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The relative efficacy of fluvial and glacial erosion over modern to orogenic timescales

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Since the late nineteenth century, it has been debated whether rivers or glaciers are more effective agents of erosion[1]. The dramatic landscapes associated with glaciated terrain have often led to the argument that glaciers are more erosive than rivers, and recent studies have documented the topographic signature of an ice-controlled limit of mountain height known as the 'glacial buzz-saw'[2,3]. Here we present a new global compilation of erosion rates, which questions the conventional view of glaciers and erosion. In regions of rapid tectonic uplift, erosion rates from rivers and glaciers both range from 1 to over 10 mm yr^{-1}, indicating that both are capable of generating erosion rates matching or exceeding the highest rates of rock uplift. Moreover, a comparison of erosion rates over timescales ranging from 10^1 to 10^7 years indicates that glacial erosion tends to decrease by one to two orders of magnitude over glacial cycles, whereas fluvial erosion rates show no apparent dependence on time. We conclude that tectonics controls rates of both fluvial and glacial erosion over millennial and longer timescales and that the highest rates of erosion (>10 mm yr^{-1}) generally result from a transient response to disturbance by volcanic eruptions, climate change and modern agriculture.

Quantitative support for the perception that glaciers are more effective erosional agents than rivers is primarily based on topographic analyses, numerical modelling, and two key studies[4,5] that compiled sediment yields measured from glaciated and non-glaciated basins. Both studies reported that, for basins of similar size, glaciers can erode at 1–10 times the rate of rivers. Moreover, modern basin-wide glacial erosion rates of over 10 mm yr^{-1} have been measured from orogens, such as the coastal ranges of Alaska, where maximum tectonic uplift rates rarely exceed 1–4 mm yr^{-1} (ref. 6, 7), reinforcing the idea that glacier erosion inhibits crustal material from rising above the elevation of the snowline, effectively providing an ice-controlled limit to mountain building.

In the decade since the last comprehensive reviews were published[4,5], advances in both geochronology and numerical modelling, driven by a renewed interest in landform development and the relationship between climate and tectonics, have led to new studies documenting both fluvial and glacial erosion rates in a variety of tectonic settings and over several timescales. A few of these studies suggest that in regions of rapid tectonic uplift, such as in the Nepalese Himalaya[8,9] and Taiwan thrust belt[10], river incision rates of over 10 mm yr^{-1} have been measured, comparable to the highest erosion rates in glaciated regions and two orders of magnitude more rapid than in less tectonically active orogens, such as southeastern Australia[11,12] or the Oregon Coast Range[13,14]. From these new data, we have compiled an expanded global dataset of sediment yield and denudation rates from glaciated and non-glaciated catchments. By taking advantage of the wide array of geochronometric tools now in use to examine variability in glacial and fluvial erosion over a range of timescales, we further address variability in the timing of the erosional signal from each type of catchment over timescales ranging from 1 to $>10^7$ yr. We also compare these rates with those from landscapes recently forced out of equilibrium by volcanic activity, climate-driven glacial surging and industrial agriculture.

Figure 1 shows the most recent compilation of published data on contemporary (1–20 yr) sediment yields from fluvial and glaciated catchments, plotted by catchment area. Sediment yields have been converted to basin-averaged erosion rates for all published studies by dividing annual to decadal sediment discharge volumes by contributing basin area. By measuring total mass transfer out of these basins, these erosion rates do not differentiate between glacial and paraglacial processes, or between fluvial incision and hillslope mass wasting. Building on the sediment yields previously reported[4], our compilation includes revised measurements of fluvial denudation[15], from rivers that drain the Greater Himalaya[16] and the Taiwan orogen[10], from rivers draining volcanoes following major eruptions[17] and more recent measurements from temperate tidewater glaciers in Alaska and Patagonia[6,18]. The data indicate that the ranges of erosion rates for both fluvial and glacial basins at catchment scales of 1–10^4 km^2 span to 0.1 to >10 mm yr^{-1} and seem to increase with basin size, although this may reflect the paucity of data for basins between 10 and 100 km^2. The highest erosion rates, far exceeding 10 mm yr^{-1}, have been measured from rapidly retreating tidewater glaciers and volcanically disturbed rivers.

Denudation rates from rivers in tectonically active regions, such as the Greater Himalaya or the active thrust belt of Taiwan, are on a par with erosion rates from tidewater glaciers in similar tectonic settings, such as Patagonia and Alaska (Fig. 1). Maximum tectonic uplift rates in these regions range from 1 to 7 mm yr^{-1}. The similar ranges of erosion rates from glacial and fluvial processes indicate that both suites of processes can accommodate the full range of tectonic uplift rates over millennial to orogenic timescales and thus that the specific geomorphic agent of erosion is of secondary importance to rates of tectonic forcing in setting the pace of orogen-scale denudation. That some of these modern erosion rates exceed tectonic uplift rates suggests a transient response in which contemporary erosion exceeds tectonic forcing.

We also find that the timescale over which erosion rates are measured may significantly influence the apparent rate of erosion[19]. Figure 2 shows a compilation of regions, glaciated and unglaciated, where basin-wide erosion rates have been measured from the same or adjacent basins over timescales ranging from 10^1 to 10^7 yrs. Glacial erosion rates measured in the period since the end of the Little Ice Age (1–100 yr) have been particularly rapid, greatly exceeding regional tectonic uplift rates in active regions such as Alaska[4,6], in part owing to the acceleration of ice flow during glacial retreat (discussed below). However, such denudation rates

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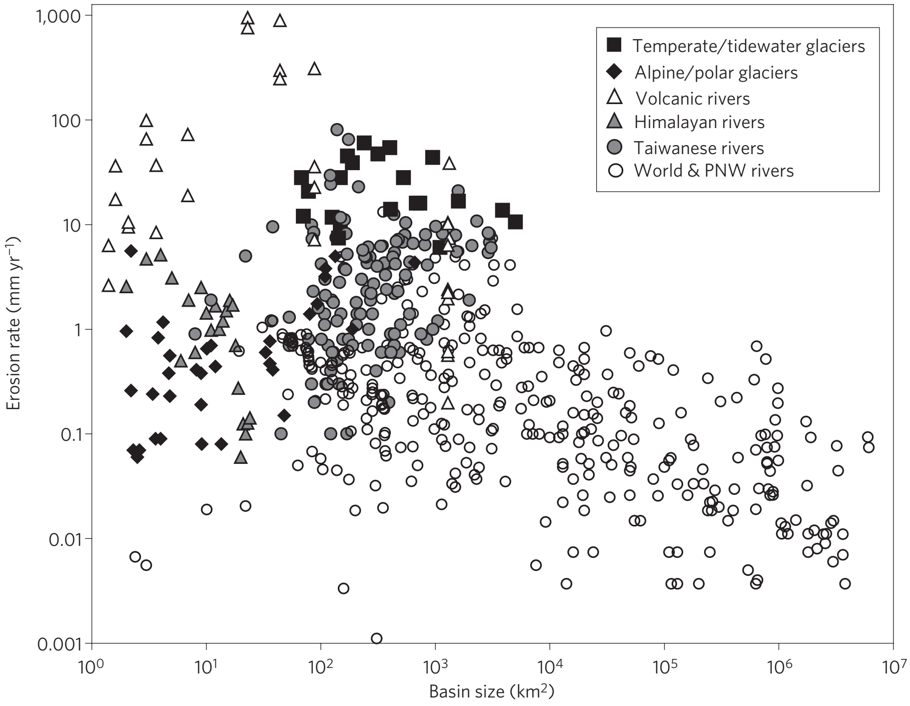

Figure 1 | Comparison of glacial, fluvial and composite landscape erosion rates versus contributing basin area, as measured by sediment yield data collected over 1–20 years. Fluvial basins are represented by circles and triangles: world rivers[15] and basins in the Pacific Northwest (PNW; refs 4, 29) are open circles; fluvial catchments in tectonically active orogens are grey circles and triangles[4,10,16] and volcanic rivers are open triangles[17]. Glaciated basins are indicated by black squares and diamonds[4,6,18].

decrease by over an order of magnitude when averaged over glacial–interglacial cycles (>10^3 yr; ref. 20), as measured from continental shelf sediment volumes, and by up to two orders of magnitude when averaged over the entire Quaternary (>1 Myr), as measured using low-temperature thermochronometers[7,21,22] (Fig. 2a). The 100-fold decrease in glacial erosion rates from decadal to orogenic timescales for the same basins suggests that rapid glacial erosion, such as is occurring today, is a transient response as glaciers reshape pre- and para-glacial landscapes. Furthermore, erosion over longer than a single glacial advance–retreat cycle (that is, >10^3 yr) averages over both periods of bedrock erosion and periods when shielding by previously deposited glacial sediments protects underlying bedrock from erosion during glacial re-advance, and must then be removed before bedrock erosion can begin anew.

In contrast, erosion rates observed from fluvial basins in the Nepalese Himalaya[8,9,16,23], Taiwan[10], the Italian Apennines[24], the Oregon Coast Range[13,14] and southeast Australia[11,12,25] all show little variability between modern rates and million-year rates for: (1) annual to decadal fluvial erosion rates measured using contemporary sediment yields from river outlets; (2) studies on the basis of terrestrial cosmogenic radionuclides from bedrock and from river sand used to estimate whole-catchment erosion rates on millennial timescales (10^4–10^5 yr); and (3) over million-year timescales from erosion rates determined using low-temperature thermochronometers (Fig. 2b). In all five cases, over a range of timescales erosion rates do not seem to have varied appreciably throughout the late Cenozoic, although the efficacy of erosion varies by two orders of magnitude between tectonically active and passive fluvial landscapes. This relatively uniform nature of fluvial erosion over a range of timescales suggests that these landscapes are currently and have been in dynamic equilibrium throughout the late Cenozoic, wherein incision and transport are controlled by the pace of tectonic uplift, even though late Cenozoic climate variability may have contributed to large changes in both river discharge and the frequency of hillslope mass wasting.

A key exception to the relative uniformity of fluvial erosion rates can be found in rivers draining active volcanoes, which show extreme rates of erosion following major eruptions[17]. If the tectonic disturbance is large, such as from recent emplacement of new volcanic material or significant seismic destabilization of hillslopes causing massive landsliding, fluvial erosion rates rise dramatically while transporting the massive slug of newly available mobile debris. Although much of the initial high sediment yield from such events can be attributed to lahars and debris flows, often in semiconsolidated deposits, sediment yield may remain elevated for several decades after lahar activity has ceased[17]. If we measure erosion rates following short-term, stochastic events, such as following volcanic eruptions, large storms, or earthquakes, rates of erosion and sediment transfer are up to two orders of magnitude greater than rates measured from the most erosive glaciers and rivers.

On the basis of analysis of this new compilation, we conclude that previous assertions that glaciers are more efficient erosional agents than rivers probably reflect both incomplete data coverage and inclusion of data from a recent period of rapid glacial erosion from retreating glaciers. Although we would expect erosion rates to be most rapid early in a period of glaciation, until landforms are re-sculpted by glacial processes, the time-dependent variability in glacial erosion rates we are seeing instead suggests that the erosional impact of glaciers is far greater during periods of warming at the end of a glacial cycle than when averaged over a full glaciation ($\sim10^5$–10^6 yrs). Several studies have recently documented a synchronous increase in retreat, ice loss and acceleration of many of the outlet glaciers in Greenland and Patagonia[26,27]. Such synchronous ice loss and flow suggests that, contrary to previous conclusions[4], sediment yields and thus calculated erosion rates are more rapid during glacial retreat, when the ice is thinning, warmer basal temperatures are enhancing flow at the bed and the glaciers are accelerating. The glaciers themselves, as well as subglacial meltwater systems, may also be remobilizing sediments

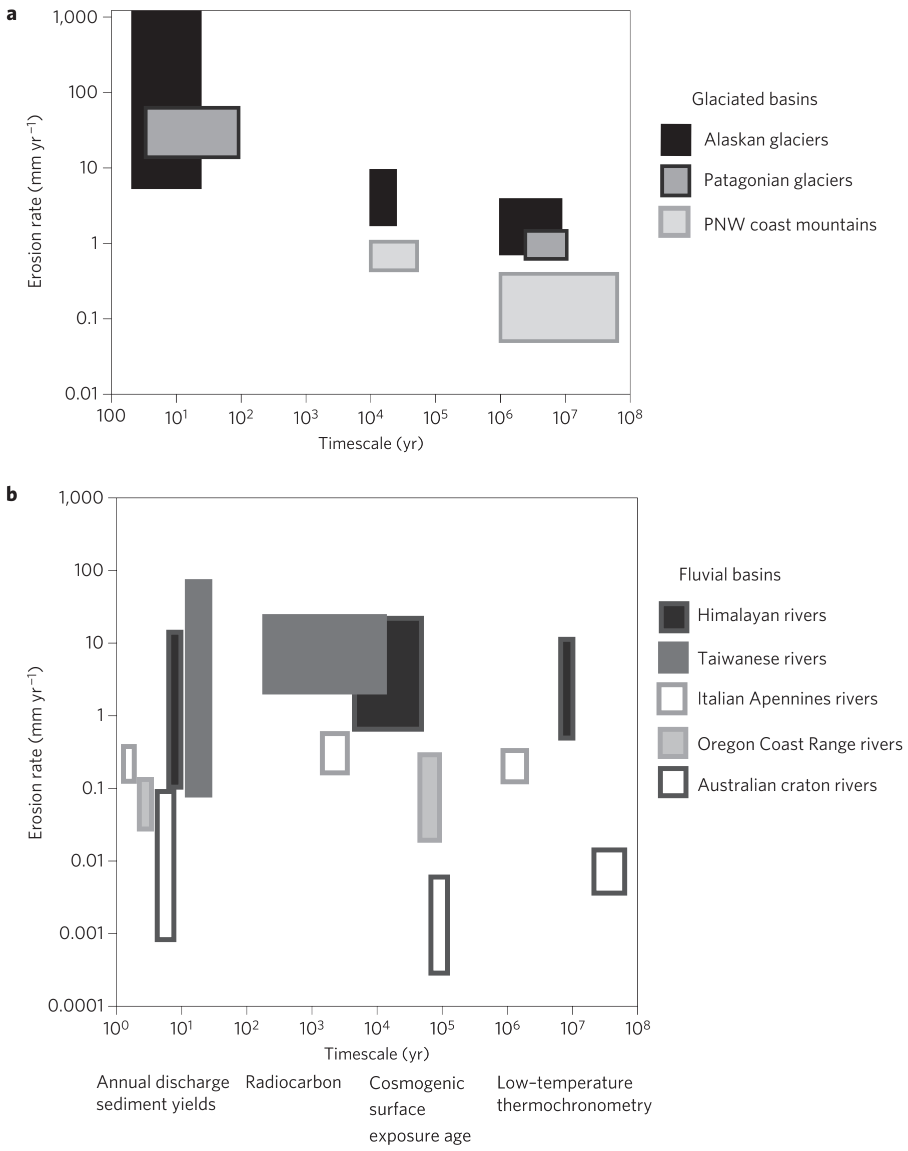

Figure 2 | Comparison of short-term and long-term erosion rates from glaciated and fluvial basins. Boxes represent ranges of erosion rates, including errors in estimation (height) and timescale of measurement (width). **a**, Erosion rates measured from the same or proximal glaciated basins in Alaska[4,7,20], Patagonia[18,22] and the coast mountains of Washington State in the Pacific Northwest (PNW; refs 29, 30). **b**, Erosion rates measured from the same or proximal fluvial basins in orogens ranging from most tectonically active to most passive: the central Himalaya[8,9,16,23], Taiwan thrust belt[10], Italian Apennines[24], the Oregon Coast Range[13,14] and the Australian craton[11,12,25].

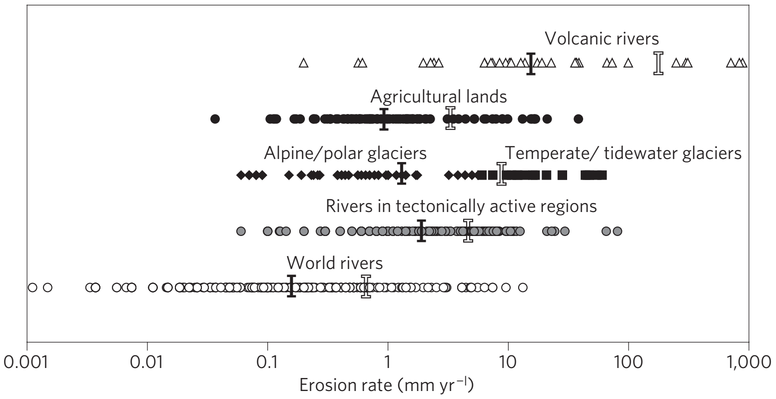

Figure 3 | Comparison of short-term erosion rates from various geomorphic agents. Erosion rates were calculated from measurements of sediment yield over timescales of 1–10 yrs. Data collected are the same as in previous figures; rates of erosion from agricultural lands (black circles) reflect conventional practices from regions around the world and from a variety of crops[28]. The median of each dataset is indicated by black bars, the mean by white bars.

deposited and stored under the ice, resulting in significantly larger modern sediment yields that represent both enhanced evacuation of subglacial sediment stores[18] and any new bedrock erosion accomplished by enhanced flow.

In the absence of large-scale tectonic or climatic disruption to landscape equilibrium, contemporary data suggest that glaciers and rivers are capable of denuding landscapes at rates adjusted to maintain equilibrium with the pace of uplift. Intriguingly, if we compare these erosion rates with rates from overland flow associated with conventional agricultural practices, as compiled previously[28], we see that farming erodes lowland agricultural fields at rates comparable to glaciers and rivers in the most tectonically active mountain belts (Fig. 3). In other words, the relatively recent advent of farming practices has accelerated erosion of many lowland basins at rates on a par with alpine erosion, rates that far exceed long-term rates not only of uplift but also of weathering and soil formation. Hence, many modern sediment-yield-based measures of basin-scale erosion may substantially reflect the impact of humans since the advent of agrarian cultures in the early Holocene.

Our revised global compilation of erosion rates reveals that the geomorphic impacts of glaciers and rivers are comparable, both in the recent past and over million-year timescales. Although Quaternary climate variability may have driven short-term fluctuations in both ice and water discharge, the similarity in fluvial and glacial erosion rates in actively deforming orogens indicates that either process can balance rates of rock uplift over millennial to orogenic timescales. Apparently, as has been suggested previously, both the glacier buzz-saw[2,3] and river incision coupled to threshold hillslopes that lower at a pace set by such incision[8] provide mechanisms by which glaciers and rivers adjust to keep pace with tectonic uplift. Consequently, tectonics remains the primary driver setting the pace of orogenic denudation. However, current measurements of glacial erosion are further complicated by the imbalance created by transient changes in glacial dynamics when periods of warming throw landscapes out of equilibrium, accelerating overall erosion rates. Similarly, fluvial systems recently affected by volcanic activity or agricultural practices may increase erosion rates by up to two orders of magnitude. Thus, many modern measures of erosion may reflect a short pulse of high rates as the landscape adjusts from one equilibrium state to another, driven by recent changes in tectonics, climate, or anthropogenic disturbance.

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References

1. Tyndall, J. On the conformation of the Alps. *Phil. Mag.* **24,** 169–173 (1862).
2. Brozovic, N., Burbank, D. W. & Meigs, A. J. Climatic limits on landscape development in the Northwestern Himalaya. *Science* **276,** 571–574 (1997).
3. Mitchell, S. G. & Montgomery, D. R. Influence of a glacial buzzsaw on the height and morphology of the Cascade Range in central Washington State, USA. *Quat. Res.* **65,** 96–107 (2006).
4. Hallet, B., Hunter, L. & Bogen, J. Rates of erosion and sediment evacuation by glaciers: A review of field data and their implications. *Glob. Planet. Change* **12,** 213–235 (1996).
5. Gurnell, A. M., Hannah, D. & Lawler, D. *Erosion and Sediment Yield: Global and Regional Perspectives* 97–104 (Intl Assoc. Hydro. Sci. Pub. 236, 1996).
6. Koppes, M. & Hallet, B. Erosion rates during rapid deglaciation in Icy Bay, Alaska. *J. Geophys. Res.* **111,** F02023 (2006).
7. Berger, A. L. & Spotila, J. A. Denudation and deformation in a glaciated orogenic wedge: The St. Elias orogen, Alaska. *Geology* **36,** 523–526 (2008).
8. Burbank, D. W. *et al.* Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalaya. *Nature* **379,** 505–510 (1996).
9. Pratt-Situala, B., Burbank, D., Heimsath, A. & Ohja, T. Landscape disequilibrium in 1,000–10,000 yr scales Marysandi River, Nepal, central Himalaya. *Geomorphology* **58,** 223–241 (2004).
10. Dadson, S. J. *et al.* Links between erosion, runoff variability and seismicity in the Taiwan orogen. *Nature* **426,** 448–451 (2003).
11. Heimsath, A. M., Chappell, J., Dietrich, W. E., Nishiizumi, K. & Finkel, R. C. Soil production on a retreating escarpment in southeastern Australia. *Geology* **28,** 787–790 (2000).
12. Bierman, P. & Caffee, M. Cosmogenic exposure and erosion history for Australian bedrock landforms. *Geol. Soc. Am. Bull.* **114,** 787–803 (2002).
13. Reneau, S. L. & Dietrich, W. E. Erosion rates in the southern Oregon Coast Range: Evidence for an equilibrium between hillslope erosion and sediment yield. *Earth Surf. Proc. Land.* **16,** 307–322 (1991).
14. Gendaszek, A. S., Stone, J. & Balco, G. Spatial models of erosion in mountain catchments constrained by cosmogenic 10-Be. *Eos* **87,** Fall Meet. Suppl., Abstr. H13E-1443 (2006).
15. Syvitski, J. P. M. & Milliman, J. D. Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. *J. Geol.* **115,** 1–19 (2007).
16. Lavé, J. & Avouac, J. P. Fluvial incision and tectonic uplift across the Himalayas of central Nepal. *J. Geophys. Res.* **106,** 26561–26591 (2001).
17. Gran, K. B. & Montgomery, D. R. Spatial and temporal patterns in fluvial recovery following volcanic eruptions: Channel response to basin-wide sediment loading at Mount Pinatubo, Philippines. *Geol. Soc. Am. Bull.* **117,** 195–211 (2005).
18. Koppes, M. N., Hallet, B. & Anderson, J. A. Synchronous acceleration of ice loss and glacial erosion, Glaciar Marinelli, Chilean Tierra del Fuego. *J. Glaciol.* **55,** 207–220 (2009).
19. Gardner, T. W., Jorgensen, D. W., Shuman, C. & Lemieux, C. R. Geomorphic and tectonic process rates: Effects of measured time interval. *Geology* **15,** 259–261 (1987).
20. Sheaf, M. A., Serpa, L. & Pavlis, T. L. Exhumation rates in the St. Elias mountains, Alaska. *Tectonophysics* **367,** 1–11 (2003).
21. Ehlers, T., Farley, K. A., Rusmore, M. E. & Woodsworth, G. J. Apatite(U–Th)/He signal of large-magnitude accelerated glacial erosion, southwest British Columbia. *Geology* **34,** 765–768 (2006).
22. Koppes, M., Hallet, B. & Stewart, R. Glacial erosion rates and climate influences in Chilean Patagonia. *Eos* **87,** Fall Meet. Suppl., Abstr. C14A-07 (2006).
23. Vance, D., Bickle, M., Ivy-Ochs, S. & Kubik, P. W. Erosion and exhumation in the Himalaya from cosmogenic isotope inventories of river sediments. *Earth Planet. Sci. Lett.* **206,** 273–288 (2003).
24. Cyr, A. & Granger, D. Dynamic equilibrium among erosion, river incision, and coastal uplift in the northern and central Apennines, Italy. *Geology* **36,** 103–106 (2008).
25. Bishop, P. SE Australian late Mesozoic and Cenozoic denudation rates: A test for late Tertiary increases in continental denudation. *Geology* **13,** 479–482 (1985).
26. Howat, I. M., Joughin, I., Tulaczyk, S. & Gogineni, S. Rapid retreat and acceleration of Helhiem Glacier, east Greenland. *Geophys. Res. Lett.* **32,** L22502 (2005).
27. Rignot, E., Rivera, A. & Casassa, G. Contribution of the Patagonia Icefields of South America to sea level rise. *Science* **302,** 434–437 (2003).
28. Montgomery, D. R. Soil erosion and agricultural sustainability. *Proc. Natl Acad. Sci. USA* **104,** 13268–13272 (2007).
29. Brandon, M. T., Roden-Tice, M. K. & Garver, J. I. Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, northwest Washington State. *Geol. Soc. Am. Bull.* **110,** 985–1009 (1998).
30. Reiners, P. W., Ehlers, T. A., Mitchell, S. G. & Montgomery, D. R. Coupled spatial variations in precipitation and long-term erosion rates across the Washington Cascades. *Nature* **426,** 645–647 (2003).

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Author contributions

Both authors contributed to the analysis and preparation of the manuscript. M.N.K. led the collection and review of the relevant literature and analysis of the datasets.

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