Modification of river meandering by tropical deforestation

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ABSTRACT

Tropical forests are the only forest biome to have experienced increased rates of forest loss during the past decade because of global demands for food and biofuels. The implications of such extensive forest clearing on the dynamics of tropical river systems remain relatively unknown, despite significant progress in our understanding of the role of trees in riverbank stability. Here, we document rates of deforestation and corresponding average annual rates of riverbank erosion along the freely meandering Kinabatangan River in Sabah, Malaysia, from Landsat satellite imagery spanning A.D. 1989–2014. We estimate that deforestation removed over half of the river's floodplain forest and up to 30% of its riparian cover, which increased rates of riverbank erosion by >23% within our study reaches. Further, the correlation between the magnitude of planform curvature and rates of riverbank erosion only became strongly positive and significant following deforestation, suggesting an important role of forests in the evolution of meandering rivers, even when riverbank heights exceed the depth of root penetration.

INTRODUCTION

The importance of trees in improving the stability of riverbanks has been documented in a variety of natural settings (Hickin, 1984; Millar, 2000). Tree roots can mechanically enhance the shear strength of riverbank materials (Abernethy and Rutherfurd, 2001) and can reduce pore water through transpiration and canopy interception, increasing the apparent cohesion of riverbank soils (Pollen-Bankhead and Simon, 2010). These effects can reduce both the prevalence of mass failures (Simon and Collison, 2002) and rates of riverbank erosion (Pizzuto and Meckelnburg, 1989; Beeson and Doyle, 1995). These enhancements may be restricted, however, to environments where root systems can extensively penetrate riverbanks. Where rooting depths are only a fraction of riverbank heights, such as along many large meandering rivers, riverbank erosion can take place at rates that are largely unaffected by the presence of trees (Constantine et al., 2009). Even so, sustained erosion could be prevented by the supply of trees and rooted sediment to the base of riverbanks from the eroded riparian corridor (Thorne and Furbish, 1995), which may also act to buttress and stabilize the riverbank profile (Parker et al., 2011). The transient nature of these eroded and failed materials inside the river channel has made it unclear whether trees are important to the long-term meandering dynamics of large rivers (Motta et al., 2014), preventing insight into the morphodynamic impacts of intensive deforestation taking place across tropical river systems worldwide (Boucher et al., 2011).

The Kinabatangan River in Sabah, Malaysia (Fig. 1), offers an important opportunity to document and assess the relationship between tropical floodplain forest and riverbank erosion. The freely meandering Kinabatangan River and its lowland floodplain have undergone substantial land-cover transformation as palm oil plantations and similar agribusinesses have replaced much of its forest through rapid deforestation clearly recorded in Landsat imagery. This recent intensification of deforestation has led to the complete removal of natural riparian cover along many reaches of the Kinabatangan, typical of many tropical rivers such as the Araguaia River in Brazil (Latrubesse et al., 2009) and the River Tana in Kenya (Wahungu et al., 2005). Using the Kinabatangan River as a natural laboratory, we assess the role of trees in controlling rates and patterns of riverbank erosion along large meandering rivers. We conclude with hypotheses explaining an observed change in the relationship between rates of riverbank erosion and modeled estimates of the curvature-driven forcing of river flow following deforestation.

STUDY AREA AND METHODS

Draining 16,800 km² of northern Borneo, the Kinabatangan River flows without obstructions for 560 km, from the interior mountains of the Maliau Basin to the Sulu Sea. With a mean annual rainfall >2000 mm and consistent mean temperatures of ~30 °C, the Kinabatangan floodplain is ideal for oil palm cultivation (Pirker et al., 2016). There is an average bankfull river width of 112.7 m (1σ = 1.4 m) (Table DR1 in the GSA Data Repository[1]), measured as the average distance between vegetated banks along all study reaches. Riverbanks are >8 m in height, populated by large trees whose roots penetrate ~2 m, and cleared sections are colonized by grass species (*Phragmites australis* and *Pennisetum purpureum*) whose roots penetrate 0.5–1.0 m (see the Data Repository for details). We studied four meandering reaches, selected to provide examples of riverbanks with varying degrees of land-cover alteration and to ensure observations of river meandering unhindered by geological (e.g., bedrock outcrop) or engineering (e.g., riverbank revetment) controls (Fig. 1).

Using sequences of Landsat satellite images (6 TM/Landsat 5, 1 ETM/Landsat 7, 1 OLI/Landsat 8 scenes), we calculated average annual rates of riverbank erosion (M_R) for the time period A.D. 1989–2014 (see the Data Repository for details). For each of the images, we corrected for atmospheric reflectance using the dark image subtraction method (Chavez, 1996) before deriving the normalized difference vegetation index (NDVI). To automate the process of consistent riverbank identification, we defined the riverbank as the location where the NDVI transitioned into values ranging from 0.39 to 0.49, values that separated densely vegetated surfaces (NDVI ≥ 0.6) from sparsely vegetated or bare-earth surfaces. Having defined the riverbanks, we then derived
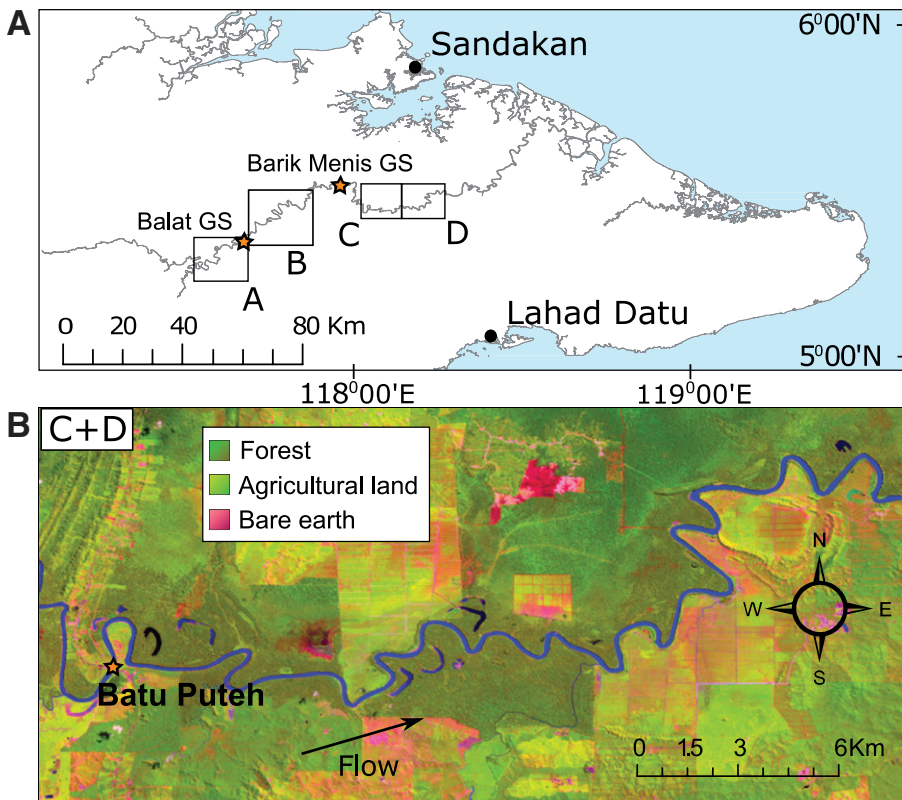
Figure 1. A: Locations of study reaches (A–D) and Barik Menis and Balat gauging stations (GS), Kinabatangan River, Malaysia. B: False-color composite of Landsat satellite bands 3, 4, and 5 taken in October 2009, showing extent of reach C and D and location of Batu Puteh village (orange star), with legend defining associated land-cover types.

channel centerlines by interpolating through digitized points located halfway between channel margins at 100 m intervals. Values of M_R were then calculated after Constantine et al. (2009) and Micheli et al. (2004), in which superposed centerlines from successive Landsat images created polygons that represented the total area of eroded bank material. Mean erosion rates for river sections spanning individual meanders were then defined as the sum of the polygon areas within each section divided by the average streamwise length of the section.

We analyzed 67 river sections, documenting river position every 5–7 yr, which provided a total of 330 M_R estimates. We then developed a land classification scheme based on the 2009 TM/Landsat 5 image to distinguish between bare earth, forest, and previously cleared land, validated using Google Earth™ imagery and through field observations (see the Data Repository for details). We applied this classification to all Landsat images, denoting undisturbed banks as *forested sections* and deforested banks as *cleared sections*. All estimates of M_R were then categorized based on the land-use classification for the eroding bank. Forested sections contributed 255 estimates of M_R and cleared sections contributed 75 estimates (from 22 distinct river sections).

Although there are higher-order models describing river meandering by curvature-driven forcing of river flows (e.g., Pittaluga and Seminara, 2011), the linear theory of meander migration (Ikeda et al., 1981) provides a simple and effective approach for assessing the role of trees in the meandering dynamics of large rivers (Perucca et al., 2007). Accordingly, M_R at any location along a meander can be stated as the product of a dimensionless coefficient (ε) and a term reflecting the near-bank flow velocity in excess of the cross-section–averaged velocity (ω). Values of ε reflect a range of physical controls on riverbank erosion by granular transport (Parker et al., 2011), but the variable is strongly determined by the material properties of the riverbank, including any effects on the critical shear stress required for particle entrainment (Constantine et al., 2009). Using a solution for ω derived by Sun et al. (1996, their equation 15), we estimated ε for every river section across all study reaches as the ratio of M_R to the maximum value of ω located within the river section during conditions of bankfull flow. Topographic data required for solutions to ω were collected using a sonic depth gauge at near-bankfull flow conditions and along cross-sections oriented perpendicular to channel margins. Discharge data recorded at Balat (1978–2013) and Barik Menis (2000–2013) gauging stations (Fig. 1) were provided by the Department of Irrigation and Drainage in Kota Kinabalu, Sabah, Malaysia (Fig. DR1

in the Data Repository). Values used in the solutions to ω and an explanation of their derivation have been provided in the Data Repository. We used two-tailed *t*-tests and Kruskal-Wallis (KW) tests to test the significance of differences in our measurements. Kolmogorov-Smirnov (KS) tests were used to assess the distinctiveness of measurement distributions. Pearson product-moment correlation coefficient (*r*) and Spearman's rank correlation coefficient (ρ) provide measures of significance for correlations. The variable α defined the significance level of statistical tests.

RESULTS AND DISCUSSION

Rates of riverbank erosion along the Kinabatangan River were found to have increased after the total removal of its riparian cover, with M_R for cleared sections averaging significantly more than for forested sections (*t*-tests: α < 0.01; KW tests: α < 0.001) (Fig. 2A). This is consistent with previous studies that have assessed the role of vegetation in riverbank erosion (Beeson and Doyle, 1995; Micheli et al., 2004). Increases in M_R following deforestation can be attributed to increases in riverbank erodibility, at least as reflected in the differences in ε. The average ε for forested sections was significantly less than the average for cleared sections (*t*-tests: α <0.001; KW tests: α < 0.001) (Fig. 2B), and KS tests confirm that the distributions of M_R and ε values for cleared sections are statistically distinct from the distributions for forested sections (α < 0.001). Based on a comparison of meander migration measurements taken from high-resolution imagery (60 cm pixel size), we estimate the standard error in our measurements of meander migration to be 0.29 m yr⁻¹ (see the Data Repository for details).

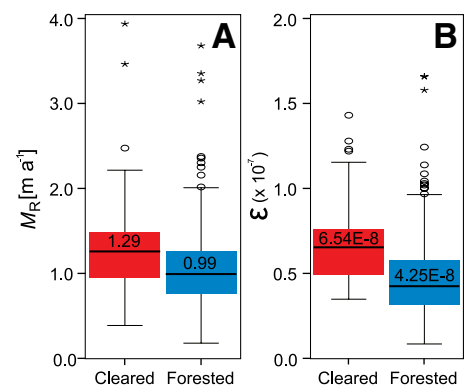Our results suggest that the mechanisms responsible for riverbank retreat may be modified

Figure 2. A: Box and whisker plot of distributions of measured values of average annual migration rates (M_R) for both land-cover classifications, Kinabatangan River, Malaysia. B: Box and whisker plot of distributions of estimated values of dimensionless coefficient of riverbank erosion (ε). For all distributions, median is reported, outliers are denoted by circles, and extreme values are denoted by asterisks.

by deforestation, as the complete removal of riparian forest appears to allow near-bank flows to more effectively erode riverbank materials. The proximity of high-momentum fluid to the outer bank is thought to have an important control on rates of riverbank erosion (Pizzuto and Meckelnburg, 1989). Values of M_R can therefore be expected to demonstrate some degree of correlation with measurements of local curvature (c) and modeled values of ω when the curvature-driven forcing of river flow induces the effective transport of riverbank materials. Within cleared river sections, mean migration rates (M_R) positively correlate with the maximum value of c located within the corresponding river section (r = 0.53, ρ = 0.45, α < 0.001) and maximum values of ω (r = 0.57, ρ = 0.53, α < 0.001) (Fig. 3). Conversely, values of M_R within forested river sections showed no such correlation with values of ω (α > 0.22) and only a weak correlation with maximum values of c which may not be significant (r = 0.132, α = 0.035; ρ = 0.114, α > 0.05) (Fig. 3). At least one other study, from the Sacramento River in California, USA, has quantified riverbank erosion as a function of planform curvature following deforestation, highlighting that erosion by curvature-driven forcing of river flow predominates only along sections of floodplain where the natural riparian cover was replaced by agriculture (Micheli et al., 2004).

We hypothesize that the increase in riverbank erosion sensitivity to curvature-driven forcing of river flows occurs because clearing riparian forest improves the ability of near-bank flows to remove riverbank materials (both intact and failed) and, by reducing riverbank shear strength, facilitates smaller, more frequent mass-failure events. Tropical forests are characterized by high rates of rainfall interception and evapotranspiration, which reduce soil water content and pore-water pressures. If deforestation enhances wetting across the riverbank, causing pore-water pressures to increase, a reduction in the apparent cohesion of riverbank materials from a loss of matric suction will increase the susceptibility of exposed riverbank surfaces to fluvial scour (Pollen-Bankhead and Simon, 2010). Furthermore, poorly rooted sediment is prone to disaggregation (Dunaway et al., 1994), particularly sediment that lacks enough cohesion (i.e., from clays and other platy minerals) to withstand the boundary shear stresses applied by the near-bank current (Simon and Collison, 2002).

Alterations to the riverbank hydrology caused by deforestation may also exacerbate a mechanical reduction in riverbank shear strength (Sidle et al., 2006). Fiber reinforcement provided by tree roots increases riverbank shear strength (Abernethy and Rutherfurd, 2001). Even when this root reinforcement has limited depth penetration, increased friction along the edges of a potential slide mass can control the size of individual failure events (e.g., slump blocks) (Milledge et al.,
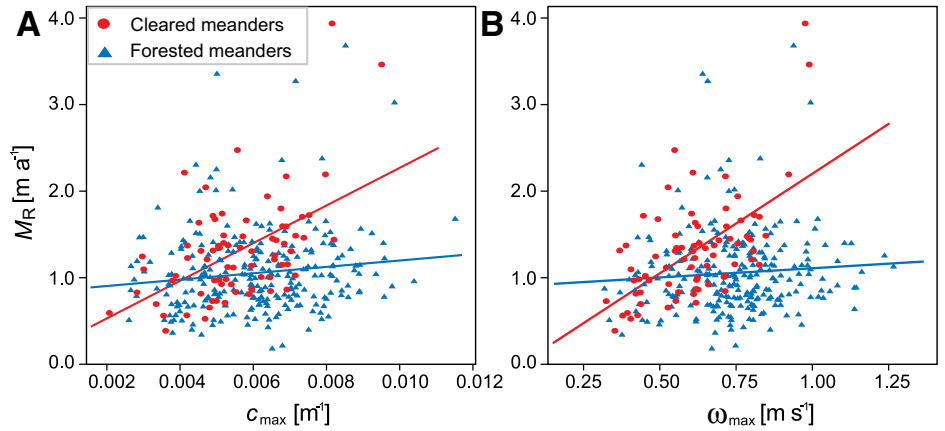

Figure 3. A: Average annual migration rates (M_R) plotted against maximum value of local curvature for individual meanders (c_{max}) for all sections within each study reach, Kinabatangan River, Malaysia. B: Values of M_R plotted against estimates of maximum velocity perturbation (ω_{max}) during bankfull-flow conditions for all sections. Values are plotted as function of history of land-cover change in both A and B.

2014; Wang et al., 2016): the greater the root reinforcement, the larger the individual failure events. By extension, deforestation will tend to decrease the size of individual failure events, but the reduced shear strength of riverbank materials will tend to increase their frequency.

Finally, the additional fiber reinforcement provided by roots may prolong the residency time of failed slump blocks that armor and buttress the riverbank, impeding the ability of near-bank flows to remove material from the bank toe and face. The depleted presence of large woody material along the riverbank face may also reduce flow roughness, improving the potential for the near-bank current to sustain its momentum and thereby its erosive power (Thorne and Furbish, 1995; Daniels and Rhoads, 2003).

Although future work is needed to fully evaluate the role of forests in controlling (1) the size and shape of riverbank mass failures and (2) the time scales for riverbank material removal, field observations provide a basis for our proposed hypotheses (Fig. 4). Along many forested river sections, we observed that large failure blocks still retaining vegetation were present at the bank toe. Along sections that had been cleared of forest, such large blocks were almost entirely absent; instead we observed smaller, unconsolidated failure blocks with evidence of cantilever failure.

CONCLUSIONS

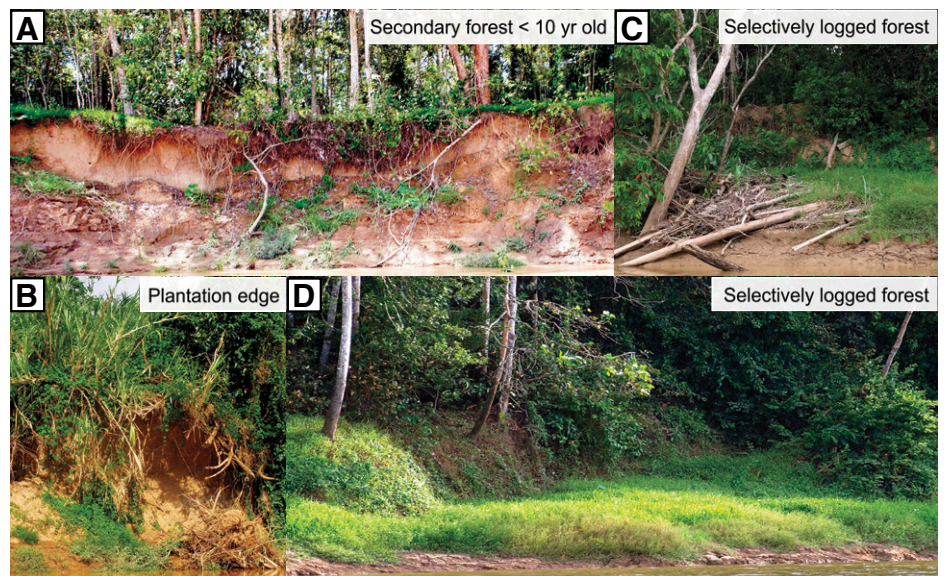For the period between 1989 and 2014, sections along the Kinabatangan River that had been

Figure 4. A,B: Examples of cleared meanders showing evidence of small mass-wasting events delivering unconsolidated material to Kinabatangan River, Malaysia. C,D: Examples of forested meanders showing evidence of large mass-wasting events with consolidated material accumulated at base of riverbank.

cleared of riparian forest show rates of channel migration >23% greater on average than those sections that remained forested. Furthermore, we find that those cleared sections exhibit a strong positive correlation between rates of riverbank erosion and estimated curvature-influenced flow along the eroding bank, a correlation that is absent along forested sections. Removal of riparian forest may alter properties of the bank in ways that accelerate material disaggregation by fluvial scour, thus affecting the relationship between rates of channel migration and curvature-driven forcing of river flows. Implications for long-term evolution of tropical river meandering in the context of floodplain deforestation are a critical area for further investigation.

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