When can single-nuclide denudation rates be trusted? - A global assessment from paired cosmogenic-nuclide constraints and machine learning

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Abstract

Watershed denudation rates, modulated by tectonic uplift and climatic variability, serve as key indicators of Earth's surface processes. Terrestrial cosmogenic nuclides measured in fluvial sediments enable quantification of basin-wide denudation rates, provided that catchments satisfy steady-state denudation conditions, with limited influence from prolonged sediment storage, burial, or recycling. Assessing whether a watershed meets these criteria is therefore essential for obtaining representative single-nuclide denudation rates. We use a global paired-nuclide dataset to develop a Random Forest (RF) classification model, with an independent Extreme Gradient Boosting (XGB) model to validate robustness. Model performance is highest in temperate and orogenic settings, whereas misclassification is more frequent in arid regions. The paired-nuclide denudation-rate ratio (E-ratio) serves as the diagnostic criterion for defining ideal (steady-state) catchments. Shapley Additive Explanations (SHAP) indicate that drainage area is the dominant predictor of steady-state conditions, followed by elevation, relief, and precipitation. Catchments with small-to-moderate areas and intermediate-to-high elevations, relief, and precipitation are more likely to yield single-nuclide estimates that reliably reflect long-term denudation. Across global datasets, the fraction of catchments meeting the steady-state criterion depends on the selected E-ratio threshold: at 1 ± 0.1, ˜50% satisfy the criterion, increasing to ˜97% at 1 ± 0.2. These results suggest that single-nuclide estimates may be biased relative to long-term steady-state denudation across a range of climatic and tectonic settings worldwide, but they remain informative for broad comparative analyses.

Keywords: cosmogenic nuclides, drainage denudation, steady state conditions, paired nuclide constraints, Random Forest, SHAP

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