



## Earth's Future

### RESEARCH ARTICLE

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#### Key Points:

- We estimate the value of the ecosystem service that riparian forest buffers provide by protecting adjacent plantations from riverbank erosion
- We find that wide riparian buffers (order tens of meters) may enhance the long-term viability of floodplain plantations
- Accounting for geomorphic contributions to ecosystem services may help align palm oil industry goals with environmental conservation

#### Supporting Information:

- Supporting Information S1

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## Can Riparian Forest Buffers Increase Yields From Oil Palm Plantations?

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**Abstract** Forests on tropical floodplains across Southeast Asia are being converted to oil palm plantations. Preserving natural riparian forest corridors along rivers that pass through oil palm plantations has clear benefits for ecological conservation, but these corridors (also called *buffers*) use land that is potentially economically valuable for agriculture. Here we examine how riparian forest buffers reduce floodplain land loss by slowing rates of riverbank erosion and lateral channel migration, thus providing the fundamentally geomorphic ecosystem service of *erosion regulation*. Using satellite imagery, assessments of oil palm plantation productivity, and a simplified numerical model of river channel migration, we estimate the economic value of the ecosystem service that riparian buffers provide by protecting adjacent plantation land from bank erosion. We find that cumulative economic losses from bank erosion are higher in the absence of a forest buffer than when a buffer is left intact. Our exploratory analysis suggests that retaining riparian forest buffers along tropical rivers can enhance the viability of floodplain plantations, particularly over time scales (approximately decades) commensurate with the lifetime of a typical oil palm plantation. Ecosystem services that stem directly from geomorphic processes could play a vital role in efforts to guide the long-term environmental sustainability of tropical river systems. Accounting for landscape dynamics in projections of economic returns could help bring palm oil industry goals into closer alignment with environmental conservation efforts.

**Plain Language Summary** Tropical meandering rivers and their floodplains provide habitats to many of the planet's critically endangered species, but they are now being threatened by recently intensified rates of deforestation driven by global demands for food and biofuels. We report that preserving tropical forest buffers along the margins of large meandering rivers can both enhance the profitability of floodplain plantations while maintaining conservation benefits by reducing the area of land lost to the river through bank erosion, which may help to bring palm-oil industry goals into closer alignment with environmental conservation efforts.

### 1. Introduction

Each year an estimated 5.5 Mha of tropical forests are lost to, or degraded by, land use conversion (Food and Agricultural Organization, 2015), primarily for agricultural expansion to meet growing demands for food and biofuel production (Hosonuma et al., 2012; Koh & Wilcove, 2008; Rudel et al., 2009). In Southeast Asia, which hosts some of the highest rates of tropical deforestation in the world (Keenan et al., 2015), agricultural expansion is dominated by the palm oil industry (Boucher et al., 2011; Stibig et al., 2014). Industrial palm oil development is not limited to Southeast Asia—Brazil, Colombia, and the Democratic Republic of Congo have a combined 102.9 Mha of lowland tropical forest identified as suitable for oil palm cultivation (Pirker et al., 2016)—but Malaysia and Indonesia presently dominate the global palm oil market, producing more than 85% of the world's supply (United States Department of Agriculture, 2015). Demand for palm oil and its derivatives is expected to increase with continued economic growth in India and China (Murphy, 2014), providing Indonesia with incentive to expand its landholdings in Kalimantan and Papua to double its production capacity before 2030 (Carlson et al., 2012). Across Malaysia and Indonesia, 9.5 Mha of land were converted to oil palm plantations between 1990 and 2010 (Wicke et al., 2011), with much of that expansion occurring at the expense of tropical forest (Koh & Wilcove, 2008).

Tropical deforestation is common near large meandering rivers (Latrubesse et al., 2009; Obidzinski et al., 2007), which provide a ready-made transportation network and access to fertile floodplains (Armenteras et al., 2006; Renó et al., 2011). The conversion of tropical riparian forests to oil palm monocultures has cumulative, globally significant environmental impacts, contributing to the global carbon budget (Baccini et al., 2012; Houghton, 2012) and degrading riparian ecosystems (Dudgeon et al., 2006; Vörösmarty et al., 2010). Riparian forest conversion and degradation fragments the landscape, restricting animal movements (Goossens et al., 2006; Yaap et al., 2010) and supporting fewer species (Edwards et al., 2010; Fitzherbert et al., 2008). Even forest preserves lose species richness over time if they become isolated fragments within a plantation matrix (Turner, 1996). Conversion of floodplain forest degrades in-stream environmental conditions by disrupting the ecosystem functions that natural riparian vegetation otherwise provides (Dislich et al., 2017). Riparian vegetation regulates not only water temperature, by filtering direct sunlight, but also the exchanges of sediment, organic matter, and water (and solutes) that collectively shape the structure and ecology of aquatic habitat (Allan, 2004). Removal of natural forest cover also has geomorphic consequences: surface runoff and soil erosion rates tend to increase, along with concentrations of suspended sediment and agricultural solutes (Luke et al., 2017; Nainar et al., 2017). Conversion of riparian forest can alter the morphology of rivers themselves, accelerating lateral migration rates (Horton et al., 2017; Micheli et al., 2004; Schultz et al., 2004) and forcing channels to become narrower and sand bedded; starved of woody debris and organic matter, these altered channels provide a less diverse aquatic habitat that supports fewer species (Allmendinger et al., 2005; Luke et al., 2017; Sweeney et al., 2004).

Riparian corridors—*buffer* zones of protected habitat that fringe the banks of river courses—may be able to mitigate some of the negative environmental impacts associated with widespread oil palm expansion. Preserving natural forest within plantation-dominated landscapes can help reduce carbon emissions by limiting deforestation and help maintain tropical ecosystem functioning that is otherwise lost in an oil palm monoculture (Larsen et al., 2005; Memmott et al., 2007; Morris, 2010). Because protected areas can only safeguard biodiversity if animals are able to move between forest patches through dedicated habitat corridors (Bruford et al., 2010; Gregory et al., 2014), riparian buffers can support some terrestrial biodiversity by serving as sanctuaries for forest-dependent species (Evans et al., 2017; Lucey et al., 2014; Turner & Corlett, 1996) and by offering continuous habitat pathways between fragments of forest matrix. Maintaining natural riparian cover along tropical rivers may help protect aquatic biodiversity by reducing the severity of impacts on freshwater ecosystems from otherwise total conversion of floodplain forest (Chellaiah & Yule, 2018; Mander et al., 2005; Naiman et al., 2010). Intact riparian forest may reduce lateral migration rates of the river channel (Horton et al., 2017; Micheli et al., 2004; Schultz et al., 2004)—and, by extension, reduce the loss of floodplain land area to erosion.

However, where rivers pass through oil palm plantations, riparian forest buffers occupy valuable land. Recent work suggests that they provide no net positive ecologic ecosystem service to adjacent plantations (Gray & Lewis, 2014), despite broader river restoration research demonstrating a variety of direct benefits to adjacent agricultural land (Tomscha et al., 2017), including mitigation of flood impacts (Schultz et al., 2004). Ecosystem functions and services constitute flows of materials, energy, and information from natural capital stocks to the benefit of human welfare (Millennium Ecosystem Assessment, 2005). Ecosystem functions refer to the habitat, properties, or processes of an ecosystem; ecosystem services are benefits that society ultimately derives from ecosystem functions, such as food production or the regulation of water, disturbance events, and erosion (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005). The assumption that total conversion of natural floodplain forest to oil palm monoculture will maximize plantation profitability leaves little incentive to maintain riparian buffers through plantations, especially if a buffer provides no apparent benefit to a plantation in return for the potential agricultural space it uses. But what if the critical ecosystem function that riparian corridors provide is as much geomorphic as it is ecologic? The ecosystem service of *erosion regulation* (Millennium Ecosystem Assessment, 2005) is fundamentally geomorphic: if riparian buffers protect plantations from losing land to riverbank erosion, how does that change their economic valuation?

Here we numerically modeled how lateral migration rates along the Lower Kinabatangan River, part of a large tropical river system used intensively for oil palm agriculture (Abram et al., 2014), might respond to the hypothetical removal or retention of adjacent riparian forest. We then estimated how those changes in migration rates might affect economic returns from oil palm on the proximal floodplain. Our results

suggest a potentially synergistic relationship between meander dynamics, riparian buffers, and expected yields from oil palm cultivation near the river edge. By first quantifying rates of meander migration in the absence and presence of riparian buffers and then weighing the potential economic benefit of natural erosion protection versus total plantation, we evaluated the direct effect that a riparian forest might have on expected yields from proximal oil palm plantation. We find that under certain conditions, maintaining riparian forest could potentially increase a plantation's long-term (multidecadal) profitability, and that the optimum width of a riparian buffer depends on the projected time frame of economic return.

Our results are empirically based but not explicitly predictive. The parameters and initial channel planform we used in the fluvial model, and the assessments of oil palm productivity we used to estimate economic impact, are specific to the Lower Kinabatangan. However, the purpose of this work is exploratory—to frame, from empirical quantities, the potential economic benefit that might result from a simple difference in lateral river erosion rates along forested versus cultivated reaches. The approach we take is generalized enough that our findings likely extend to naturally forested tropical floodplains beyond Southeast Asia.

## 2. Methods

Our analysis focuses on Sabah, in northern Borneo (Figure 1). Sabah is Malaysia's largest oil palm growing state, supporting 1.5 Mha of plantation and producing 28% of the nation's palm oil (Malaysian Palm Oil Board, 2014). The largest river in Sabah is the Kinabatangan, which drains a catchment of ~16,000 km<sup>2</sup> and extends 560 km from the interior mountains of the Maliau Basin to the Sulu Sea. With mean annual rainfall exceeding 2,000 mm and consistent mean temperatures ~30 °C, the Kinabatangan floodplain is ideal for oil palm cultivation (Pirker et al., 2016). Between 1990 and 2010, the majority of the Kinabatangan's floodplain forest was converted to oil palm plantations (Abram et al., 2014), leaving a fragmented landscape of protected forests partially connected by riparian buffers.

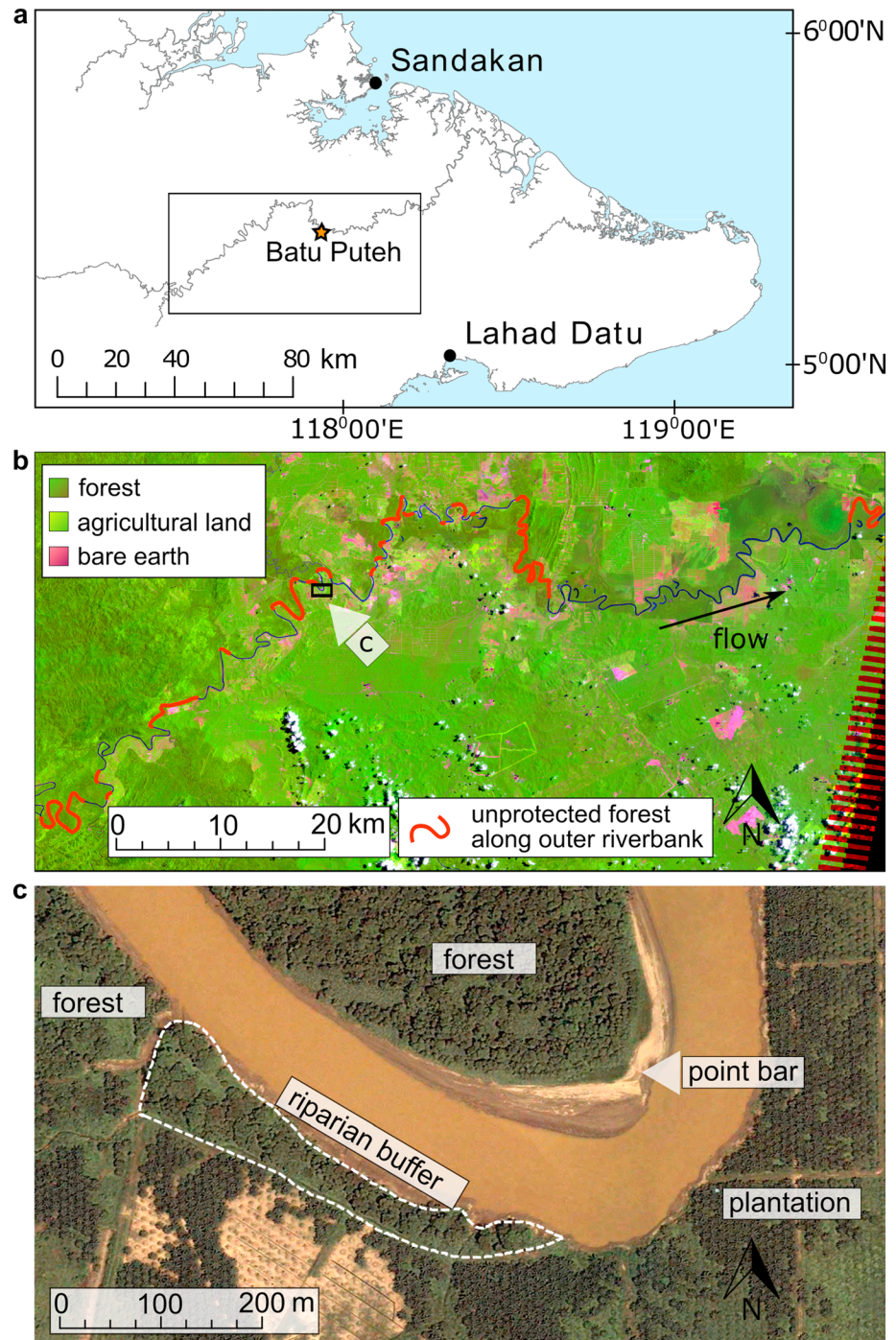
We used a numerical model of river meander migration to simulate future channel planform position along a continuous 210-km stretch of the Lower Kinabatangan, given different hypothetical scenarios for forest removal in specific, discontinuous sections of unprotected riparian forest marked for future conversion to plantation (Figure 1b). (Here *unprotected* refers to any riparian forest not currently designated for wildlife sanctuary by the Sabah government. For the purposes of this work, we assume that this official designation is permanent.) Of this 210-km length, a total of 76 km, or ~36%, is unprotected. We assessed the impact that riparian buffers along these unprotected segments could have on expected yield from oil palm cultivation adjacent to the river.

Although we modeled the full river planform, our analyses of crop yield only consider land directly affected by river migration: land along the eroding (outer) bank of a meander bend; and new land (i.e., a point bar) accreted along the noneroding (inner) bank of a river bend, deposited as a result of lateral channel migration. Eroding river banks are where the geomorphic ecosystem service of erosion regulation (Millennium Ecosystem Assessment, 2005) by riparian vegetation actively functions, and these sections are where our findings are best constrained. However, for the sake of comparison, we ran two sets of simulations related to point bars on the noneroding (inner) bank. For the first set, we assumed that point bars are not amenable to oil palm growth and so are left fallow. For the second set, we assumed that point bars are cultivated, such that they might partially offset losses to erosion on the opposite bank. The assumption of fallow point bars is more realistic for a number of reasons (see Text S1 in the supporting information), but we pursued the theoretical alternative to test its relative effects. We did not address the benefits of flood mitigation or other ecosystem services that riparian vegetation can provide—but a more comprehensive valuation would likely increase net benefits of riparian buffering.

### 2.1. Fluvial Model

We employed the linear theory of meander migration (Ikeda et al., 1981; Johannesson & Parker, 1989) in a deliberately simplified, parameterized model of channel planform dynamics. The linear theory of meander migration accommodates consideration of relative vegetation effects via an adjustable coefficient of bank erodibility, and we use parameter values for channel morphology and bank erodibility that are representative of the Lower Kinabatangan at the reach scale (averaging across multiple meander bends; Horton et al., 2017). Variants of this model have been used to capture the statistical characteristics and dynamics of channel





**Figure 1.** Study site, land cover characteristics, and sections of forest along eroding riverbanks. (a) Location of study reach and the settlement at Batu Puteh (shown using the World Geodetic System (WGS) 1984 UTM Zone 50°N projected coordinate system). (b) Landsat L5 image captured on 17 September 2005, showing the study domain, defined land cover types, sections of river with unprotected forest on the eroding bank, and the location of panel (c). (c) A single meander exhibiting examples of each land cover type (forest, plantation, riparian buffer, and point bar) considered in this study. Dotted white line marks the remnants of a riparian buffer that originally traced the length of the meander. (Image from Google Earth™.)

planform change over extended spatial scales (Camporeale et al., 2005; Howard & Knutson, 1984; Motta et al., 2012; Perucca et al., 2007; Stølum, 1996; Sun et al., 1996). The abstractions in its design (see Text S1) do not preclude the utility of this model for analytical insight. The objective of this paper is not to explicitly predict the future channel position for the Kinabatangan River but rather to frame and compare the potential

repercussions of different forest-clearing scenarios in the context of realistic river meandering behavior—and this model, even at coarse spatial scales, provides sufficient realism.

Our numerical model of channel centerline migration includes three main components. The first component evaluates simplified river hydrodynamics and assigns a velocity perturbation to each point along the river. The second evaluates the vegetation along the eroding bank and assigns the appropriate erosion coefficient and corresponding migration rate. The third simulates channel migration by moving each point the ascribed distance normal to the river centerline.

The linear theory of meander migration (Ikeda et al., 1981) proposes a linear relationship between meander migration rates and a flow velocity term:

$$M = \varepsilon \omega \quad (1)$$

where  $M$  is the rate of meander migration (m/a),  $\varepsilon$  is a dimensionless coefficient of riverbank erosion, and  $\omega$  (m/a) is the velocity perturbation along the outer bank, such that  $\omega = u_b - u_m$  where  $u_b$  is the depth averaged, near-bank flow velocity (m/a), and  $u_m$  is the cross sectionally averaged flow velocity (m/a). The dimensionless coefficient  $\varepsilon$  is a scaling factor that captures riverbank susceptibility to erosion, which abstracts a variety of factors including bank material properties, hydrological conditions, and the influence of vegetation.

To evaluate the velocity perturbation ( $\omega$ ) for all discretized points (50-m spacing) along the river centerline, the model employs a numerical solution (Sun et al., 1996) that assumes an initial value of  $\omega = 0$  and a constant channel width (see Text S1). We assigned a coefficient of riverbank erosion ( $\varepsilon$ ) based on bank vegetation type. A binary land cover classification (forested or cleared) was evaluated using a polygon shapefile detailing the extent of forest cover evident in the 2014 Landsat 8 image, confirmed by field observations (Horton et al., 2017), and modified according to each scenario of forest clearing. Each point along the river centerline was assigned a coefficient of riverbank erosion corresponding to the land cover classification at an orthogonal distance  $b$  (half of one river width) in the direction of migration. We used  $\varepsilon = 4.3(\pm 2.4) \times 10^{-8}$  for forested sections and  $\varepsilon = 6.5(\pm 2.4) \times 10^{-8}$  for cleared sections, taken as the average ratio of mean migration rate to the maximum velocity perturbation along aggregated sections of river (forested and cleared), reflecting an observed increase in riverbank erodibility following riparian forest removal (Horton et al., 2017; see Text S1).

The crucial aspect of this assumption behind erodibility is that the value assigned to cleared sections is greater than the value assigned to forested sections. The relative difference between the two parameter values that we used ( $\sim 1:1.5$ ) is lower than relative differences reported in other studies (Micheli et al., 2004; Perucca et al., 2007), making our formulation a comparatively conservative assessment of the impact of forest clearing on meander migration rates.

Given values of  $\omega$  (m/a) and  $\varepsilon$  at each point along the river centerline, each point was moved a distance (m) of  $Ma = \varepsilon \omega$  (equation (1)) in the direction of migration, simulating one iteration of channel migration (where  $a = 1$  year). The direction of centerline point migration is orthogonal to the centerline curve (Motta et al., 2012), found by numerically evaluating the unit tangent vector at each point and rotating it 90° clockwise or anticlockwise depending on the sign of the velocity perturbation ( $\omega$ ). Modeled centerline position was rediscrretized at a spacing of 50 m every 25 iterations to maintain a regular spacing between centerline points. Using a continuous river domain that encompasses the reaches of interest means that upstream/downstream boundary effects on modeled planform evolution are negligible. (Model parameters are listed in Table S1.)

## 2.2. Conversion Scenarios and Bank Erosion Rates

Along reaches of unprotected forest, delineated from the 2014 Landsat 8 image (Figure 1b), we imposed a set of digitized polygons representing a riparian buffer of a given width. We assumed that any unprotected forest beyond a given buffer width from the channel is converted to oil palm plantation. Each buffer width that we considered constitutes one scenario of forest clearing (Table 1) and generated a distinct set of model outputs.

For each scenario we modeled annual centerline migration and calculated mean bank erosion rates at 25-year intervals (up to 100 years), corresponding approximately to a full plantation cropping cycle (from planting to maturity to decline and replanting; Abram et al., 2014; Butler et al., 2009). To produce a set of polygons representing the area of eroded bank material, we superimposed two channel centerlines from model

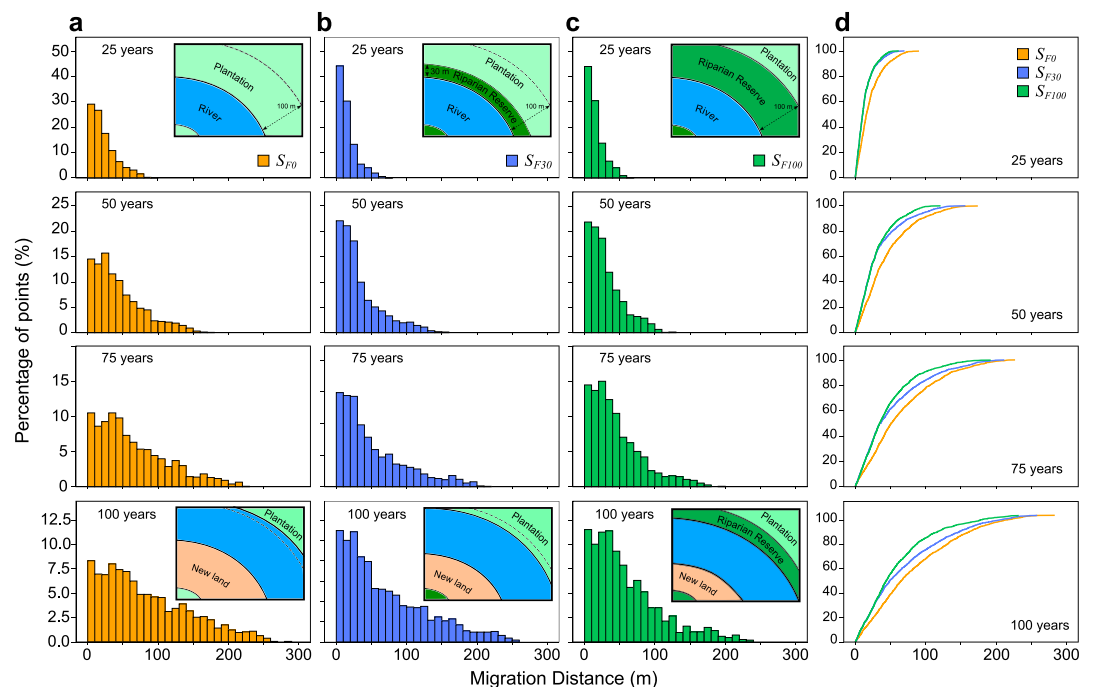
**Table 1**  
Summary of Notation

Width of riparian buffer zone (m)	Scenario of forest-clearing model outputs	Projection of expected yield with inner bank fallow (SA; IB = 0)	Projection of expected yield with inner bank cultivated (SB; IB > 0)
0	$S_{F0}$	$SA_{F0}$	$SB_{F0}$
10	$S_{F10}$	$SA_{F10}$	$SB_{F10}$
20	$S_{F20}$	$SA_{F20}$	$SB_{F20}$
30	$S_{F30}$	$SA_{F30}$	$SB_{F30}$
40	$S_{F40}$	$SA_{F40}$	$SB_{F40}$
50	$S_{F50}$	$SA_{F50}$	$SB_{F50}$
100	$S_{F100}$	$SA_{F100}$	$SB_{F100}$

planforms 25 years apart (C. Constantine et al., 2009; Micheli et al., 2004). To estimate the mean area of riverbank eroded per unit length of river ( $m^2/m$ ) per 25, 50, 75, and 100 years for each forest-clearance scenario (Table 1), we summed the areas of the channel change polygons that crossed into unprotected-forest polygons and divided the total area of the channel change polygons by the corresponding river length (using the original 2014 river centerline). We also calculated distributions of centerline migration at 50-m increments along the channel length at 25-year intervals (Figure 2 and Table S2).

### 2.3. Projections of Expected Yield

To model the expected yield from oil palm cultivated in close proximity to the river edge, we made two assumptions. First, we assumed that a 3-m fallow buffer is maintained between the riverbank and productive plantation—a distance consistent with our field observations and which approximately matches the typical radius of a single tree in plantation spacing (~7 m between any two trees). Second, we assumed that land along the eroding bank was 100% productive, which results in a conservative estimate for the impact riverbank erosion has on expected yields.



**Figure 2.** Distributions of centerline migrations for three forest clearance scenarios. Model outputs for the distribution of centerline point migrations taken at an along-channel spacing of 50 m after 25, 50, 75, and 100 years for columns (a)  $S_{F0}$ , (b)  $S_{F30}$ , and (c)  $S_{F100}$ . (d) Cumulative distributions of centerline point migrations for  $S_{F0}$ ,  $S_{F30}$ , and  $S_{F100}$ . Insets show schematic illustrations of the typical initial condition and final position of a meander bend under the three scenarios. Summary statistics of these distributions are provided in Table S2.

Using typical values of yields gained from existing oil palm plantations along the Kinabatangan floodplain (Abram et al., 2014), we modeled the mean expected yield from land along the eroding bank within existing forested sections over a 100-year (annum a) period. We restricted our calculations to 100-m distance from the riverbank position, delineated from the 2014 position, to provide estimates of mean yield per hectare of adjacent land such that

$$Y = \sum_{t=1}^{r-1} (1 - R)E_{100} + \sum_{t=r}^{100} (0.97 - Tt)E_{100} + IB \quad \exists r \in R : (T(r - 1) - 0.03) < R \text{ and } (Tr - 0.03) > R \quad (2)$$

where  $Y$  is the total expected yield (\$ [100 m]<sup>-1</sup> of river),  $R$  is the width of the initial riparian buffer zone (ha [100 m]<sup>-1</sup>),  $E_{100}$  is the net present value of 100% productive land with an 11% discount rate (\$ [ha a]<sup>-1</sup>; Abram et al., 2014),  $T$  is the model output of mean riverbank erosion per year (which varies with time in years  $t$ ; ha [100 m a]<sup>-1</sup>), 0.97 reflects the 3-m fallow land immediately adjacent to the river's edge, and  $IB$  is the contribution to yield from the conversion of new material accreted as a point bar on the inner bank (\$).

The initial condition expressed in equation (2) thus describes a generic 100 × 100-m (1-ha) square (analogous to a control volume in other physical systems) with one edge on the riverbank. The condition to equation (2) defines  $r$  as the time when the bank erosion begins to encroach on productive land. The summation from  $t = 1$  to  $t = (r - 1)$  describes yield accumulated from all plantation land until encroachment by erosion; the summation after  $t = r$  describes yield accumulated (up to 100 years) from an eroding area of plantation. The discount rate in equation (2) modifies the present value of palm oil yield according to its projected future worth. (A discount rate assumes the real value of a commodity declines over time; the rate of that decline is typically expressed as a percentage.) A discount rate of 11% comes from the assessment of Kinabatangan oil palm productivity by Abram et al. (2014). A different (lower, higher) discount rate changes (increases, decreases) the cumulative yield values (Figure S1) but does not affect when in time the cumulative yield curves reach their maxima.

We considered two scenarios for the contribution of the inner bank ( $IB$ ): one in which the inner bank is left fallow (scenarios  $SA_{F0-F100}$ ) and a second in which the inner bank is cultivated (scenarios  $SB_{F0-F100}$ ). (A summary of scenario notation is given in Table 1.) If new land on the inner bank—created by meander migration and representative of point bar accretion as the modeled channel maintains a constant width—is left fallow, then it contributes nothing to the expected yield of the domain, and the  $IB$  term in equation (2) equals 0. If the inner bank is cultivated, then  $IB$  depends on the productivity of newly formed point bars (see Text S1). Given that in-channel bars are prone to frequent and persistent inundation, we assumed that oil palm planted in newly accreted land are marginally productive at 25% (Abram et al., 2014; Corley & Tinker, 2015). We also assumed that as the river migrates away from the initial position of the inner bank, an increasing proportion of land on the inner bank becomes sufficiently distant from the river channel that it gains productivity (with a step change from 25% to 100%).

Contribution to the expected yield from cultivating newly accreted land on the inner bank was expressed as

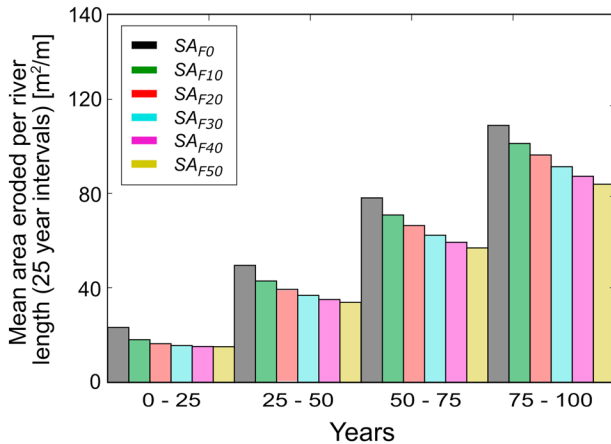
$$IB = \sum_{t=1}^{100} (TtE_{25} + 0.2TtE_{100}) \quad (3)$$

where  $E_{25}$  is the net present value of 25% productive land with an 11% discount rate (\$ [ha a]<sup>-1</sup>); the coefficient 0.2 is the proportion of land on the inner bank sufficiently distant from the river channel to gain productivity (see Text S1).

#### 2.4. Time-Dependent Profitability

Typically unproductive for the first 30 months, plantations are not considered mature until their third year (Corley & Tinker, 2003). Yields then increase rapidly, reaching maximum productivity after 9 years (Butler et al., 2009). Our long-term estimates for expected yields are driven by mean annual values calculated over a full plantation life cycle (Abram et al., 2014) and do not incorporate the inherent variability of a plantation's productivity within its life cycle. Therefore, to evaluate strategies for generating short-term profit within the first 10 years after implementing each forest-clearing scenario (for  $IB = 0$ ), we account for the lagged productivity of newly established plantations by making the  $E_{100}$  term in equation (2) time dependent, using a time series of annual yield values for new plantations reported by Abram et al. (2014).





**Figure 3.** Mean area of land lost per unit length of river. Mean area of land lost per unit length of river ( $m^2/m$ ) for each forest clearance scenario after 25, 50, 75, and 100 years. Values are listed in Table S3.

### 3. Results

#### 3.1. Simulated Channel Migration

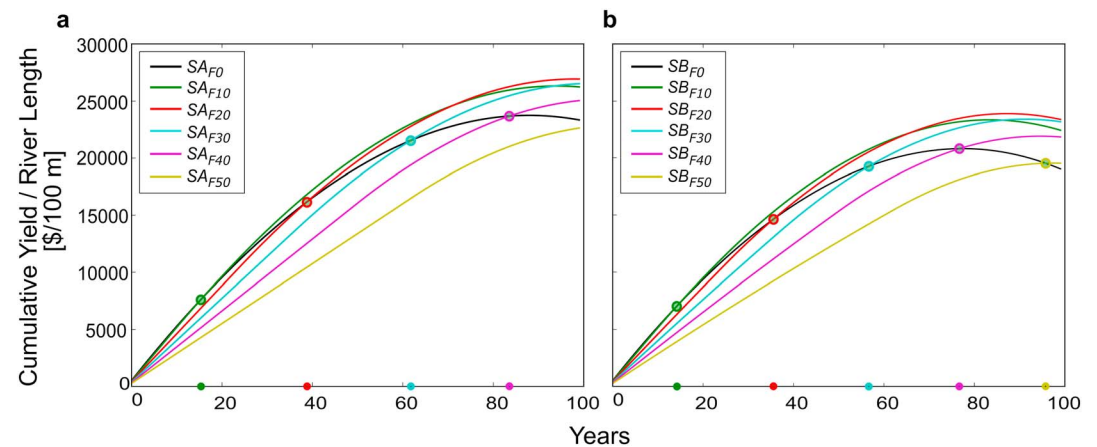
Overall, removing all riparian forest results in larger incursions by erosion into the floodplain, both in the short term and long term (Figure 2 and Table S2). The distribution of centerline migrations for the no-buffer scenario ( $S_{F0}$ ) shows fewer points migrating  $<10$  m and more points migrating  $>50$  m (Figure 2a) relative to the 30- and 100-m buffer scenarios ( $S_{F30}$ , Figure 2b;  $S_{F100}$ , Figure 2c), indicating that complete deforestation may induce lateral migration along sections of river that might not otherwise migrate when riparian forest is present. Migration rates at a given location are lower in the presence of a forest buffer; land loss accelerates once the river erodes through the buffer and into cleared plantation land at that location. At each 25 year interval, the geomorphic effect of maintaining a wide riparian buffer becomes more pronounced. After 50 years, the distributions of migration distance under the 30- and 100-m buffer scenarios ( $S_{F30}$ , Figure 2b;  $S_{F100}$ , Figure 2c) differentiate as the wider riparian buffer

( $S_{F100}$ ) reduces the number of points migrating longer distances (Figure 2d). After 100 years, the area of land lost (mean area of land lost per 100 m of river) with no buffer ( $S_{F0}$ ) is  $>25$   $m^2/m$  greater than with a 100-m buffer ( $S_{F100}$ )—the spatial equivalent of three rows of oil palms (Figure 3 and Table S3).

#### 3.2. Expected Yields From Land in Close Proximity to the River Edge

We used estimates of expected yields from existing oil palm plantations on the Kinabatangan floodplain (Abram et al., 2014) to quantify the potential impact of river migration on the mean long-term yield from land in close proximity to the eroding bank ( $\leq 100$  m from the 2014 river position).

For the no-buffer scenario ( $SA_{F0}$ ) with no contribution to yield from the inner bank ( $IB = 0$ ), the projections for mean cumulative yield per unit length of river ( $\$ [100 m]^{-1}$ ) show that the initial increase in yield from supplanting all riparian forest with oil palm is eventually counteracted by the resulting increase in riverbank erosion, ultimately limiting the long-term return (Figure 4a). Given a 10-m buffer ( $SA_{F10}$ ), the mean cumulative yield from land within 100 m of the eroding bank exceeds yield from the no-buffer scenario ( $SA_{F0}$ ) after  $\sim 15$  years (Figure 4a and Table 2). Buffers  $>30$ -m wide appear to affect migration distances to similar extents over multiple decades ( $<50$  years), preserving high-yield areas for the longest periods (Figure 4a).



**Figure 4.** Expected cumulative yield for different forest clearance scenarios. (a) Model outputs of the expected cumulative yield ( $\$ [100 m]^{-1}$ ) for SA scenarios (no yield from land accreted on inner bank). (b) Model outputs of the expected cumulative yield for SB scenarios (including yield from land accreted to the inner bank). Circles indicate where each scenario exceeds the baseline scenario of total forest clearance ( $S_{F0}$ , or no riparian buffer).



**Table 2**  
Time Before Forest Clearance Scenarios Become Economically Advantageous Relative to Total Forest Removal  $S_{F0}$  Under Each Set of Assumptions (SA, SB, and Productivity Proportional to River Proximity)

Width of riparian buffer (m)	Time (a) before scenario > $SA_{F0}$	Time (a) before scenario > $SB_{F0}$	Time (a) before scenario > $S_{F0}$ assuming proportional productivity
10	15.2	14.0	3.0
20	38.6	35.3	7.0
30	61.5	56.4	23.9
40	83.2	76.3	44.4
50	N/A	95.4	63.8

Note. N/A = not applicable.

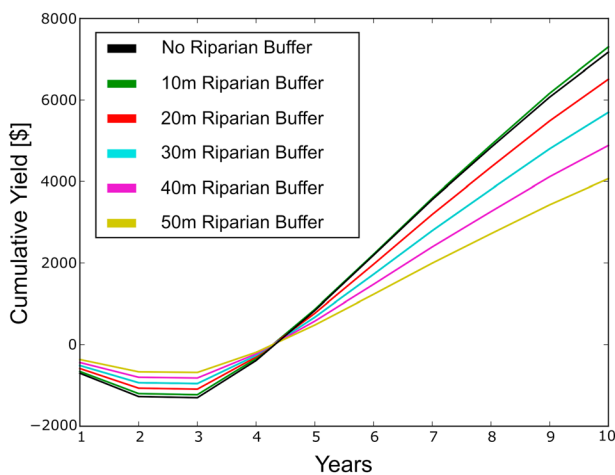
Accounting for the potential (if improbable) cultivation of the inner bank ( $IB > 0$ ) adds planted area but does not boost expected yields. Marginally productive (25%) land on the inner bank cannot offset the fixed costs of palm planting and maintenance (Abram et al., 2014). In projections of cumulative yield when  $IB > 0$  (the SB scenarios), the net loss from planting out the inner bank compounds losses from high rates of channel migration. The positive net benefit derived from riparian buffers is realized sooner when  $IB > 0$  (Figure 4b and Table 2).

Note that the no-buffer scenarios without ( $SA_{F0}$ ) and with ( $SB_{F0}$ ) contribution to yield from the inner bank both exhibit a local maximum for cumulative yield (Figure 4). Because the initial condition describes a generic  $100 \times 100$ -m (1-ha) control volume with a mean yield value (equation (2)) extending inland from the riverbank, the trend in cumulative yield (at 100% productivity) from cultivated land within the control volume is positive until the river erodes into cultivated land behind it (a migration distance of  $> 100$  m). As bank erosion and lateral migration continue, the trend in cumulative yield reverses and becomes only negative. When  $IB > 0$  ( $SB_{F0}$ ) the maximum occurs earlier than when  $IB = 0$  ( $SA_{F0}$ ) because of the additional net loss (after the fixed costs of planting) that the marginally productive inner bank incurs.

### 3.3. Short-Term Profitability

For time scales  $< 10$  years, the highest revenues arise from the no-buffer scenarios ( $SB_{F0}$  and  $SA_{F0}$ ) as the conversion of all available land to oil palm plantation increases yields enough to compensate, at least initially, for the negative consequence of increased bank erosion and accelerated channel migration. However, this apparent short-term profitability changes when we consider that newly established oil palm plantations are typically unproductive for the first 3 years (Butler et al., 2009; Corley & Tinker, 2003). If we examine the

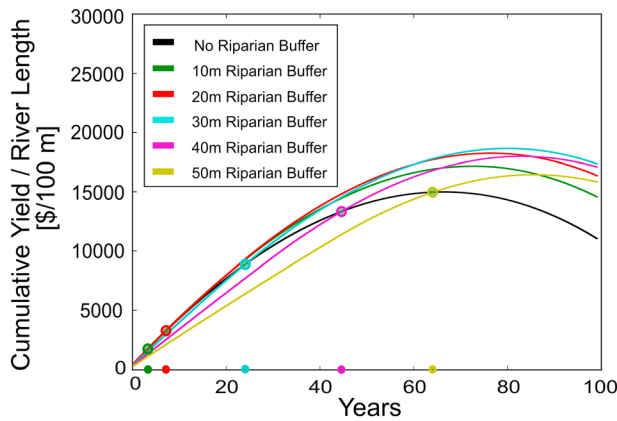
mean cumulative yield per unit length of river ( $\$ [100 \text{ m}]^{-1}$ ) for the first 10 years of a plantation lifecycle and account for the lagged productivity of a new plantation, then we find that a riparian buffer is necessary to maximize the potential return from land in close proximity to the eroding bank at the shortest (multiannual) time scales (Figure 5).



**Figure 5.** Expected yields from newly established plantations. Modeled results for the first 10 years of SA using annual yield values (Abram et al., 2014) that account for the time-dependent (lagged) productivity of a plantation early in its life cycle.

### 3.4. Propagating Edge Effect

Because regular inundation and excess soil moisture is detrimental to the cultivation of oil palm, plant productivity likely increases with distance from the river (Abram et al., 2014; Corley & Tinker, 2015). Therefore, estimated yield that assumes all land on the eroding bank is productive at 100% may underestimate the impact of river migration. To examine the possible effect of productivity being proportional to river distance, we considered the simple, hypothetical case of a *propagating edge effect* or *spatial externality* (Parker, 2007). We assumed that (1) land within 20 m of the eroding bank is 50% productive and (2) that this reduced productivity tracks inland with the eroding bank as the river migrates through the floodplain. Although our choice of spatial gradient is arbitrary (we do not account explicitly for combined effects of flooding, channel seepage, and floodplain drainage), our results



**Figure 6.** Expected cumulative yield for forest clearance scenarios with an edge effect externality. Modeled expected cumulative yield, assuming a reduction in productivity that is proportional to river proximity (and no yield from land accreted on the inner bank). Circles indicate where each scenario exceeds the baseline scenario of total forest clearance ( $S_{F0}$ , or 0-m riparian buffer).

demonstrate that a gradient in productivity at the riverbank (such that productivity increases with distance from the channel) intensifies the impact of river migration on expected yields and increases the long-term economic value of riparian forest buffers (Figure 6).

### 3.5. Highest-Yield Scenarios

The scenarios (i.e., recommended buffer widths, based on the parameters we use) that produce the highest expected yields over short (0–10 years), medium (10–50 years), and long terms (50–100 years) are summarized in Table 3. If we assume lower productivity in close proximity to the riverbank (Figure 6), then the highest-yield scenarios require a wider riparian buffer. Changes in riverbank erodibility ( $\epsilon$ ) parameterization will likewise affect both time scale and corresponding buffer width. Although the maximum yields without (SA) and with (SB) contributions from the inner bank are of different magnitudes, the recommended buffer widths are the same for both sets of scenarios.

### 3.6. Regarding Model Sensitivity

The erodibility coefficient ( $\epsilon$ ) for forested versus nonforested channel reaches is the primary parameter by which we control the fluvial model (see Text S1). We test the sensitivity of the economic projections to the erodibility coefficient (forested and nonforested) by running the  $IB = 0$  (SA) scenarios with coefficient values  $\pm 1$  geometric standard deviation about their respective means (the values we otherwise use and report). These comparisons thus frame upper and lower bounds for the economic projections in each forest clearance scenario (Figure S2 and Table S4). We find that our recommended buffer widths (Table 3) hold for this inclusive range of erodibility coefficients.

Empirical observations of migration rate versus velocity perturbation suggest a nonlinear fitting for the erodibility coefficient ( $\epsilon$ ) may be more appropriate for forested channel sections (Horton et al., 2017), because above a threshold velocity perturbation, rates of lateral migration tend to change very little along forested reaches. Therefore, we tested an alternative formulation of the erodibility coefficient for forested river sections that describes this observed nonlinearity (Text S1 and Figure S4). Applied across the full span of the river (Figure S5 and Tables S5–S7), the nonlinear model results have a little effect on the economic projections, shortening the time to improved economic returns by a few years—but not enough to affect the recommended buffers in Table 3.

## 4. Discussion

Modeling the expected return from oil palm plantations in close proximity to the Kinabatangan River under different scenarios of future forest conversion suggests that retaining riparian buffers along tropical river boundaries has the potential to increase the profitability of floodplain agriculture. The increase is most evident in long-term economic projections (Figure 4) and also holds true at shorter time scales (Figure 5), given the lagged productivity of newly established plantations (Butler et al., 2009; Corley & Tinker, 2003). By reducing initial planting expenditure and safeguarding young palms from being lost to erosion before they generate revenue, riparian buffers have the potential to increase the short-term profitability of newly established plantations along with the long-term expected yields from mature stands.

These results have important implications for the conservation and management of riparian forest marked for future conversion to oil palm. At present, the palm oil industry may hear in arguments for ecological

**Table 3**

*Actions to Maximize Expected Yields Based On Range (in Years) of Economic Forecast and Productivity of Land Adjacent to the River's Eroding Bank*

Range of forecast (a)	Action assuming 100% productivity at eroding bank	Action assuming reduced productivity with river proximity
Short (0–10)	Maintain initial 0- to 10-m riparian buffer	Maintain initial 10- to 20-m riparian buffer
Medium (10–50)	Maintain initial 10-m riparian buffer	Maintain initial 20-m riparian buffer
Long (100)	Maintain initial 20-m riparian buffer	Maintain initial 30-m riparian buffer

conservation little incentive to set aside potential plantation area for riparian buffers. However, if riparian buffers provide a fundamentally geomorphic ecosystem service (erosion regulation) that is economically advantageous to an adjacent plantation, then palm oil producers may have more motivation to designate and maintain areas of tropical forest along river courses—to the mutual benefit of agricultural producers and tropical forest ecosystems.

#### 4.1. Maximizing Return From Floodplain Plantations

By reducing meander migration rates, riparian buffers have the potential to increase the expected yield from plantations on eroding riverbanks. How best to use this provision to maximize economic return from floodplain plantations depends on the duration of the desired return and the level of productivity along the eroding riverbank (Table 3). Predictions of river channel response to specific management actions at specific sites would require a more computationally sophisticated model operating at a higher spatiotemporal resolution than we have used here. Nevertheless, our results suggest that preserving a riparian forest buffer can enhance the expected return from an otherwise converted floodplain.

We did not test scenarios where rehabilitated forest was used to create a buffer, but such approaches have proven successful in other systems (Schultz et al., 2004). For a given scenario, our simulations assume a buffer of uniform width along each unprotected reach of the river. However, a more efficient, nuanced application of a buffer might involve relaxing the fixed-width condition and instead coupling local buffer width to the local bank erosion rate. Under the condition of a fixed-width buffer, sections of river that undergo little migration lose potential yield to a redundant ecosystem service; similarly, plantations especially vulnerable to rapid river migration could be better protected by using a wider buffer. Initial widths of riverbank forest buffers could therefore be varied according to expected distances of bank migration over a given time span. This would reduce the area of land lost to the river along sections that migrate rapidly and would allow proportionally more forest conversion along relatively static reaches. Forest connectivity could be better maintained along the length of the river (at least until broken by meander migration), providing the benefits of a continuous forest corridor (Bruford et al., 2010; Gregory et al., 2014).

#### 4.2. Conservative Estimates

Because several components of this analysis involve conservative estimates of rates and effects, our assessments are likely to underrepresent the potential for riparian forest buffers to enhance the economic return from floodplain plantation.

First, the values we use for the coefficient of erosion, taken as the ratio of mean migration rate to the maximum velocity perturbation along aggregated sections of river, are conservative estimates when applied to local point values of velocity perturbation along the river centerline. This likely underestimates meander migration along both forested and cleared sections of the river. Riparian buffers derive their economic worth from slowing the migration of the river through the floodplain; underestimating migration will thus tend to undervalue the economic worth attributed to riparian buffers. Even where the linear theory ascribes high migration rates to high curvatures in forested reaches and allows forested reaches to erode continuously as a function of planform curvature (where erosion of real forested riverbanks may be episodic; Horton et al., 2017), the model may underrepresent the potential for riparian forest to reduce land loss.

Second, meander migration rates represented in our model only account for riverbank erodibility as a function of riparian forest absence or presence. We do not consider any secondary effects of forest removal, such as increased sediment loading, increased mean average discharge, magnitude and frequency of peak flows, or the duration of high flows that can affect bank erosion, migration rates, and otherwise alter the river's internal flow regime (Costa et al., 2003; Liu et al., 2015). Forest removal from tropical floodplains has been shown to increase sediment delivery to river systems (Annammala et al., 2012; Gomi et al., 2006), which may drive more rapid river evolution by the addition of coarse-grained material (including increased migration rates; J. Constantine et al., 2014; Dunne et al., 2010; Wickert et al., 2013) and alter the geochemistry and ecological functioning of the river by the addition of suspended particulates (Alonso, 1975). If sediment loading from forest clearing increased meander migration rates, accelerating loss of plantation to bank erosion, and propagating a wave of such change downstream, the full economic benefit of maintaining riparian buffers—both upstream and down—would increase.

Third, we consider reduced meander migration rates as an ecosystem service provision for land in close proximity ( $\leq 100$  m) to the river edge, but flood impacts following the removal of floodplain forests may adversely affect the productivity of established plantations at larger scales (Corley & Tinker, 2015; Liu et al., 2015). Flood events along the Kinabatangan can extend hundreds of meters inland from the river's banks (Estes et al., 2012); persistent flood impacts, whether through increased frequency or duration, are likely to be far more economically detrimental than those caused by meander migration, particularly over short (multiannual) time scales.

### 4.3. Geomorphic Ecosystem Function

Through soil formation and retention (a *supporting* service) and erosion regulation (a *regulating* service), geomorphological processes directly contribute to two of the four broad categories of ecosystem services (Millennium Ecosystem Assessment, 2005). Still, major studies of ecosystem services tend to emphasize the functional interaction between biological ecosystem elements rather than nonliving elements of the landscape, inadvertently undervaluing the contribution of geomorphic processes to human wellbeing (Everard & Quinn, 2015; Gordon & Barron, 2013; Hupp et al., 2009; Tomscha et al., 2017).

River floodplains are especially important within the ecosystem services spectrum: occupying  $< 1.5\%$  of global surface area, they underpin an estimated 25% of terrestrial ecosystem services (Tockner & Stanford, 2002). Integral to floodplain environments are fluvial geomorphic processes. As sediment erosion, deposition, and transportation reshape the physical fluvial system, they influence ecosystem structure and functioning (Naiman et al., 2010). Fluvial geomorphic processes control sinuosity; the formation and erosion of in-channel bars and islands; the number, network, and density of channels; and the size and connectivity of floodplains—all of which directly contribute to habitat diversity and availability of ecological niches (Thorp et al., 2006). Ecosystem service diversity, quality, and complexity increases with ecosystem biodiversity, productivity, and metabolism, which are enhanced by habitat complexity (Thorp et al., 2010). Collectively, this suggests that ecosystem services may be enhanced in environments where geomorphic processes can operate naturally on the landscape. To quantitatively describe the suite of ecosystem services afforded by floodplain landscapes, sustainability science will need to better understand the reciprocal influences between linked habitat types, functions, and services performed and provided by fluvial processes and landforms (Everard & Quinn, 2015; Tomscha et al., 2017).

Our results demonstrate one way in which natural interactions between in-channel fluvial processes and the adjacent floodplain environment can have direct consequences on the profitability of floodplain agriculture. Although the economic valuations that we use are specific to oil palm on the Lower Kinabatangan, our construction of the problem—how to gain economic benefit by using natural processes of erosion regulation to reduce bank erosion and land loss—is transferrable across other freely meandering river systems with naturally forested floodplains.

## 5. Conclusion

This investigation quantifies the effects of riparian forest buffers on expected yield from an adjacent tropical oil palm plantation, given the capacity for riparian forest to reduce rates of riverbank erosion, meander migration, and loss of arable land. The channel migration rates that we modeled—along with their implications for riparian buffering—are derived from parameterization, calculation, and analysis of planform, floodplain, and plantation characteristics along the Kinabatangan River. Our results suggest that preservation of riparian buffers can enhance profitability of adjacent plantations by slowing land loss. Further work is required to identify and quantify the full range of benefits—including sustainable source certification (Carlson et al., 2018)—potentially afforded to oil palm plantations by riparian buffers.

Were the palm oil industry to revise their current forest management practices to incorporate riparian buffer zones as a geomorphic means of reducing rates of arable land lost to bank erosion, the consequences of such an action would extend beyond improved agricultural productivity. Riparian forest buffers provide vital ecological functions that help regulate the aquatic environment and mitigate some of the negative consequences associated with deforestation and oil palm expansion (Chellaiah & Yule, 2018; Mander et al., 2005; Naiman et al., 2010). Maintaining reaches of riparian forest along tropical rivers would also benefit terrestrial biodiversity by preserving natural habitat (Lukey et al., 2014; Turner & Corlett, 1996) and by serving as



connective corridors for genetic mixing between forest patches otherwise fragmented by oil palm monoculture (Bruford et al., 2010; Gregory et al., 2014).

Because rapid, large-scale land conversion has geomorphic consequences (Lazarus, 2014), geomorphic ecosystem services have an important role to play in efforts to guide long-term environmental sustainability. *Building with nature* efforts have a long legacy in floodplain management and river restoration research (Darby & Sear, 2008) and also extend to other geomorphic systems, including deltas (Paola et al., 2011) and coastlines (Cheong et al., 2013; Temmerman et al., 2013; van Slobbe et al., 2013). Insight into the dynamics of management interventions that make use of natural processes is essential to understanding how human-dominated landscapes (Di Baldassarre et al., 2013; Werner & McNamara, 2007) and novel ecosystems (Ellis, 2011) will evolve in the future.

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