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Extreme event-driven sediment aggradation and erosional buffering along a tectonic gradient in southern Taiwan

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ABSTRACT

In most landscape evolution models, extreme rainfall enhances river incision. In steep landscapes, however, these events trigger landslides that can buffer incision via increased sediment delivery and aggradation. We quantify landslide sediment aggradation and erosional buffering with a natural experiment in southern Taiwan where a northward gradient in tectonic activity drives increasing landscape steepness. We find that landscape response to extreme rainfall during the 2009 typhoon Morakot varied along this gradient, where steep areas experienced widespread channel sediment aggradation of >10 m and less steep areas did not noticeably aggrade. We model sediment export to estimate a sediment removal timeline and find that steep, tectonically active areas with the most aggradation may take centuries to resume bedrock incision. Expected sediment cover duration reflects tectonic uplift. We find that despite high stream power, sediment cover may keep steep channels from eroding bedrock for up to half of a given time period. This work highlights the importance of dynamic sediment cover in landscape evolution and suggests a mechanism by which erosional efficiency in tectonically active landscapes may decrease as landscape steepness increases.

INTRODUCTION

Topography in tectonically active landscapes results from competition between rock uplift and erosion. On short time scales, precipitation paces landscape evolution through its control on river incision (Whipple and Tucker, 1999; Dadson et al., 2003). The commonly used stream power model of bedrock river evolution suggests that incision increases with event size above an incision threshold (Lague et al., 2005; DiBiase and Whipple, 2011). However, as precipitation intensity increases, so does hillslope susceptibility to landslides (Caine, 1980; Guzzetti et al., 2007). Extreme events can trigger hundreds of thousands of landslides, burying channels with sediment and stopping mechanical bedrock incision (Sklar and Dietrich, 2001; Ouimet et al., 2007; Finnegan et al., 2014). This effect is termed erosional buffering. The legacy of these events, and how this depends on local tectonics, remains an open question.

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Typhoon Morakot hit southern Taiwan on 6–10 August 2009 and brought more rainfall than any other storm in Taiwanese recorded history, with some areas receiving >3000 mm of rainfall over ~100 h (Chien and Kuo, 2011) and triggered $>15,000$ landslides (Lin et al., 2011). We used a combination of field, remote, and numerical techniques to quantify sediment aggradation and estimate sediment export in 15 drainage basins affected by the typhoon. We show that this extreme event occurring across a strong gradient in landscape steepness has a temporal legacy that varies over three orders of magnitude. In southern Taiwan, typhoon Morakot triggered widespread landslides that caused severe river channel sediment aggradation in areas with the steepest hillslopes. This sediment aggradation halted incision in channels that previously eroded bedrock. After quantifying aggradation and modeling sediment export, we find that incision resumed within a year in basins with relatively little rock uplift, while steeper basins will not resume incision for decades or centuries.

FIELD AREA AND METHODS

Topography in Taiwan results from the collision of the Eurasian plate and the Philippine Sea plate (Teng, 1990; Shyu et al., 2005). The southern tip of Taiwan is part of the emerged accretionary prism, where uplift results from accretion of the Luzon Volcanic Arc onto the Asian continental margin (Huang et al., 1997; Chang et al., 2003; Giletycz et al., 2019). The oblique collision fuels an emergent orogen that propagates southward (Suppe, 1981; Teng, 1990). Rock uplift started earlier and is faster in the north of the study area than in the south; this tectonic pattern yields gradients in landscape steepness (Figs. 1A and 1B) that increase with distance north of the southern tip of Taiwan (Yanites et al., 2018).

Sediment Mass Balance

We used a survey of landslides triggered by Typhoon Morakot (Marc et al., 2018), to estimate the volume of storm-mobilized sediment. We employed power-law area-volume scaling (Larsen et al., 2010) to estimate landslide volume from the mapped area (see the Supplemental Material[1] for details on the methods). Summing individual landslide volumes, we calculated total landslide sediment in 15 drainage basins (Fig. 1C).

We used a new method to estimate the volume of sediment that aggraded in each drainage basin without a post-Morakot digital elevation model (DEM). We mapped post-Morakot channel outlines using the first available post-storm Google Earth™ imagery with channels at low flow; image dates range from 2009 to 2012. We then extracted elevations along mapped channel outlines from a pre-Morakot 5-m-resolution DEM made from orthorectified aerial photographs (at low flow). We interpolated between

[1]Supplemental Material. Methods for landslide volume estimation, channel aggradation mapping, sediment transport modeling, and recurrence estimate. Please visit https://doi.org/10.1130/GEOL.S.15152574 to access the supplemental material, and contact editing@geosociety.org with any questions.

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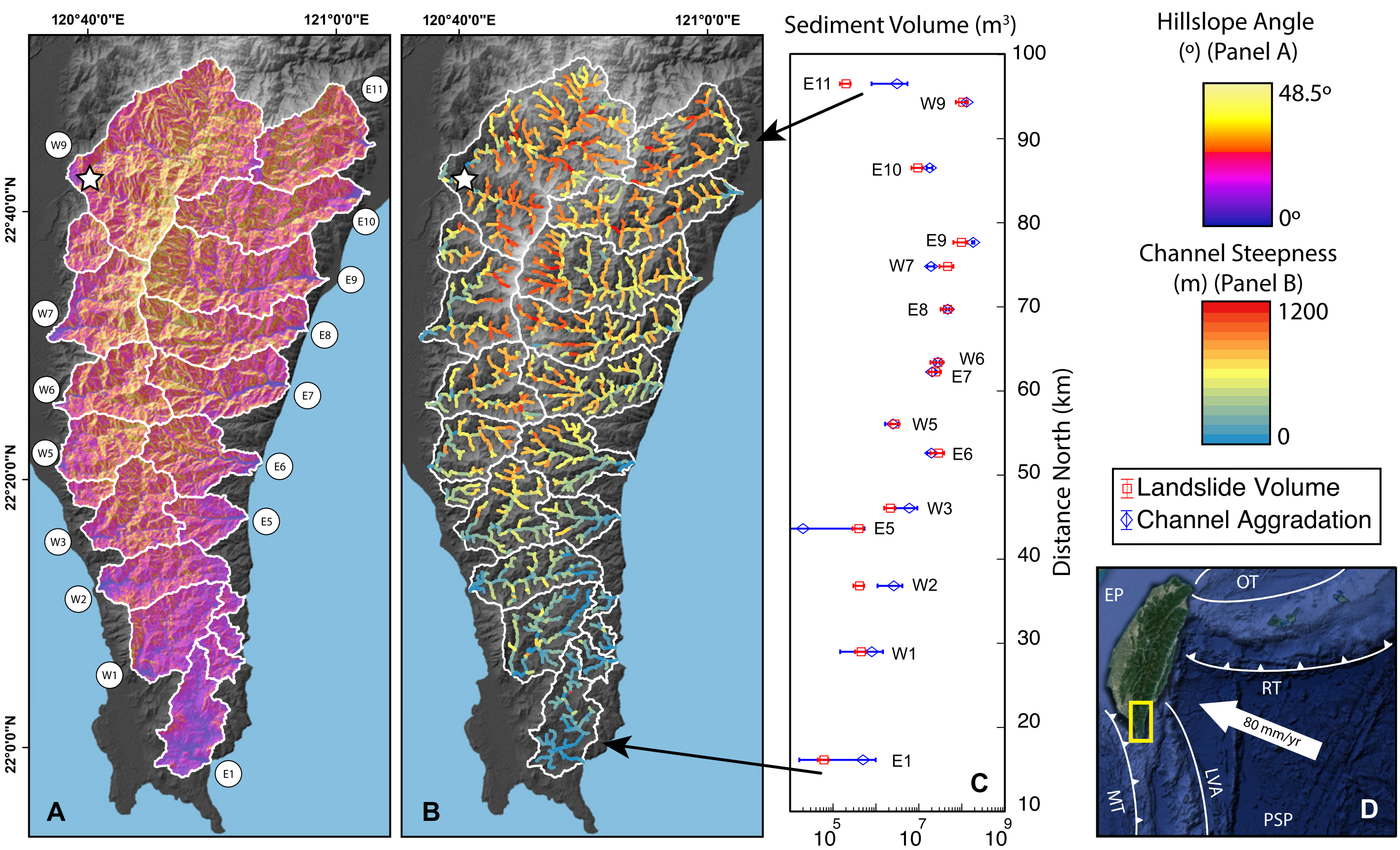

Figure 1. (A) Hillslope angle in southern Taiwan. Drainage basins are outlined in white. White star is Ailiao River gauging station. (B) Map of channel steepness calculated using TopoToolbox (Schwanghart and Kuhn, 2010). (C) Volume of sediment calculated from landslides (red squares) and channel aggradation (blue diamonds) versus distance north of the southern tip of Taiwan. Each point represents one drainage basin. Note that the x-axis shows variation over four orders of magnitude. (D) Location of the study area (yellow rectangle) and the regional tectonic setting of Taiwan. EP—Eurasian plate, PSP—Philippine Sea plate, OT—Okinawa Trough, RT—Ryuku Trench, LVA—Luzon Volcanic Arc, MT—Manila Trough.

points using an inverse distance weighting function and assume that this surface is representative of the post-Morakot aggradation surface (Fig. S1 in the Supplemental Material). We calculated aggraded sediment volume by subtracting pre-Morakot channel elevation from this post-Morakot channel elevation (Fig. 2; Figs. S2 and S3). Results from this calculation are shown as blue diamonds in Figure 1C, with error bars resulting from the ±50 cm vertical error of the DEM.

We estimated sediment export at basin outlets with a bedload sediment transport model (Wong and Parker, 2006) using grain sizes from 36 field surveys (Figs. S4–S6) and mean daily discharge (Fig. 1). We scaled discharge from the Ailiao River (W9 in Fig. 1) by drainage area to estimate the discharge of ungauged basins. Channel slope was measured from the DEM at the mouth of each basin. We used a rating curve between channel width measured from Google Earth™ imagery and gauged river discharge to estimate changing channel width (see the Supplemental Material and Figure S7). There are only 11 dates where both measurements exist ($R^2 = 0.53$). We calculated bedload flux from 11 August 2009 to 31 December 2019 and estimated total sediment flux for a range of bedload fractions (⅓ to ½) (Turowski et al., 2010). We do not account for background sediment delivery during the decade of sediment transport modeling, so sediment export time scales represent a minimum estimate.

Recurrence Estimation

To estimate the frequency of landslide-triggering events like Typhoon Morakot, we used a combination of suspended sediment discharge and basin-averaged denudation rate data. These events may be storms, earthquakes, or other events that trigger large numbers of landslides. The one basin in our study area for which both data sets are available continually since Typhoon Morakot is the Ailiao River (W9).

An expression for average hillslope sediment export of a basin is

$$A = \frac{Bt + E}{t}, \qquad (1)$$

where A is the average denudation rate from cosmogenic radionuclides (CRN) (mm/yr), B is the background rate of sediment export in years without an extreme landslide event estimated from suspended sediment discharge (mm/yr), E is hillslope denudation from a single extreme event (mm), and t is time between extreme events (yr). We used a rating curve relating suspended sediment concentration and water discharge to estimate background sediment flux over the past 50+ years (Fig. S8). Again, we varied bedload fraction from ⅓ to ½ to calculate a range of total sediment flux and find a background denudation rate of 0.9–1.2 mm/yr. Hillslope denudation from Morakot (E) is determined by summing landslide volumes and dividing by basin area (Fig. 3A; Table S1). Average denudation rate was determined from CRN (Chen et al., 2020; Fellin et al., 2017).

RESULTS

Landslide activity during Typhoon Morakot varied greatly across the study area. Landslide initiation increased with distance north of the southern tip of the island (Fig. 1; Fig. S8); <0.1% of basin area was impacted by landslides in the south, while northern basins experienced landslides in ~7% of their area (Table S1). Estimates of basin-averaged hillslope denudation from typhoon Morakot (E) range from 10^{-3} m in southern basins to 10^{-1} m in northern basins (Table S1).

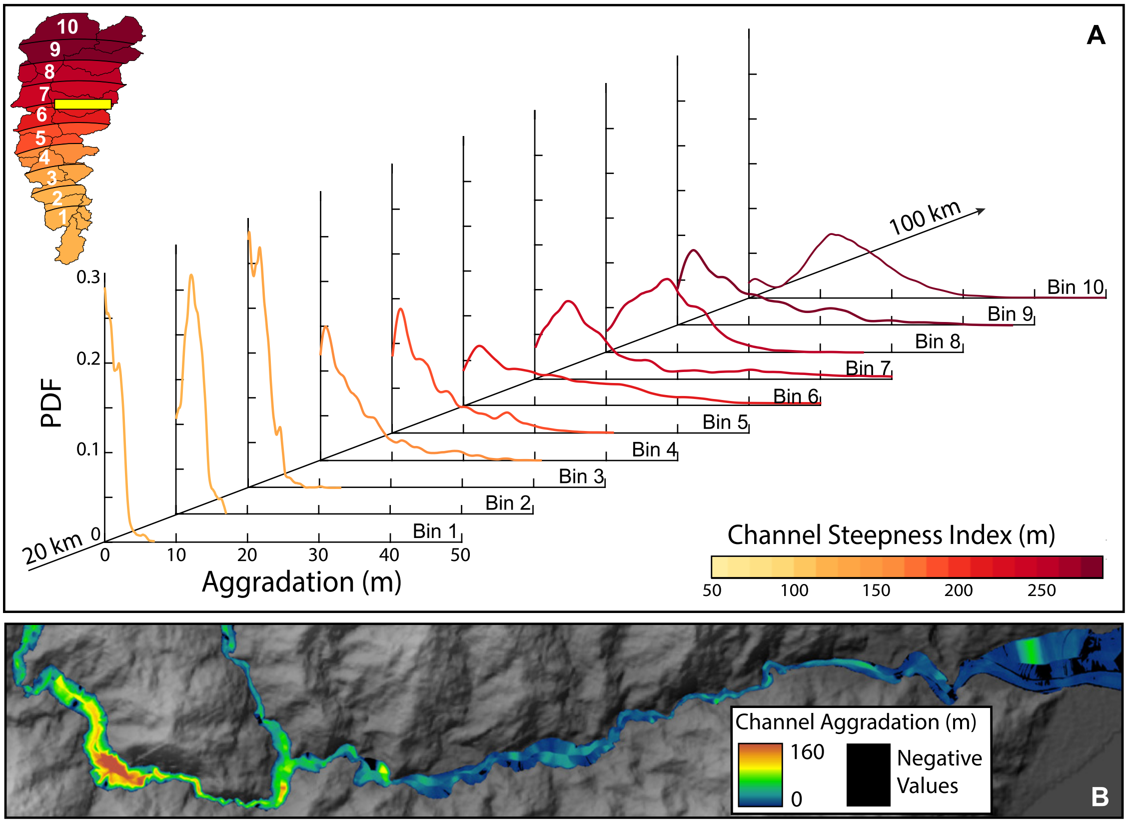

Figure 2. (A) Distribution of sediment aggradation in southern Taiwan. X-axis is cross-sectionally averaged aggradation depth. Y-axis is probability density function (PDF) of channel aggradation depths in each distance bin. Z-axis is distance from the southern tip of Taiwan. Lines colored by average channel steepness index in each distance bin, which are defined in the inset. PDF of aggradation in the southern bins is centered around zero, while PDF of aggradation in northern bins peaks above 10 m. (B) Example of mapped aggradation. Location is shown by the yellow box in panel A inset.

We summed aggradation in each basin and found that while basin area varies from 55 to 407 km^2, the volume of aggraded sediment varies from 10^4 to 10^8 m^3 and increases with distance from the southern tip of the island (Fig. 1). Channel aggradation in southern basins was not easily detectible beyond the error of the DEM, whereas northern basins saw average channel aggradation thickness of 10^1 m (Fig. 2).

We find a pattern of increasing sediment transport capacity with distance north due to increasing channel slope and river discharge (Fig. 3B). Our sediment transport model shows that sediment export from 11 August 2009 to 31 December 2009 varies from 10^5 to 10^7 m^3 in the studied basins.

Strong similarity is seen between spatial trends in short- and long-term denudation across the orogen when the sediment release during typhoon Morakot is compared with the denudation rate averaged over 10^2–10^4 yr calculated from CRN (Chen et al., 2020; Fellin et al., 2017) (Fig. 3A). We measured or calculated the variables from Equation 1 and solved for t. For sediment export to match denudation rates determined with CRN, extreme events must recur with a frequency of 50–200 yr, a finding consistent with the recurrence estimated for typhoons of this size in the region (Chu et al., 2011). Erosion rates from CRN in landslide-dominated catchments are temporally variable, which could either increase or decrease recurrence estimates. Due to the strength of the trend across the study area, however, we do not believe this detracts from our results.

DISCUSSION

We observed patterns of Morakot sediment aggradation and post-storm sediment export that increase with distance from the southern tip of Taiwan. The gradient in sediment export since typhoon Morakot is insufficient to balance the gradient in sediment aggradation (Fig. 3). The ratio of modeled sediment transport to sediment aggradation in low-steepness southern basins suggests that if any aggradation occurred there, the sediment was quickly removed. This is supported by the widespread exposure of bedrock in the thalweg of the southern rivers (Fig. S10). Steep northern basins, in contrast, may require 100 yr or more to export this sediment, as only ~10% of aggraded volume has been removed in the past 10 yr, though changes in channel width could accelerate this process (Croissant et al., 2017). We observe that a few channels have narrowed, leaving terraces at channel edges. These terraces appear to be retreating rapidly, however (Fig. S11), so this sediment will likely be mobilized, and this should not affect the duration of erosional buffering at the drainage basin scale. Two northern basins that experienced little Morakot precipitation deviate from the trend. We find that differences in the predicted duration of sediment cover correlate closest with the tectonically driven gradient in landscape steepness in the study area.

Using repeat times of 50–200 yr from our recurrence estimate, and duration of erosional buffering from 1–100 yr from sediment transport modeling, we find that the southernmost basins will have their bedrock channel incision buffered for less than 1% of any given time period, while steeper northern basins may experience erosional buffering for 50% or more of the same time period in response to extreme events (Fig. 3). We note that we are comparing data from different time scales and assuming that landslide-triggering events are generally of equal size, an assumption that ignores event-size variability. As such, our recurrence times are first-order estimates that suggest that these events are important, but not predictive tools. Future work should quantify the impact of distributions of landslide-triggering events over landscape evolution time scales on erosional efficiency.

We limited our analysis to the southern 100 km of Taiwan, but note that landslides were triggered by Morakot farther north. This decision was made to minimize the impact of variable lithology and precipitation. North of our study area, lithology varies systematically toward higher metamorphic grade (Ho, 1986), which impacts landslide initiation. Mean annual precipitation also generally increases to the north, which impacts sediment export rates. In our study area, lithology and mean precipitation are mostly uniform. While precipitation from typhoon Morakot varied across the study area

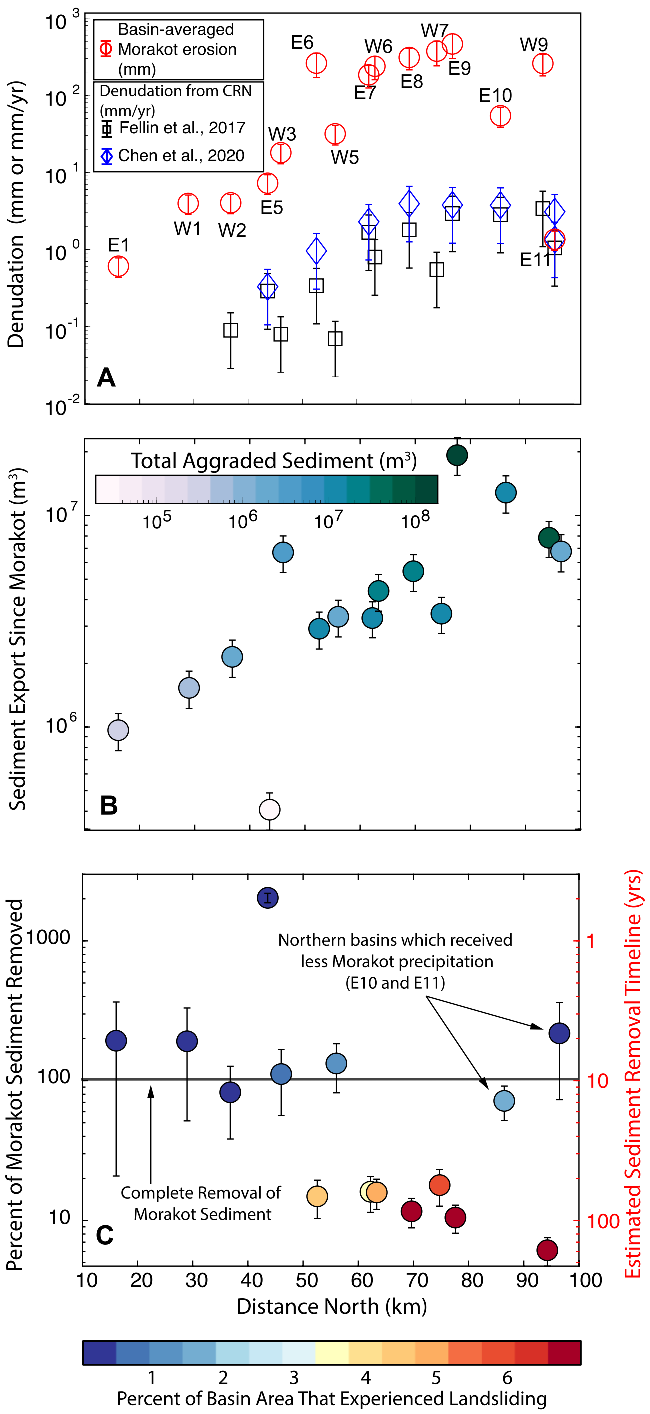

Figure 3. (A) Comparison shows trends in hillslope denudation from Typhoon Morakot in Taiwan (in 2009) with long-term rates of hillslope denudation from cosmogenic radionuclides (CRN) over the same contributing area. CRN data are rates (mm/yr), and data from this study are denudation from a single extreme event (mm), which explains the difference in magnitude between the data sets. (B) Sediment flux from each studied drainage basin calculated from 11 August 2009 to 31 December 2019. Error bars result from using a range of bedload fractions from ⅓ to ½. Points are colored by total aggraded sediment volume in each basin. (C) Percent of typhoon Morakot sediment removed from 11 August 2009 to 31 December 2009 and sediment removal timeline estimated using the fraction of sediment removed in the past decade. Points are colored by percent of basin area that experienced landsliding. Error bars carry from panel B and incorporate uncertainty in channel aggradation.

(Chien and Kuo, 2011), the variation does not detract from the correlation between sediment aggradation and landscape steepness. Our reasoning for this is twofold. First, hillslopes in southern catchments are not steep enough to yield many landslides even if precipitation from typhoon Morakot were greater in the south. Second, while precipitation from typhoon Morakot does increase with distance north in our study area, this increase is at least partially a result of orographic amplification of rainfall.

We find good agreement between measured volumes of aggraded channel sediment and estimates of released landslide sediment, which suggests that most material released by typhoon Morakot was quickly delivered to channels, and that long-term hillslope storage of landslide material is a minor factor. There are two drainage basins where these estimates do not agree: W2 and E11 (Fig. 1C); we attribute this to the tendency to overestimate aggradation in areas with very steep slopes and the possible underprediction of landslide volume when using power-law scaling from a global data set.

The conclusion that river channels in the steepest parts of this study area may be buried by sediment for up to 50% of the time suggests that incision rates during periods of bedrock exposure may be far higher than rates averaged over landscape evolution time scales. Indeed, incision of >10 cm has been observed in a single year in the Central Mountain Range (Hartshorn et al., 2002). This idea is supported by the ubiquity of steep hillslopes throughout this study area and the rest of the island, because without active river incision, these hillslopes would quickly erode.

CONCLUSIONS

Our study found that landscape steepness, landslide initiation resulting from Typhoon Morakot, and aggradation of landslide sediment all correlate with distance from the southern tip of Taiwan. While sediment transport capacity also increases with distance north, the gradient is insufficient to balance the pattern of sediment aggradation, which suggests that erosional buffering is stronger in northern than southern basins. Burial of bedrock rivers buffers river incision for months to perhaps centuries following Typhoon Morakot, decreasing erosional efficiency more in the most tectonically active basins. This suggests that bedrock incision may not increase monotonically with tectonic activity because extreme events leave a legacy on the landscape that lasts longest in areas with the steepest hillslopes. This erosional buffering effect is a factor that is overlooked in most models of landscape evolution, and it may impact our understanding of landscape evolution, climate-tectonic interactions, and natural hazards.

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