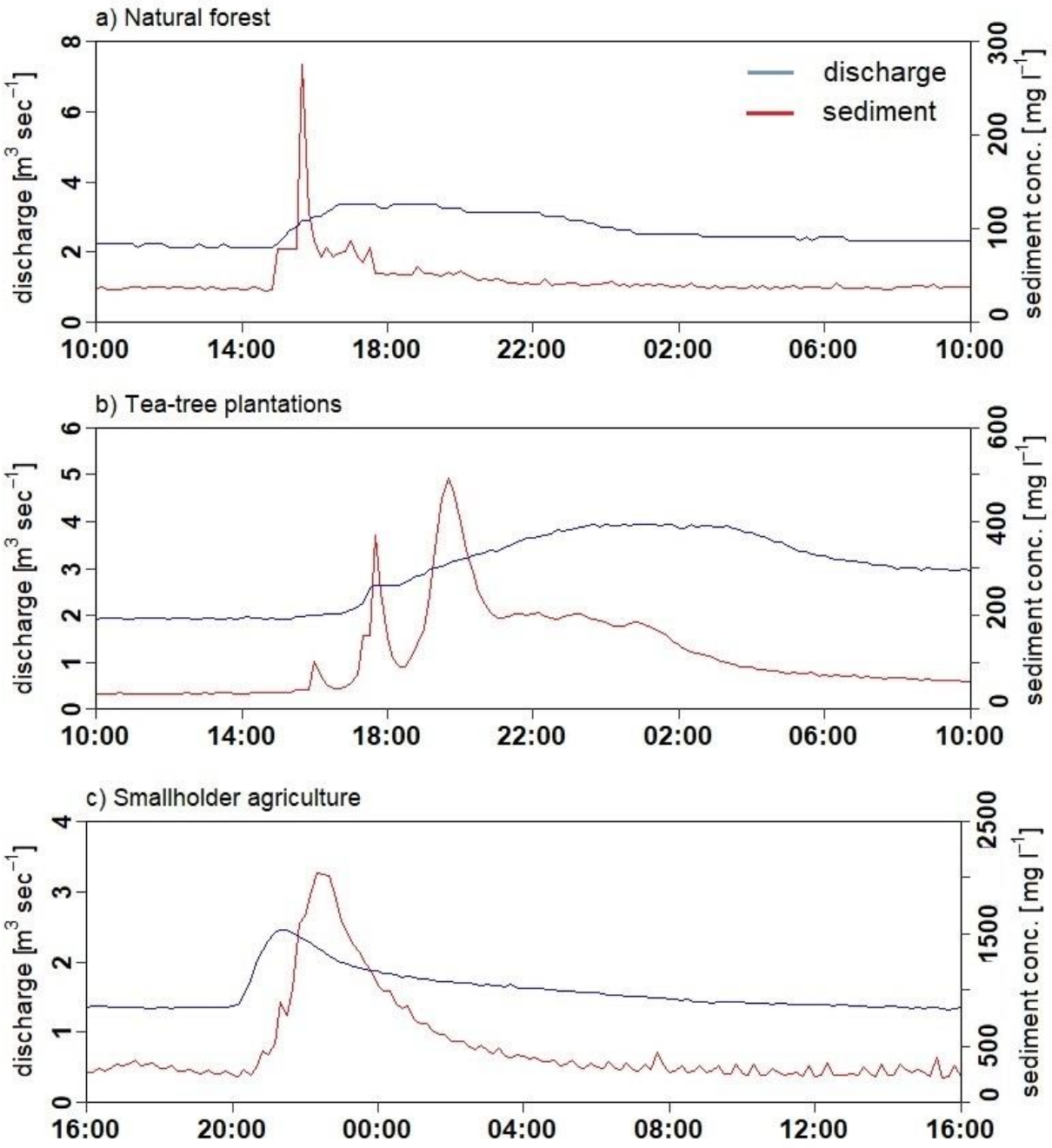

Figure 7 Typical shape of the sedigraph (sediment conc.=concentration [mg l^{-1}] and hydrograph (discharge [m^3 sec^{-1}] (10 minute resolution) for events in the natural forest (02/06-03/06/2018 10:00), the tea-tree plantation (24/04-25/04/2018 10:00) and the smallholder agriculture (17/05-18/05/2018 16:00) catchment in the South-West Mau, Kenya.

4.5 Seasonal variability of suspended sediment

Throughout the study period, we observed distinct seasonal variability in suspended sediment yield for the natural forest, tea-tree plantations and smallholder agriculture with higher yields in periods of high discharge and rainfall. In climates with strong seasonality of rainfall, seasons can explain sediment dynamics (Horowitz 2008; De Girolamo *et al.* 2015), as we observed in this study. Wet seasons or high-flow events generate the largest proportion (80-95%) of the annual sediment load, as observed by De Girolamo et al. (2015), Sun et al. (2016) and Vercruysse et al. (2017) in other areas, while the sediment load is the smallest in the dry season with less than 5% in our study. The seasonal differences were more pronounced in the smallholder agriculture catchment compared to the other two catchments explained by the high catchment surface connectivity and low vegetation cover.

5 Conclusions

This study presents the first long-term high-resolution sediment dataset in Kenya. The four years of continuous data for the natural forest, tea-tree plantation and smallholder agriculture catchments provide critical insights in contrasting sediment dynamics of the tropical montane Mau Forest Complex. The analysis revealed that land use is a critically important driver for sediment supply, where smallholder agriculture generates six times more annual suspended sediment yield than a catchment dominated by natural forest. Besides vegetation cover, a strong catchment surface connectivity through unpaved tracks and gullies from hillslopes to the fluvial network is thought to be the main reason for the differences in sediment yields. However, further work is required to test this hypothesis. Catchments with a high tree cover, such as the natural forest and the tea-tree plantations seem to have similar water pathways with a dominance of subsurface flow. In contrast, in the highly disturbed landscape such as that of the smallholder agriculture catchment, surface runoff dominates and soil erosion increases suspended sediment yield. This superficial water pathway results in the more pronounced seasonal impact of rainfall in the smallholder agriculture compared to the other two catchments, also due to varying vegetation cover. Delayed sediment response to rainfall and a slow depletion in sediment supply in the smallholder agriculture and tea-tree plantations suggests that the wider catchment area is supplying sediment from a range of sediment sources, especially in the catchment dominated by

smallholder farming. In contrast, the fast depletion in sediment supply in the natural forest suggests the importance of nearby sediment sources and temporarily stored sediment.

Land scarcity and population growth bring enormous pressure on natural forest ecosystems. Forest conversion will increase sediment production, which will affect, not only many people in the Sondu River basin who rely on the rivers for drinking water, but also Lake Victoria which is already affected by increased sediment supply. The implementation of catchment management, such as soil conservation measures and better engineering of rural trackways is essential to reduce sediment supply to water bodies. However, a detailed sediment source fingerprinting analysis is necessary to identify the main contributing sediment sources. This will support the application of better management strategies at the source to prevent sediment entering the stream network. Sediment yields reported in other sediment studies in montane smallholder agriculture catchments were higher than in our study, which provide a warning of potentially higher sediment loss in the future unless mitigation strategies are implemented.

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