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

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Abstract

We thank Warrick et al. (2014) for the Comment on our recent synthesis of 10Be-derived denudation rates (Willenbring et al., 2013), in which we suggested that gently sloping areas, representing ~90% of the Earth's land surface, have sufficiently high rates of denudation to produce a majority of mass fluxes to the world's ocean.

First, Warrick et al. take issue with labeling our global cosmogenic nuclide denudation fluxes "sediment" and with the inferred comparisons to other sediment yield apportionment studies. We apologize for instances of unclear wording related to the terms: sediment production, sediment to the oceans, and mass flux. Unlike sediment gauging data, cosmogenic nuclides measure total mass loss in surface environments averaged over millennial time scales, and they tend to not miss large landscape-changing events with low recurrence intervals (Kirchner et al., 2001). We aimed to quantify the spatial patterns of long-term, pre-anthropogenic mass fluxes from continents. We stated that previous sediment yield studies are not directly comparable, and this is correct because chemical weathering is included in total denudation, and there are differences in terms of averaging time scales and the effects of sediment storage.

Keywords

sediment, continental, flux, apportionment, flat, mostly, earth, scales, reply, time, millennial, over, GeoQuest

Disciplines

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

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We thank Warrick et al. (2014) for the Comment on our recent synthesis of ^{10}Be-derived denudation rates (Willenbring et al., 2013), in which we suggested that gently sloping areas, representing ~90% of the Earth's land surface, have sufficiently high rates of denudation to produce a majority of mass fluxes to the world's ocean.

First, Warrick et al. take issue with labeling our global cosmogenic nuclide denudation fluxes "sediment" and with the inferred comparisons to other sediment yield apportionment studies. We apologize for instances of unclear wording related to the terms: sediment production, sediment to the oceans, and mass flux. Unlike sediment gauging data, cosmogenic nuclides measure total mass loss in surface environments averaged over millennial time scales, and they tend to not miss large landscape-changing events with low recurrence intervals (Kirchner et al., 2001). We aimed to quantify the spatial patterns of long-term, pre-anthropogenic mass fluxes from continents. We stated that previous sediment yield studies are not directly comparable, and this is correct because chemical weathering is included in total denudation, and there are differences in terms of averaging time scales and the effects of sediment storage.

Second, Warrick et al. noted that our estimate of the total flux of sediment and solutes, i.e., mass flux (4.4 Gt/yr), is lower than previously published estimates derived from sediment gauging data, which range from ~8.3–51.1 Gt/yr (Willenbring et al., 2013, our table DR2). After our paper was published, we became aware that our mass flux estimates were affected by log transformation bias (Ferguson, 1986) and by the systematic underestimation of topographic gradients in the 1 km Global 30-Arc-Second Elevation Data Set (GTOPO30) (Kirchner and Ferrier, 2013). Correcting for these biases yields global mass fluxes that are broadly consistent with previously published estimates.

Third, Warrick et al. note correctly that various data sets and expectations from theory exist for a positive relationship between slope and erosion. Indeed, the entirety of the cosmogenic nuclide–derived denudation rate data set attests to a first-order topographic control on denudation. However, in post-orogenic terrains where chemical weathering may be the dominant term in the denudation flux, denudation rates will be largely slope-independent (e.g., Chadwick et al., 2013). We did not intend to imply that empirical relationships between *erosion* and slope were flawed at any range of slopes, but that, at specific narrow ranges of slope values, the various second-order controls on *total denudation* obscure the first-order control of topography that we see at the larger global scale in our compilation.

Fourth, our result that gently sloping areas dominate the global mass flux from the continents was based on the product of denudation rates over the world's drainage areas, using an exponential relationship between denudation rates measured from cosmogenic nuclides and basin slopes as the controlling variable to extrapolate to unmeasured basins and slopes. Warrick et al. commented that the existing collection of basins with cosmogenic nuclide–derived denudation rates is a biased representation of global basins. Moreover, they note that the number of sampled basins is small for both extremes of Earth's slopes. This is because measurements of basin-scale erosion have been acquired for a variety of purposes other than creating an unbiased data set of global denudation, and because areas of supposedly high denudation were largely avoided for concerns relating to limitations of the technique. Notwithstanding, since we finished our compilation, new publications (e.g., Siame et al., 2011) report cosmogenic nuclide measurements in steep orogenic terrains like those mentioned by Warrick et al. These new data do not deviate from the exponential pattern. As we noted in our paper, the question remains: What are the gross mass losses from Earth's gently sloping regions? We agree that this is an important gap in our understanding of continental denudation. Chemical weathering does occur in floodplains (e.g., Lupker et al., 2012); even places that are actively aggrading still experience some mass loss at slow, steady rates (1–10 mm/k.y.). Our figure 3B, which shows the apportionment of the mass flux considering different mean values, acts as a sensitivity analysis given the uncertainty in rates in low sloping areas. This area will be fertile ground for future research, and we argue that chemical weathering in floodplains and gently sloping topography could be grossly under-appreciated.

Regardless of whether mass fluxes from mountains or low-sloping areas dominate global budgets, denudation in gently sloping parts of the world has to be an important component of understanding solute and sediment budgets, if only because this is where the vast majority of agricultural and other anthropogenic influences occur and where humans have the most leverage to amplify fluxes above background rates (Kirchner and Ferrier, 2013). We thank Warrick et al. for further highlighting a research need of long-term river load measurements in low-sloping areas, and for providing a good argument for developing new methods to do so. We also thank them for their collective contributions to understanding global sediment fluxes.

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