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Forum Comment

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Earth is (mostly) flat: Apportionment of the flux of continental sediment over millennial time scales

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Recent synthesis of ^{10}Be-derived denudation rates by Willenbring et al. (2013) suggests that the “flat” areas of the world, those with average slopes of <~100 m/km and representing ~90% of Earth’s land surface, have adequately high rates of denudation to produce most of the sediment transported to the world’s oceans. This finding is based on the product of interpolated denudation rates (L/T) over the world’s drainage areas (L^2) using landscape slope as the controlling variable. We suggest that these findings are incorrect on several grounds.

First, Willenbring et al. have mixed two related—but different—concepts: “gross” basin denudation and river sediment discharge. Gross basin denudation (L/T) is an integrated rate of regolith degradation; river sediment discharge (L^3/T or M/T) is a measure of flux in a river, and it cannot be calculated by multiplying denudation rates and watershed areas because this ignores sediment transport through a basin (e.g., Trimble, 1977). Although Willenbring et al. acknowledge this where they state that such comparisons are “impossible” (p. 345), we are told throughout the paper that their results are related to rates of sediment discharged “to the oceans” (p. 343, 344, 346). Both cannot be true.

Second, the denudation estimates presented by the authors—even if they were correct—simply do not add up. For example, the global values reported by Willenbring et al. are substantially lower than all previous estimates of global river sediment discharge (see their table DR2 in GSA Data Repository 2013091). Because global river sediment discharge to the ocean, even before human-caused effects, is ~15–20 Gt/yr, and sediment conveyance losses over time scales characterized by ^{10}Be are likely equivalent to these rates (Milliman and Farnsworth, 2011), global gross denudation is likely an order of magnitude greater than the 4.4 Gt/yr estimated by Willenbring et al.

These errors become clear when individual basins are examined. For example, the Amazon River receives 2.3–3.1 Gt/yr of sediment from the Andes (Aalto et al., 2006) but discharges only ~1 Gt/yr in the lower river at Obidos (Dunne et al., 1998). Thus, the $\sim 4 \times 10^6$ km^2 “flat” lower basin of the Amazon currently traps a net 1.3–2.1 Gt/yr of sediment. If Willenbring et al. were correct that ~10 mm/kyr of denudation occurred in the flat Amazonia, then only ~0.1 Gt/yr of sediment would be generated in these lowlands, which is ~4% (at most) of the total “gross” denudation of this basin’s steep headwaters.

Third, there are important data gaps in both flat and steep landscapes. For instance, the authors’ data set includes no measurements for slopes <11 m/km, which combined represent ~50% of Earth’s landscape. To fill this data gap, Willenbring et al. extrapolate relationships from higher sloped areas. As such, there was no assessment whether the relationship used was representative of the global conditions in areas that were largely unrepresented in the database, such as the expansive flat areas in the world’s deserts and boreal regions where fluvial processes are of limited importance. For steep landscapes, the data are limited to only two basins where denudation rates exceed 5000 mm/kyr As such, the data set does not include areas with the highest denudation rates and sediment yields in the world (e.g., Taiwan, New Zealand, Southeast Asia, and southeastern Alaska; Milliman and Farnsworth, 2011), and this data gap certainly contributes to the underestimation of global denudation.

Fourth, while the use of a constant denudation rate for flat areas of Earth’s surface is computationally attractive, this concept is counter to decades of research and basic principles of physics. Strong slope dependencies are found in: (1) reported denudation and erosion rates of the lower-relief regions of the world over both short- and long-term time scales; (2) the range of geomorphic transport laws and landscape evolution models that successfully mimic morphodynamic patterns over geologic time scales; (3) all sediment transport algorithms, whether at the river-order scale or at the local scale of the hydraulic gradient; and (4) all appropriate experimental laboratory data (e.g., Burbank and Anderson, 2011). These dependencies include both eroding bedrock channels (detachment-limited transport) and alluvial channels and eroding soils (transport limited). Combined, this suggests that a constant sediment production rate for all flat areas <200 m/km is not justified. Furthermore, many of these flat areas are net sinks—not sources—of sediment, and they would require “negative” sediment production rates in calculations of discharge “to the ocean” (Willenbring et al., p. 343, 344, 346).

While a number of other problems should be discussed (e.g., a model derived from watersheds orders-of-magnitude larger than the grid spacing, incorrect statements about correlations between slope and denudation [p. 344] and residuals summing to zero [p. 344], misrepresentation of watershed sizes in the histogram of their figure 1, no assessment of uncertainty, no corrections for floodplain storage, elimination of data based on a basin size threshold rather than a morphologic threshold, and a global slope-area curve [their figure 3A] with units inconsistent with a continuous distribution function and without data above 250 m/km), length constraints require us to end our discussion here.

In conclusion, the methods and findings of Willenbring et al. include incorrect assumptions, insufficient data sets, unreliable extrapolations, and computational errors. Combined, this results in overestimation of sediment contributions from “flat” areas and a gross underestimation of sediment contributions from “steep” areas of the world. The conclusions are therefore invalid.

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