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## An unshakable carbon budget for the Himalaya

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51 **An unshakable carbon budget for the Himalaya**

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60

61 **The erosion and weathering of mountain ranges exert a key control on the long-term ( $10^5$ - $10^6$**   
62 **yr) cycling of carbon between the Earth's surface and the crust. The net carbon budget of a**  
63 **mountain range reflects the co-existence of multiple carbon sources and sinks, with**  
64 **corresponding fluxes remaining difficult to quantify. Uncertain responses of these carbon**  
65 **fluxes due to the stochastic nature of erosional processes further complicates the**  
66 **extrapolation of short-term observations to longer, climatically relevant timescales. Here, we**  
67 **quantify the evolution of the organic and inorganic carbon fluxes in response to the 2015**  
68 **Gorkha earthquake (Mw 7.8) in the Central Himalaya. We find that the Himalayan erosion**  
69 **acts as a net carbon sink mainly due to efficient biospheric organic carbon export. Our high-**  
70 **resolution time-series encompassing four monsoon seasons before and after the Gorkha**  
71 **earthquake, reveal that coseismic landslides did not significantly perturb large-scale**  
72 **Himalayan sediment and carbon fluxes. This muted response of the Central Himalaya to a**  
73 **geologically-frequent perturbation such as the Gorkha earthquake further suggests that our**  
74 **estimates are representative of at least interglacial timescales.**

75 Mountain building and associated erosion are key players in the cycling of carbon  
76 between the reservoirs of the Earth's surface and the crust, controlling the long-term evolution  
77 of the global climate. The weathering of silicate minerals coupled to carbonate precipitation in  
78 the oceans, as well as the erosion, riverine transport and burial of biospheric Organic Carbon  
79 (OC) on continental margins represent major carbon sinks with respect to the Earth's surface<sup>1,2</sup>.  
80 While both mechanisms are enhanced in highly erosive environments such as the Himalaya<sup>3-5</sup>,  
81 their relative importance remains unclear. Enhanced silicate weathering rates associated with  
82 the uplift of the Himalaya were initially suggested as the main driver of the global Cenozoic  
83 cooling<sup>6</sup>, but more recent work shows the importance of the organic pathway in the Himalayan  
84 carbon budget<sup>7,8</sup>.

85 Globally, these carbon sinks are counterbalanced by CO<sub>2</sub> emissions from volcanic activity  
86 and metamorphic reactions, the latter constituting an important carbon source in the Central  
87 Himalaya<sup>9</sup>. While these carbon sources are not directly related to erosion, other, yet poorly  
88 constrained, mechanisms of carbon release during erosion have been identified. The oxidation  
89 of rock-derived organic carbon<sup>1,10</sup> and sulfuric acid-mediated weathering of carbonate rocks<sup>11</sup>  
90 have the potential to offset the previously mentioned carbon sinks<sup>5</sup>. Chemical weathering in  
91 the Central Himalaya is dominated by the dissolution of carbonates<sup>12</sup>, and it has been shown  
92 that the sulfide oxidation coupled to carbonate weathering is likely an important carbon source  
93 in this environment<sup>12-14</sup>. Defining the carbon budget of Himalayan erosion, therefore, requires  
94 quantification and comparison of all of the above-mentioned sources and sinks.

95 While the carbon fluxes associated with the erosion of various mountain ranges have  
96 been estimated<sup>5,15</sup>, their integration over longer timescales remains challenging due to the

97 stochastic nature of erosional processes dominating sediment and solute fluxes in most  
98 mountainous landscapes. This is especially important regarding the proposition that extreme  
99 events such as earthquakes or floods could dominate the long-term budget of erosional carbon  
100 fluxes<sup>16,17</sup>. Large earthquakes, coupled with coseismic landsliding, in particular, have been  
101 shown to increase the riverine OC export<sup>18,19</sup>, and fresh landslide scars can serve as loci for  
102 enhanced chemical weathering rates of silicates and sulfide oxidation<sup>20,21</sup>.

103 In the tectonically active Central Himalaya, major earthquakes are geologically-frequent  
104 events with return times of 250-500 years<sup>22</sup>. As these events are still rare on an observational  
105 timescale, their impact on the carbon budget of the Himalaya is unknown. In April 2015, the  
106 Central Nepalese Himalaya was hit by the Mw 7.8 Gorkha earthquake and several strong to  
107 major aftershocks<sup>23</sup>. The fault rupture caused > 25,000 coseismic landslides in the steep valleys  
108 of the Upper Himalaya<sup>24</sup> (Fig. 1).

109 In this study, we assess the net carbon budget (organic and inorganic sources and sinks)  
110 of erosion in the Narayani catchment in the Central Himalaya. Our set of daily suspended  
111 sediment and water samples of the Narayani River during the monsoon seasons of a pre-  
112 earthquake year (2010) and three years following the Gorkha earthquake (2015-2017) provides  
113 a unique opportunity to evaluate the influence of such an extreme event on the carbon budget  
114 of a large portion of the Himalaya. It also allows us to refine the carbon budget of Himalayan  
115 erosion by evaluating the magnitude of the main carbon sinks and sources associated with the  
116 erosion of the Himalaya.

117

## 118 **Organic carbon export and chemical weathering time-series**

119           With a catchment area of 32,000 km<sup>2</sup>, the Narayani river basin covers around a third of  
120 the Nepalese Himalaya (Fig. 1). Our sampling station lies at the Himalayan front, near  
121 Narayanghat, shortly before the Narayani enters the Gangetic floodplain. The Indian Summer  
122 Monsoon (June-September) dominates the precipitation regime in the catchment and is  
123 responsible for around 80% of the annual water discharge<sup>25</sup>. The Narayani River annually  
124 exports around 100 Mt of sediments to the Gangetic floodplain (equivalent to ca. 1.6 mm/yr of  
125 erosion), around 95% of which is transported during the monsoon season<sup>26,27</sup>. The Gorkha  
126 earthquake, whose epicenter was located in the Narayani basin, heavily impacted the eastern  
127 part of the catchment with coseismic landslides, while the western part was mostly spared (Fig.  
128 1). Coseismic landslides mobilized a total of ca. 0.20 ± 0.01 km<sup>3</sup> material in the Narayani  
129 catchment, which is around four times the interseismic annual volume of sediment yield of the  
130 Narayani, and equivalent to an average surface lowering over the entire catchment of ca. 6.3 ±  
131 0.4 mm (Methods). The Narayani provides an ideal catchment area for studying the effect of  
132 such an extreme event at a scale large enough to be of global importance.

133           With our daily suspended sediment and water samples, we calculate the river  
134 suspended sediment yield, and the carbon fluxes linked to erosion of successive monsoon  
135 seasons. Records of total discharge and sediment yield (<sup>27</sup>; Department of Hydrology and  
136 Meteorology of Nepal (DHM); this study) of the Narayani from 8 years before the earthquake,  
137 reveal that the monsoon in 2015, which started shortly after the Gorkha earthquake, was  
138 particularly weak (Fig. 2). Despite the active coseismic landsliding in the catchment<sup>24</sup>, the total  
139 sediment yield of the Narayani does not reveal a detectable earthquake signal and falls within

140 the observed trends before 2015. Sediment fluxes (relative to monsoon discharge), however,  
141 peaked a year later. This peak in sediment yield is likely attributable to a delayed response to  
142 the Gorkha earthquake and the reactivation or mobilization of landslide material that had not  
143 previously connected to the fluvial network<sup>24</sup>. However, this high sediment yield disappears in  
144 2017 despite an equally intense monsoon. As landslide rates have been shown to decay to  
145 background values in 1-4 years after a large earthquake<sup>28</sup>, we interpret that the Gorkha  
146 earthquake signal dissipated by 2017.

147 To constrain the fluxes of biospheric OC ( $OC_{bio}$ , fresh OC derived from soils and plant  
148 debris) export, we measured the total organic carbon (TOC) content and the radiogenic ( $^{14}C$ )  
149 isotopic compositions of OC in riverine suspended sediment samples (Methods). The TOC  
150 content of the suspended sediments from the Narayani varies between 0.04 and 0.99 % and the  
151 fraction modern (Fm) of the OC spans a large range, varying between 0.27 and 0.91 (Extended  
152 Data Fig. 3). Our high-resolution time-series (with measurements up to every second day)  
153 reveal a large variability in TOC concentrations and  $^{14}C$  signatures of suspended sediments. For  
154 disentangling the  $OC_{bio}$  and petrogenic OC ( $OC_{petro}$ , rock-derived OC) inputs, we employ a binary  
155 mixing model using the TOC and the radiocarbon signatures of the bulk samples as well as a  
156 biospheric and a petrogenic end-member (Methods and Extended Data Fig. 3). Soil samples  
157 from the Narayani catchment mostly reflect a recent biospheric endmember (Fm 1.1 – 0.9),  
158 whereas the petrogenic end-member was assigned an Fm value of 0. Hydrodynamic processes  
159 do not significantly affect OC concentrations within the water column in large and turbulent  
160 Himalayan river systems<sup>29</sup>, including the Narayani (Supplementary Information). We can,  
161 therefore, confidently assume that suspended sediment samples collected from surface waters

162 are representative of the  $OC_{\text{bio}}$  content in the whole water column. Using the measured daily  
163 sediment load and discharge data from the DHM, we are able to estimate the total amount of  
164  $OC_{\text{bio}}$  exported by the Narayani River during a monsoon season and upscale it to a year  
165 (Methods).

166 Major ion concentrations measured in filtered river water (every day for the monsoon  
167 2010; every second day for monsoons 2015-2017) provide estimates for silicate and carbonate  
168 weathering rates by carbonic and sulfuric acid, respectively. We calculate the relative amounts  
169 of silicate and carbonate weathering using a forward Monte Carlo approach with known  
170 elemental ratios of the weathering products of the main lithologies of the Central Himalaya<sup>12,13</sup>  
171 (Methods). We consider the  $CO_2$  removal over timescales  $>10^4$  yr for which one mole of carbon  
172 is removed from the Earth's surface through carbonate precipitation per mole of Ca and Mg  
173 derived from silicate weathering by carbonic acid<sup>2</sup> ( $Ca_{\text{sil}}$  and  $Mg_{\text{sil}}$ ). The carbon source through  
174 carbonate weathering by sulfuric acid is calculated using the  $SO_4^{2-}$  concentration and the known  
175 ratio of carbonate to silicate weathering (Methods). In Himalayan rivers, the proportion of  $SO_4^{2-}$   
176 derived from sulfide oxidation has been estimated to 60-100% (<sup>12,14</sup>). Per mole of carbonates  
177 weathered by sulfuric acid, half a mole of carbon is released to the atmosphere on timescales  
178 of  $10^5$ - $10^7$  yr (<sup>11</sup>).

179 To complement our analysis of the carbon budget of Himalayan erosion, we estimate  
180 the  $OC_{\text{petro}}$  oxidation rate in the Narayani basin with Rhenium (Re) data from the literature.  
181 Dissolved Re concentrations serve as a proxy to trace the fluxes of carbon released through  
182 rock-derived carbon oxidation<sup>10,30</sup>. Compiling Re concentrations of Himalayan rivers and  
183 sediments<sup>30-33</sup> allows us to provide a first-order estimate of the carbon flux released through



184  $OC_{\text{petro}}$  oxidation in the Central Himalaya (Methods). It should, however, be noted that these  
185 estimates do not allow us to derive annually resolved  $OC_{\text{petro}}$  oxidation fluxes estimates since Re  
186 was not directly measured in our samples.

187

## 188 **Carbon fluxes over four monsoon seasons**

189 The fraction of  $OC_{\text{bio}}$  in the total sediment load of the Narayani is diluted with increasing  
190 runoff (Fig. 3a), which has been proposed to result from a lower degree of soil erosion relative  
191 to mass wasting during the monsoon<sup>27</sup>. At higher discharge the concentration of  $OC_{\text{bio}}$  remains  
192 constant despite changing runoff, which suggests that the  $OC_{\text{bio}}$  is supply-limited, similar to the  
193 total sediment load in the Narayani<sup>26,27</sup>. The slightly higher concentrations of  $OC_{\text{bio}}$  in the year  
194 2015 could be associated with material evacuated from coseismic landslides or could  
195 alternatively be linked to the lower sediment load during this weak monsoon season. The  
196 unusually large sediment yield observed in 2016 (Fig. 4a) is accompanied by a substantially  
197 higher  $OC_{\text{bio}}$  export compared to the other years on record (Fig. 4b). This ca. 85% increase in  
198  $OC_{\text{bio}}$  export (Source Data Fig. 4) combined with a ca. 130% higher than expected sediment yield  
199 (from the linear relationship between the total discharge and the monsoonal sediment yield,  
200 Fig. 2) is likely a delayed manifestation of the coseismic landslides associated with the Gorkha  
201 earthquake. However, this earthquake signal in the total sediment and the  $OC_{\text{bio}}$  export 2016 of  
202 the Narayani disappears a year later, suggesting that significant portions of the landslide  
203 sediments are either not or only very slowly evacuated.

204 As reported in previous studies, our results show that chemical weathering in the  
205 Central Himalaya is dominated by carbonates, with around 10% of the cations being derived  
206 from silicate weathering<sup>12,34,35</sup>. The calculated  $\text{Ca}_{\text{sil}}$  and  $\text{Mg}_{\text{sil}}$  concentrations do not significantly  
207 vary between the different years (Fig. 3b). The concentration of  $\text{SO}_4^{2-}$  coupled with carbonate  
208 weathering, displays a typical dilution pattern that has been described for anion concentrations  
209 in the Himalaya<sup>12,35</sup> (Fig. 3d). When summing up these carbon fluxes per monsoon season (Fig.  
210 4c and 4d), we observe that the carbon source through sulfuric acid weathering is ~2.5 times  
211 higher than the carbon sink through silicate weathering, which lies in the same order of  
212 magnitude as recently proposed<sup>14</sup>. Both of these carbon fluxes did not significantly increase  
213 after the Gorkha earthquake at the scale of the Narayani basin.

214

### 215 **Minor earthquake impact on the Himalayan carbon budget**

216 Our data suggest that, in contrast to other seismically impacted systems, the Central  
217 Himalaya had a muted response to the Gorkha earthquake. The Mw 7.9 earthquake that struck  
218 Wenchuan in 2008 resulted in widespread coseismic landsliding<sup>36</sup>, increased riverine sediment  
219 fluxes<sup>37</sup> and doubled  $\text{OC}_{\text{bio}}$  export over four years after the earthquake<sup>18</sup>. Similar to the  
220 Narayani, the catchment studied after the Wenchuan earthquake was only partly affected by  
221 coseismic landslides (0.14 and 0.27% (<sup>37</sup>) of the respective catchment areas). Furthermore,  
222 sediment cores from a mountain lake in the Southern Alps of New Zealand revealed that over  
223 the last ~1000 yr large earthquakes were responsible for 27% of the sediment flux<sup>38</sup> and 43% of  
224 the  $\text{OC}_{\text{bio}}$  export<sup>19</sup> in its catchment.

225 Despite similar moment magnitudes, the coseismic landslides after Wenchuan  
226 earthquake mobilized a substantially larger volume of material ( $\sim 2.3 \text{ km}^3$  <sup>(36)</sup>) than the total  
227 landsliding associated with the Gorkha earthquake ( $\sim 0.8 \text{ km}^3$  <sup>(24)</sup>). In addition, the landslide  
228 density in the Central Himalaya during the year 2015 was only 4-6 times higher relative to that  
229 during interseismic periods<sup>39</sup>. This increase in landslide density following the Gorkha  
230 earthquake was significantly lower than the 22 times higher landslide density in the year after  
231 an earthquake of similar strength in 1999 in Taiwan<sup>28</sup>. While the relatively weak earthquake  
232 impact on landsliding rates in the Central Himalaya can partly be linked to the seismic rupture  
233 characteristics<sup>40</sup>, the short major earthquake recurrence<sup>22</sup> and high density of interseismic  
234 landsliding<sup>39</sup> result in a landscape that is in quasi-equilibrium with frequent mass wasting. The  
235 addition of coseismic landslide material equivalent to around four years of interseismic erosion  
236 in the Narayani catchment was therefore likely not sufficient to significantly perturb the  
237 geochemical fluxes in this highly erosive system. The magnitude of a perturbation relative to  
238 background conditions exerts thus an important influence on the system's response.

239 Earthquakes with a larger moment magnitude than the Mw 7.8 Gorkha earthquake  
240 trigger more landslides<sup>36</sup> but the long recurrence-time of great (Mw >9) earthquakes in the  
241 Himalaya, which is on the order millennia<sup>41</sup>, means that they do not dominate the long-term  
242 erosion budget<sup>39</sup>. We similarly assume that long-term carbon fluxes associated with erosion  
243 processes in the Central Himalaya would not be significantly impacted by larger and less  
244 frequent earthquakes compared to Gorkha.

245

## 246 **The net carbon budget of the Central Himalayan erosion**

247 Integrating the mean carbon fluxes at the Himalayan outlet constrained for four years  
248 reveals that the Central Himalayan erosion acts as a net carbon sink with respect to the Earth's  
249 surface (Fig. 4e). Due to relatively low interannual variability and stability with respect to  
250 seismic perturbations, we propose that these Himalayan carbon fluxes are representative for  
251 long-term periods with relatively stable climatic conditions, such as interglacials. The magnitude  
252 of carbon removal through  $OC_{bio}$  export (and subsequent burial) is around ten times larger than  
253 the sink resulting from silicate weathering (and subsequent carbonate precipitation). This  
254 finding further underlines the predominant role of the organic carbon cycle in the Himalaya<sup>7,8</sup>.  
255 Moreover, our results demonstrate that the relative contribution of  $OC_{bio}$  export versus silicate  
256 weathering to the carbon sink at the outlet of the Himalaya is higher than previously found in  
257 Neogene sediments of the Bay of Bengal<sup>7,42</sup>. As highlighted for other mountain ranges<sup>5</sup>, the  
258 oxidative weathering of  $OC_{petro}$  and sulfuric acid weathering of carbonates are important carbon  
259 sources that must be included in the net carbon budget of the Himalayan erosion. The  
260 comparison of the  $OC_{petro}$  oxidation flux with the calculated riverine export of  $OC_{petro}$  suggests  
261 that ca. 36% of the total OC in the bedrock is lost to oxidation within the catchment  
262 (Supplementary Information). This oxidation rate remains lower than that previously calculated  
263 for Taiwan<sup>43</sup>.

264 Overall, these results provide additional insights into the erosional carbon budget of a  
265 tectonically active and highly erosive mountain range. We emphasize that carbon fluxes were  
266 calculated for the outlet of the Himalayan front, from where the solutes and sediments transit  
267 through the Gangetic floodplain before being discharged in the Bay of Bengal. It has been

268 shown that Himalayan  $OC_{bio}$  is oxidized and replaced during floodplain transit<sup>8</sup>. Nevertheless,  
269 the constant OC concentration of sediments during transport and the high OC burial efficiency  
270 in the Bay of Bengal<sup>42</sup> imply that the OC burial flux is unaffected by floodplain transfer. In  
271 contrast, chemical weathering rates have been shown to double from the Himalayan front to  
272 the Indian Ocean<sup>13,44</sup>. Further weathering of carbonates by sulfuric acid during floodplain  
273 transfer is probably small given that sulfides oxidize readily upon exposure at the surface in the  
274 upland areas<sup>14,45</sup> and are not detected in the sediment load downstream in the Gangetic  
275 floodplain<sup>46</sup>. At the same time, oxidation rates of rock-derived OC are likely to increase in the  
276 Ganges by 50-70% (<sup>47</sup>). Hence, while some of the carbon fluxes likely increase during the  
277 transport through the Gangetic floodplain, the overall carbon budget from the Central Himalaya  
278 is unlikely to be significantly shifted in one direction.

279

280 This unique time-series dataset from before and after the 2015 Gorkha earthquake  
281 allows us to evaluate the impact of an extreme event on the carbon fluxes of the Central  
282 Himalayan erosion. Unlike previously studied systems<sup>18,19</sup>, Himalayan carbon fluxes were not  
283 significantly perturbed by a major earthquake. This budget reveals that the erosion of a large  
284 Himalayan catchment acts as a net carbon sink, although this sink is smaller than previously  
285 thought<sup>6-8</sup> and reflects the complex interplay of processes that must be considered in  
286 developing net erosional carbon budgets. Due to relatively low interannual variability,  
287 Himalayan carbon fluxes can be integrated on timescales of at least interglacials. While the  
288 export and burial rates of  $OC_{bio}$ , as well as chemical weathering rates in the Ganges-  
289 Brahmaputra basin, both fluctuate on glacial-interglacial timescales<sup>48,49</sup>, it has recently been

290 shown that erosion rates in this basin remained relatively stable during the late Cenozoic<sup>50</sup>. As  
291 erosion exerts a primary control on carbon fluxes<sup>5</sup>, we speculate that our carbon budget for the  
292 Central Himalaya may be relevant on late Cenozoic timescales representing a long-term net  
293 carbon sink.

294

#### 295 **Data availability**

296 All data analyzed in this study are available in the Research Collection of ETH Zurich at  
297 <http://hdl.handle.net/20.500.11850/487683>.

298

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425

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432

#### 433 **Author contributions**

434 L.M. and M.L. designed the study. M.L., C. F.-L., J.L., A.G. and S.G. organized and maintained  
435 daily sampling in Narayanghat. J.L. provided the depth profile samples and L.M., M.L., C.F-L., J.L.  
436 and S.G. conducted the soil sampling. L.M., N.H. and F.W.-L. prepared the samples and  
437 performed the measurements. S.G. conducted the landslide volume calculation. L.M., M.L. and  
438 T.E. made the carbon flux calculations. All authors contributed to the interpretation of the data  
439 and the redaction of the manuscript.

440

#### 441 **Competing interests**

442 The authors declare no competing interests.

443

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446 (lena.maerki@alumni.ethz.ch).

447

#### 448 **Figure captions**

449 **Fig. 1: Map of the Central Himalaya and location of the studied drainage basin.** The Narayani  
450 catchment (dashed outline) and the sampling station in Narayanghat are displayed. The  
451 epicenter of the 2015 Gorkha earthquake is shown by the star, and red dots illustrate the  
452 mapped coseismic landslides<sup>24</sup>. The topographic map is from Hydrosheds  
453 (<http://hydrosheds.cr.usgs.gov>).

454

455 **Fig. 2: Total water discharge and sediment yield of the Narayani River during different**  
456 **monsoon seasons.** River during different monsoon seasons. Total discharge as a function of the  
457 sediment yield of the monsoon months June-July-August-September (JJAS) of the Narayani in  
458 Narayanghat (discharge data and sediment loads from 2001-2012 from the Department of  
459 Hydrology and Meteorology of Nepal and ref.<sup>27</sup>). Uncertainty on the sediment export is reported  
460 as 10% of the estimated value to account for the depth correction of the surface sediment load<sup>27</sup>  
461 and uncertainties on water discharge reported by the Department of Hydrology and  
462 Meteorology of Nepal are unknown but likely smaller than the symbol. Dashed lines illustrate  
463 the 0.997 confidence interval of the linear regression between discharge and sediment yield.  
464 Grey points show records after the April 2015 Gorkha earthquake.

465

466 **Fig. 3:  $OC_{bio}$ ,  $Ca_{sil}+Mg_{sil}$  and  $SO_4^{2-}$  carb as a function of the discharge of the Narayani River. a.**  
467 Biospheric organic carbon ( $OC_{bio}$ ) as weight percent of the total suspended sediment. Literature  
468 data are from ref.<sup>8</sup> (pre-earthquake). The typical error bar includes the 10% uncertainty in the  
469 total sediment yield<sup>27</sup> and the standard deviation of the

470  $OC_{bio}$  apportionment calculation. **b.** Concentrations of Ca and Mg derived from silicate  
471 weathering through carbonic acid ( $Ca_{sil}+Mg_{sil}$ ). Literature data are from refs.<sup>12,34,35</sup> (pre-  
472 earthquake) and ref.<sup>13</sup> (post-earthquake). The reported typical error is associated to  
473 the systematic uncertainty (standard deviation) in the silicate apportionment of Ca and Mg  
474 fluxes and the end-member  $Ca_{sil}$  and  $Mg_{sil}$  elemental ratios. **c.** Concentration of the fraction of  
475  $SO_4^{2-}$  associated with carbonate weathering ( $SO_4^{2-}_{carb}$ ). Literature data are from refs.<sup>12,34,35</sup> (pre-  
476 earthquake) and ref.<sup>13</sup> (post-earthquake). The typical error bar illustrates the 30% uncertainty  
477 due to the proportion of  $SO_4^{2-}$  which is derived from sulfide oxidation<sup>12,14</sup>. Panels a, b and c are  
478 plotted against the daily water discharge of the Narayani River in Narayanghat provided by the  
479 Department of Hydrology and Meteorology of Nepal.

480

481 **Fig. 4: Total carbon fluxes and mean net erosional carbon budget for the Narayani basin**  
482 **through four monsoon seasons.** Total export during four monsoon seasons of **a.** suspended  
483 sediments (error bars indicate 10% error due to the depth correction of the surface sediment  
484 load<sup>27</sup>); **b.**  $OC_{bio}$  (error bars include uncertainty in the total sediment yield and the standard  
485 deviation of the  $OC_{bio}$  calculation from total OC); **c.**  $Ca_{sil} + Mg_{sil}$  (for the errors the standard  
486 deviation of the elemental ratios defining  $Ca_{sil}$  and  $Mg_{sil}$  are propagated); and **d.**  $SO_4^{2-}_{carb}$  (error  
487 bars indicate the range of 100-70% of  $SO_4^{2-}$  which is derived from sulfide oxidation<sup>12,14</sup>). Round  
488 symbols illustrate the Gorkha earthquake that happened shortly before the monsoon 2015. **e.**  
489 Mean carbon fluxes from the four studied years of erosion in the Narayani basin in t of  
490 C/(km<sup>2</sup>yr) and in moles of C/(km<sup>2</sup>yr). Total fluxes in tC/(km<sup>2</sup>yr) and in tC/yr are indicated in  
491 square brackets. Error bars are calculated by the mean of the above-described errors, and for

492 *the  $OC_{petro}$  oxidation, the error of the oxidation rate calculation is propagated (see also*  
493 *Methods). Red bar illustrates the sum of the carbon fluxes, and its error bar is propagated with*  
494 *a Monte Carlo simulation.*

495

## 496 **Methods**

### 497 **Calculation of coseismic landslide volume and lowering rates**

498 The total volume of coseismic landslide material in the Narayani catchment was  
499 calculated using the earthquake-triggered landslide inventory from ref.<sup>24</sup> and the area-volume  
500 scaling parameters from ref.<sup>51</sup> (Extended Data Table 1). We here used the global parameters  
501 from ref.<sup>51</sup>. The uncertainties were propagated with a Monte Carlo approach ( $n = 10^4$ ). The  
502 mean landscape surface lowering rate was obtained by dividing the landslide volume within the  
503 catchment by the Narayani catchment surface area (32,000 km<sup>2</sup>).

504

### 505 **Sampling**

506 Surface suspended sediments were taken in the middle of the Narayani river during the  
507 monsoon seasons (June-September) 2010 and 2015-2017 (Source Data Fig. 3). The sampling in  
508 2010 is described in more detail in ref.<sup>27</sup> and is similar to the sampling during the other years.  
509 For samples in 2015-2017, 3L of surface water was taken at the sampling station in  
510 Narayanghat (27.73° N; 84.43° E). The water was immediately filtered with a pressure filtration  
511 unit through 0.2 µm polyethersulfone (PES) membranes, and the sediment sample was stored



512 in a dark and cool place until return to the laboratory. 250 ml of the filtered river water was  
513 collected for measurements of major ions.

514 Sediment sampling of four depth profiles (Source Data Extended Data Fig. 4) within the  
515 water column was performed in 2011 in Narayanghat and is further described in ref.<sup>27</sup>. At the  
516 sampling location, the Narayani channel is around 15-20 m deep. Samples of both tributaries  
517 shortly before the confluence, which is situated around 2 km upstream of the sampling station  
518 and samples from both sides of the Narayani river, were taken during different field campaigns  
519 between 2015 and 2017 (Source Data Extended Data Fig. 5). For the samples NEQ-17204 - NEQ-  
520 172-39, 10-20L of surface water was filtered as described above and stored in a cool place.  
521 Samples NEP-15-02 – NEP-17-43 were taken with a bucket or a sediment sampler from the  
522 surface water and filtered through a pressure filtration unit similar as described above.

523 Soil samples (Extended Data Table 2) cover a variety of conditions such as elevation and  
524 annual precipitation within the Narayani catchment and were collected between 2009 and  
525 2017. The samples are further described in ref.<sup>52</sup>. The samples integrate the surface soil layer of  
526 a depth of up to 15 cm. The uppermost few cm of the soils were removed for not including  
527 vegetation and litter in the surface soil samples.

528

### 529 **Determination of the total sediment yield of a monsoon season**

530 Out of the 488 studied days, for 28 days the sediment load was not measured and was  
531 therefore estimated based on water discharge. For estimating the missing sediment load data,  
532 we applied the method described in ref.<sup>27</sup>. Briefly, a digital filter<sup>53</sup> was used to separate the

533 total discharge of the Narayani in the baseflow and the direct discharge<sup>26</sup> with the parameters  
534 used in ref.<sup>27</sup> (Extended Data Fig. 1). The missing sediment load was subsequently calculated  
535 with the linear regression between the direct discharge and the sediment load data (Extended  
536 Data Fig. 2).

### 537 **TOC, $\delta^{13}\text{C}$ and radiocarbon measurement of suspended sediments**

538 Sediment and soil samples were frozen upon arrival at ETH Zürich and subsequently  
539 freeze-dried. Sediments were weighed for calculating the surface sediment load and carefully  
540 removed from the filters. Soil samples were sieved at < 2 mm. An aliquot of the sediments and  
541 soils was milled in a Retsch zirconium ball mill. ~50 mg of the milled samples were weighed into  
542 combusted silver capsules. Samples were fumigated in HCl vapor for removal of inorganic  
543 carbon (3 days at 60 °C), and neutralized with NaOH (4 days at 60 °C). The capsules were  
544 subsequently wrapped in tin boats, and TOC and its isotopic compositions were measured on a  
545 coupled online elemental analyzer-isotope ratio mass spectrometer-accelerator mass  
546 spectrometer (EA-IRMS-AMS) system<sup>54</sup> at the Ion Beam Physics Institute of the ETH Zürich.  
547  $^{13}\text{C}/^{12}\text{C}$  ratios are reported in  $\delta^{13}\text{C}$  notation relative to the Vienna Pee Dee Belemnite (VPDB)  
548 standard and the  $^{14}\text{C}$  content is reported as fraction modern (Fm).

549 In addition to routine standard measurements by AMS<sup>54</sup>, an internal standard consisting  
550 of a suspended sediment sample was measured eight times in different batches (including  
551 different fumigation batches). The standard deviation of the results is used as typical  
552 uncertainty on the measurements (TOC: mean  $0.24\% \pm 0.01$ ; Fm: mean  $0.51 \pm 0.03$ ;  $\delta^{13}\text{C}$ : mean  
553  $-24.02 \text{ ‰} \pm 0.17$ ).

554

### 555 **Determination of OC<sub>bio</sub> yield**

556 A binary mixing model was applied to disentangle the concentrations of OC<sub>bio</sub> and OC<sub>petro</sub>  
557 ([OC<sub>bio</sub>] and [OC<sub>petro</sub>]) in the total OC of the suspended sediment (Extended Data Fig. 3). With  
558 the following assumptions similar to the method applied in ref.<sup>43</sup> we are able calculate the  
559 concentrations (%) of OC<sub>bio</sub> and OC<sub>petro</sub> in the total sediment:

$$560 \quad [OC_{tot}] = [OC_{bio}] + [OC_{petro}] \quad (1)$$

$$561 \quad Fm_{tot} * [OC_{tot}] = Fm_{bio} * [OC_{bio}] + Fm_{petro} * [OC_{petro}] \quad (2)$$

562 The rock-derived OC<sub>petro</sub> is characterized by Fm<sub>petro</sub> = 0 because its age exceeds the <sup>14</sup>C half-life  
563 by more than an order of magnitude. We can therefore rewrite equations 1 and 2:

$$564 \quad Fm_{tot} * [OC_{tot}] = Fm_{bio} * [OC_{bio}] \quad (3)$$

$$565 \quad [OC_{bio}] = [OC_{tot}] - [OC_{petro}] \quad (4)$$

566 If we combine the equations we obtain:

$$567 \quad Fm_{tot} * [OC_{tot}] = Fm_{bio} * ([OC_{tot}] - [OC_{petro}]) \quad (5)$$

568 From where we can calculate [OC<sub>petro</sub>]

$$569 \quad [OC_{petro}] = [OC_{tot}] - (Fm_{tot} * [OC_{tot}]) / Fm_{bio} \quad (6)$$

570 And [OC<sub>bio</sub>]

$$571 \quad [OC_{bio}] = [OC_{tot}] - [OC_{petro}] \quad (7)$$

572 The radiocarbon signature of 17 surface soils from the Narayani basin (Extended Data  
573 Table 2) was used to define the Fm of the  $OC_{bio}$  endmember ( $Fm_{bio} = 1.1 - 0.9$ ).  $OC_{tot}$  and  $Fm_{tot}$   
574 are the measured values, and standard deviations are derived from the internal standard as  
575 described above. A Monte Carlo simulation ( $n=10^5$ ) was used to randomly sample within the  
576  $Fm_{bio}$  endmember and the standard deviation of  $OC_{tot}$  and  $Fm_{tot}$ . Errors of the model were  
577 defined by the standard deviation of the model results. This approach for determining  $OC_{bio}$  is  
578 not as sensitive to possible autocorrelation biases as previous studies<sup>47</sup>. In the latter study, the  
579  $OC_{petro}$ , was determined by the intersection of the linear correlation between the TOC and the  
580 value of  $TOC * Fm$ . This method and the calculations done in our study, however, give broadly  
581 similar results.

582 In order to calculate the total sediment yield, the surface sediment load was corrected  
583 for increasing concentrations with the depth of the water column. For this purpose, we use the  
584 method proposed by ref.<sup>27</sup> (equation 3.2), which integrates the surface sediment concentration  
585 for depth and water velocity in the Narayani river. The daily discharge data of the Narayani river  
586 was provided by the Department of Hydrology and Meteorology of Nepal (DHM), enabling  
587 calculation of daily sediment yield of the Narayani during the four studied monsoon seasons.  
588 With these data we were able to calculate the total amount of  $OC_{bio}$  exported by the Narayani  
589 in a given day for which TOC and Fm measurements are available. We observe a high daily  
590 variability in our TOC and Fm data without any significant correlation to the runoff, the  
591 sediment load or the season at the time of sampling. We upscale the estimate to the entire  
592 monsoon and hence interpolate across days without TOC and Fm measurements as follows:

593  $\Sigma[\text{OC}_{\text{bio}}(\text{measured})] * \Sigma \text{daily sediment yield (all)} / \Sigma \text{daily sediment yield (with Fm and TOC}$   
594  $\text{measurement})$

595 The concentration of TOC and its radiocarbon signature of surface sediments is taken to  
596 be representative of the whole water column (Supplementary Information and Extended Data  
597 Fig. 4). Suspended sediment samples from upstream the major confluence close to the  
598 sampling station confirm that incomplete mixing of the sediments from this confluence does  
599 not have a major influence on the TOC and radiocarbon concentration in Narayanghat  
600 (Supplementary Information and Extended Data Fig. 5).

601

#### 602 **Chemical weathering rates calculated by major ion chemistry**

603 The concentrations of major cations in water samples from 2010 were determined with  
604 an Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) at the CRPG Nancy.  
605 Major cations and anions of samples from 2015-2017 were measured by Ion Chromatography  
606 (IC) at ETH Zürich. All results are reported in the Source Data Fig. 3. Ion concentrations were  
607 corrected for atmospheric input, as suggested by ref.<sup>12</sup> and using ion concentrations of  
608 rainwater from ref.<sup>55</sup>. Concentrations of Cl and SO<sub>4</sub> for the year 2010 were estimated by  
609 correlating the concentrations of the measured years to river discharge (Supplementary  
610 Information and Extended Data Fig. 6 and 7).

611 Concentrations of Ca and Mg derived from silicate weathering through carbonic acid  
612 (Ca<sub>sil</sub> and Mg<sub>sil</sub>) were calculated using elemental ratios of silicates and carbonates in the Central

613 Himalaya from refs.<sup>12,13</sup>. A Monte Carlo simulation (n=10<sup>5</sup>) sampled randomly within a normal  
614 distribution with the following standard deviation.

$$615 \text{Mg}_{\text{sil}} = K * x ; x=0.5 \text{ with standard deviation of } 0.25 \text{ (ref.}^{12}) \quad (8)$$

$$616 \text{Ca}_{\text{sil}} = (\text{Na-Cl}) * y ; y=0.4 \text{ with standard deviation of } 0.15 \text{ (ref.}^{13}) \quad (9)$$

617 The proportion of silicate weathering relative to carbonate weathering ( $x_{\text{sil}}$ ) was calculated:

$$618 X_{\text{sil}} = (1.8 * (\text{Na} - \text{Cl}) + 2 * \text{K}) / (\text{Na} + \text{K} + 2 * \text{Mg} + 2 * \text{Ca}) \text{ (modified from ref.}^{12}) \quad (10)$$

619 All the concentrations in equations 8-12 have been corrected for atmospheric input.

620         Secondary calcite precipitation along the Narayani and its tributary might slightly bias  $x_{\text{sil}}$   
621 (<sup>13,56</sup>), but at the scale of the whole catchment, we assume that its effect is minor. For the years  
622 2015-2017, where every second day was measured, the days without measurement had to be  
623 interpolated for the calculation of total fluxes per monsoon. Interpolation was done by taking  
624 the average of the measurements from the day before and after. This method takes into  
625 account previously reported seasonal changes of weathering rates and dilution effects in the  
626 beginning of the monsoon season<sup>12,56</sup>. Using the daily discharge data from the DHM we are able  
627 to calculate the total flux of  $\text{Ca}_{\text{sil}}$  and  $\text{Mg}_{\text{sil}}$  per monsoon.

628         For calculating the long-term carbon sink through silicate weathering, we subtract the  
629 amount of  $\text{Ca}_{\text{sil}}$  and  $\text{Mg}_{\text{sil}}$  derived from sulfuric acid weathering as the latter does not involve  
630 any carbon uptake. We here assume that sulfuric acid reacts with carbonates and silicates in  
631 the same relative proportions as carbonic acid<sup>57</sup>. As the chemical weathering regime of the  
632 Himalaya is dominated by carbonates<sup>12</sup>, we notice that the hypothesis that sulfuric acid only

633 weathers carbonate minerals would not have a significant effect on our total carbon flux  
634 calculations.

635 We can use  $x_{\text{sil}}$ :

$$636 \quad \text{SO}_{4,\text{sil}} = \text{SO}_{4,\text{tot}} * x_{\text{sil}} \quad (11)$$

637 We define the proportion of Mg and Ca in the total ions derived from silicate weathering:

$$638 \quad (\text{Mg}_{\text{sil}} + \text{Ca}_{\text{sil}})_{\text{SO}_4} = \text{SO}_{4,\text{sil}} * ((\text{Ca}_{\text{sil}} + \text{Mg}_{\text{sil}}) / (\text{Ca}_{\text{sil}} + \text{Mg}_{\text{sil}} + \text{K}/2 + (\text{Na-Cl}) / 2)) \quad (12)$$

639 where Na-Cl is the total Na derived from silicate weathering<sup>12</sup>. We then calculate the  $\text{Mg}_{\text{sil}}$  and  
640  $\text{Ca}_{\text{sil}}$  that has been weathered through carbonic acid.

$$641 \quad (\text{Mg}_{\text{sil}} + \text{Ca}_{\text{sil}})_{\text{HCO}_3} = (\text{Mg}_{\text{sil}} + \text{Ca}_{\text{sil}})_{\text{tot}} - (\text{Mg}_{\text{sil}} + \text{Ca}_{\text{sil}})_{\text{SO}_4} \quad (13)$$

642 Finally, one mole of carbon per mole of  $\text{Ca}_{\text{sil,HCO}_3}$  or  $\text{Mg}_{\text{sil,HCO}_3}$  can be removed from the  
643 Earth's surface through carbonate precipitation and is thus considered as a long-term ( $>10^5$  yr)  
644 carbon sink. As cation exchange between sediments and seawater is negligible<sup>58</sup> we do not take  
645 into account K and Na for the long-term carbon removal through silicate weathering.

646 For determining the proportion of carbonates weathered by sulfuric acid we can modify  
647 equation 11:

$$648 \quad \text{SO}_{4,\text{carb}} = \text{SO}_{4,\text{tot}} * (1 - x_{\text{sil}}) \quad (14)$$

649 The main uncertainty of the sulfuric acid weathering rate calculation derives from the  
650 unknown proportion of  $\text{SO}_4^-$  derived from evaporites. The latter produces  $\text{SO}_4^-$  during  
651 weathering but does not produce sulfuric acid which could act as a weathering agent. Previous

652 studies estimate the evaporitic input in the Narayani basin as negligible to up to 40% of the  
653 total  $\text{SO}_4^-$  (<sup>12,14</sup>). We, therefore, use error bars between 100 – 70% for the calculated values. For  
654 calculating total fluxes per monsoon, we use the same interpolation as described above for  
655 silicate weathering.

656

### 657 **OC<sub>petro</sub> oxidation calculation with dissolved Re**

658 The release of carbon through OC<sub>petro</sub> oxidation in the Narayani catchment was  
659 estimated using Re as a tracer for the weathering of OC<sub>petro</sub> <sup>10,30,59</sup>. This gives us a first-order  
660 estimation of the magnitude of the carbon flux linked to OC<sub>petro</sub> oxidation but does not allow us  
661 to account for annual differences of this carbon flux. We compiled dissolved Re and major  
662 cations concentration data from global rivers <sup>10,15,30,31,59,60</sup>. While the total dataset displays a  
663 relatively weak linear correlation between the sum of cations and the Re concentration ( $r^2 =$   
664 0.41), Himalayan rivers show a strong linear relationship as suggested earlier<sup>31</sup> ( $r^2 = 0.83$ )  
665 (Extended Data Fig. 8). We calculate the mean flux of dissolved Re ( $\text{Re}_{\text{flux}}$ , 40.7 kg/monsoon)  
666 over the four studied monsoon seasons based on the regression between Re and total cation  
667 concentrations obtained from all Himalayan rivers. A Monte Carlo simulation ( $n=10^5$ ) sampled  
668 randomly within a normal distribution in the one-sigma confidence interval of the regression  
669 for estimating a mean Re concentration for each studied monsoon season based on the mean  
670 annual sum of cations. Data of Re concentrations in bulk suspended sediments from the  
671 Narayani from refs. <sup>32,33</sup> ( $\text{Re}_{\text{sd}}$ ;  $2.7\text{-}4.8 * 10^{-10}$  pg/g) are used together with the mean OC<sub>petro</sub>



672 concentration of samples from this study ( $OC_{sd}$ ). The  $OC_{petro}$  oxidation rate is finally calculated  
673 as described in ref.<sup>59</sup> with a Monte Carlo simulation ( $n=10^5$ ):

$$674 \quad C_{released} = Re_{flux} * (OC_{sd}/Re_{sd}) * f_c - f_{graphite} \quad (15)$$

675 Where  $f_c$  is the factor correcting for Re from inorganic phases and for the ratio of Re dissolved  
676 during  $OC_{petro}$  oxidation in soils ( $0.5 < f_c < 1$ ; <sup>10,59,61</sup> and  $f_{graphite}$  corrects for the fraction of  
677 crystalline graphite that is less prone to oxidation ( $0.3 < f_{graphite} < 0.5$ ; estimated from data from  
678 ref.<sup>47</sup>).

679

#### 680 **Upscaling from a monsoonal to an annual carbon budget**

681 The erosion as well as the carbon fluxes in the Central Himalaya, are mostly driven by the  
682 monsoonal precipitation. In order to render our carbon flux calculations comparable to other  
683 studies, we up-scale the monsoonal carbon budget to annual values based on the following  
684 assumptions. For the total  $OC_{bio}$  export we considered that ~95% of the annually suspended  
685 sediments of the Narayani are discharged during the monsoon<sup>26</sup> and that the relative  
686 importance of soil erosion increases during the dry season<sup>27</sup>. We, therefore, assume that the  
687  $OC_{bio}$  discharged during the monsoon represents 90% of the annual  $OC_{bio}$  export. The  
688 monsoonal total OC and  $OC_{petro}$  export is assumed to follow the total sediment flux constituting  
689 95% of the annual flux. For the silicate weathering budget, we follow ref.<sup>56</sup> who showed that in  
690 the Central Himalaya, ~60% of the annual silicate weathering flux is occurring during the  
691 monsoon. As the monsoon accounts for ~80% of the total water discharge of the Narayani  
692 River<sup>26</sup>, we assume this same proportion for carbonate weathering by sulfuric acid and  $OC_{petro}$

693 oxidation. This calculation is conservative, as the fraction of sulfuric acid relative to carbonic  
694 acid is likely decreasing during the monsoon in the headwaters of the Narayani<sup>56</sup>.

695 **References Methods**

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