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Characterizing landscape-scale erosion using 10Be in detrital fluvial sediment: Slope-based sampling strategy detects the effect of widespread dams

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Key Points:
- Dams and their reservoirs, which are ubiquitous on most rivers, affect ^{10}Be concentrations in detrital sediment
- We demonstrate and test a detrital sediment sampling design reflecting the distribution of subbasin average slopes
- Slope-driven regression model simulates erosion rates of previously sampled basins well for samples collected >25 km downstream of dams

Supporting Information:
- Supporting Information S1
- Table S1–S3
- Software S1

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Characterizing landscape-scale erosion using ^{10}Be in detrital fluvial sediment: Slope-based sampling strategy detects the effect of widespread dams

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Abstract Concentrations of in situ ^{10}Be measured in detrital fluvial sediment are frequently used to estimate long-term erosion rates of drainage basins. In many regions, basin-averaged erosion rates are positively correlated with basin average slope. The slope dependence of erosion allows model-based erosion rate estimation for unsampled basins and basins where human disturbance may have biased cosmogenic nuclide concentrations in sediment. Using samples collected from southeastern North America, we demonstrate an approach that explicitly considers the relationship between average basin slope and erosion rate. Because dams and reservoirs are ubiquitous on larger channels in the field area, we selected 36 undammed headwater subbasins (average area 10.6 km^2) from which we collected river sand samples and measured ^{10}Be concentrations. We used these data to train a predictive model that relates average basin slope and ^{10}Be-inferred erosion rate. Applying our model to 28 basins in the same region previously studied with ^{10}Be, we find that the model successfully predicts erosion rates for basins of different sizes if they are undammed or if samples were collected >25 km downstream of dams. For samples collected closer to dams, measured erosion rates exceed modeled erosion rates for two-thirds of the samples. In three of four cases where paired samples were collected upstream of reservoirs and downstream of the impounding dam, ^{10}Be concentrations were lower downstream. This finding has implications for detrital cosmogenic studies, whether or not samples were collected directly downstream of dams, because dams obstruct most major rivers around the world, effectively trapping sediment that originated upstream.

Plain Language Summary Measuring the rate at which Earth eroded before humans arrived and changed the landscape is tricky business. Over the last two decades, geologists have used a collection of chemical and isotopic techniques, based on counting atoms rare in nature, to estimate how quickly parts of the landscape erode. They've collected and analyzed thousands of samples and now we know that some regions of the globe erode so rapidly that the landscape changes a few centimeters every hundred years whereas other landscape are so stable, only a hair's width of rock will erode per millennium. The problem is that dams can get in the way. Working in the heavily dammed southeastern United States, we show that samples collected within 25 kilometers of dams often lead to inaccurate results, overestimating long term erosion rates. We conclude that recent, human impacts on the landscape are likely even more damaging than previously thought, stripping soil and farm land at an unsustainable rate.

1. Introduction

Since the mid-1990s, concentrations of in situ produced ^{10}Be measured in samples of fluvial sediment [*Bierman and Steig*, 1996; *Brown et al.*, 1995; *Granger et al.*, 1996] have been used to estimate spatially and temporally averaged rates of erosion for drainage basins. Samples of river sediment are considered to have ^{10}Be concentrations representative of background, temporally-integrated erosion rates, because in most environments the upper meter or so of hillslope material moving into river channels is mixed by physical and biological stirring [e.g., *Jungers et al*., 2009]. These data have been used to understand the relationship between erosion rate and climate, tectonic setting, and lithology [e.g., *Matmon et al*., 2003b; *Portenga and Bierman*, 2011; *Schmidt et al*., 2016; *Kirchner et al*., 2001; *Schaller et al*., 2001]. Because the method is both expensive and time consuming, some regional studies rely on a limited number of ^{10}Be measurements made in subbasins and averaged, sometimes using area weighting, to generate a landscape-scale, average erosion rate [e.g., *Lupker et al*., 2012].

In most ^{10}Be basin-scale erosion rate studies, sand-sized river sediment is analyzed and assumed to be isotopically representative of material moving through the system [*Bierman and Steig*, 1996; *Brown et al*., 1995; *Granger et al*., 1996]. However, most of the world's rivers have been dammed, trapping at least some of the sediment moving downstream [*Syvitski et al*., 2005], and thus invalidating to an unknown degree, the assumption that samples collected anywhere downstream of dams are representative of the entire basin upstream. Although samples are not typically collected directly downstream of dams, the ubiquity of dams throughout the world suggests that at least some and likely many detrital samples from larger drainage basins have dams somewhere upstream trapping sediment.

In many studies [e.g., *Cox et al*., 2009; *Granger et al*., 1996; *Matmon et al*., 2003a; *Riebe et al*., 2000] as well as a global compilation of $>$1200 measurements of ^{10}Be in fluvial sediment [*Portenga and Bierman*, 2011], the best predictor of basin-scale erosion rate is average drainage basin slope or related metrics including relief. Such a relationship makes sense, as slope is positively related both to diffusive and advective sediment flux [*Bierman and Montgomery*, 2014]. Slope/erosion rate correlations suggests that models based on drainage basin average slope can be used to estimate erosion rates of basins in which ^{10}Be has not been measured [*Linari et al*., 2016].

However, the dependence of erosion rates inferred from ^{10}Be measurements on average basin slope means that if the population of sampled subbasins does not have the same distribution of average basin slopes as the landscape of interest, the resulting average erosion rate may not accurately represent the landscape as a whole. We first identified this bias in a data set collected from the Blue Ridge escarpment in southeastern North America [*Sullivan*, 2007]. In order to address our inadvertent sampling bias, we made a postfacto attempt at correction based on the slope dependence of erosion [*Linari et al*., 2016]. This experience led us to develop a transferable sampling approach/experimental design that we have used since and that we detail in this paper.

Here, we consider erosion of southeastern North America from the rugged Blue Ridge highlands to the west and the adjacent rolling but more subdued topography of the Piedmont to the east. Much of the area is underlain by quartz-bearing lithologies and thus appropriate for ^{10}Be measurement in detrital fluvial sediment. The area was settled by Europeans in the 1700s and land use for agriculture and forestry since then has been intensive (as reviewed in *Trimble* [1977] and *Reusser et al*. [2015]) with significant soil loss (reviewed in *Meade* [1982]). On human time scales, sediment delivery ratios (the amount of sediment eroded divided by sediment yield) are low and inversely proportional to basin area [*Roehl*, 1962]. This suggests storage of recently eroded sediment at the foot of slopes and in river floodplains where it is accessible for reworking by the river [*Meade*, 1982]. Dams, both high-head and run-of-the-river are common; the National Inventory of Dams, accessed 20 March 2017, indicates in the four states considered here, there are over 14,000 dams. The larger reservoirs store significant amounts of sediment.

In this study, we (i) present our method for ensuring representative sample collection in terrains where erosion rate is related to average basin slope, a common occurrence; (ii) use the resulting data to train and test a simple, slope-dependent linear regression model that estimates the erosion rate of unsampled basins, and (iii) show that sediment collected at different distances below dams is often not representative of sediment upstream and suggest approaches to address this issue including the use of the linear regression model as a proxy for erosion rate in basins where dams have influenced the concentration of ^{10}Be in river sediment.

2. Materials and Methods

2.1. Selection of Basins for Sampling

For this study, we consider southeastern North America and build upon the work of *Reusser et al*. [2015]; this current paper includes more samples, provides a detailed rationale for sample collection strategy, and reinterprets some data presented in *Reusser et al*. [2015] in light of new findings about the impact of dams on ^{10}Be concentrations in river sediment.

For this study, we subdivided the 10 large basins examined by *Reusser et al*. [2015] (Figure 1 and supporting information Table S1) into smaller drainage basins resulting in 5104 unique subbasins (average area 19 km^2). We did this using various hydrology tools in ESRI ArcGIS™, publicly available data (http://water.usgs.gov/GIS/huc.html), and 1 arcsecond digital elevation models (DEMs) (http://seamless.usgs.gov). We chose 4 of the 10 large basins in *Reusser et al*. [2015] (Roanoke, Pee Dee, Savannah, and Chattahoochee; 3053 potential sample sites) for sampling (Figure 1) because they all have headwaters in the higher-slope Blue Ridge province west of the Piedmont and thus represent the greatest spatial variability of slope in our study area.

We used the probability density function of average basin slopes to design a representative sampling approach for each of the four large basins (Figure 1). Because the majority of the study area lies in the topographically subdued Piedmont, we evenly spaced ten slope divisions between 0° and 25° and collected the largest percentage of samples in 3–7° range, which dominates the slope histogram (Figure 1d). The long tail of the frequency distribution with much higher slopes (up to 25°) reflects the steeper Blue Ridge physiographic province.

2.2. Field Sampling

We collected samples in December 2006 and June 2008. At each sample site, we collected and wet-sieved samples of active channel sediment, or recent overbank deposits, to a grain size fraction of 250–1000 μg for in situ ^{10}Be analysis. We sampled 36 basins to train the slope/erosion rate model (supporting information Table S2); all of these basins were undammed. We chose basins that were small enough that lithology/land use/slope are similar within each basin and small enough to avoid storage of significant sediment in terraces; sampled basins were accessible by car and large enough to have consistent flow (i.e., sampled sediment is fluvially transported and not the result of colluvial, downslope transport). The 36 training basins were, on average, slightly smaller (average area, 11 km^2) than the basins used to determine the distribution of basin slopes (19 km^2). Average basin slope ranges from 1.9° to 24.7° for the 36 model-training basins.

At some locations within the study area, we intentionally collected samples both below hydroelectric dams and upstream of their associated reservoirs to investigate the influence of dams along rivers on the concentration of in situ ^{10}Be measured in river sediment (distance from nearest upstream dam listed in supporting information Table S1). We used Google Earth to measure the distance between sampling points and the nearest dam upstream. To test for temporal variance in ^{10}Be concentration, we resampled a site midway down the Savannah River ~1.5 years after the initial sampling (initial sampling 12/5/2006 SAP17; resampled 6/11/2008 as SAP55; supporting information Table S1). Information about the larger basins used to test the model is reported in an earlier paper [*Reusser et al*., 2015] that focused on quantifying human impact by comparing ^{10}Be-based, long-term erosion rates with short-term soil loss and sediment yield.

2.3. Sample Preparation, Isotopic Analysis, and Data Reduction

We prepared all samples at the University of Vermont using standard laboratory methods for quartz purification [*Kohl and Nishiizumi*, 1992] and ^{10}Be extraction [*Corbett et al*., 2016]. We measured ^{10}Be/^{9}Be ratios at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory [*Rood et al*., 2010, 2013]. All measured isotopic ratios were blank corrected using one process blank included with every batch of 11 samples and normalized to the 07KNSTD3110 standard, which has an assumed ^{10}Be/^{9}Be ratio of 2850 $\times 10^{-15}$ [*Nishiizumi et al*., 2007].

We summarized ^{10}Be production at all elevations within each basin to a single elevation (i.e., the effective elevation, *Portenga and Bierman* [2011]) and calculated background in situ ^{10}Be erosion rates (E) using the effective elevation and mean basin latitude and longitude as entry data for the CRONUS online calculator [*Balco et al*., 2008].

2.4. Modeling

Using erosion rate data from the 36 training samples, selected to represent the distribution of basin average slopes in our study area (Figure 1d), we developed and then tested a linear regression model

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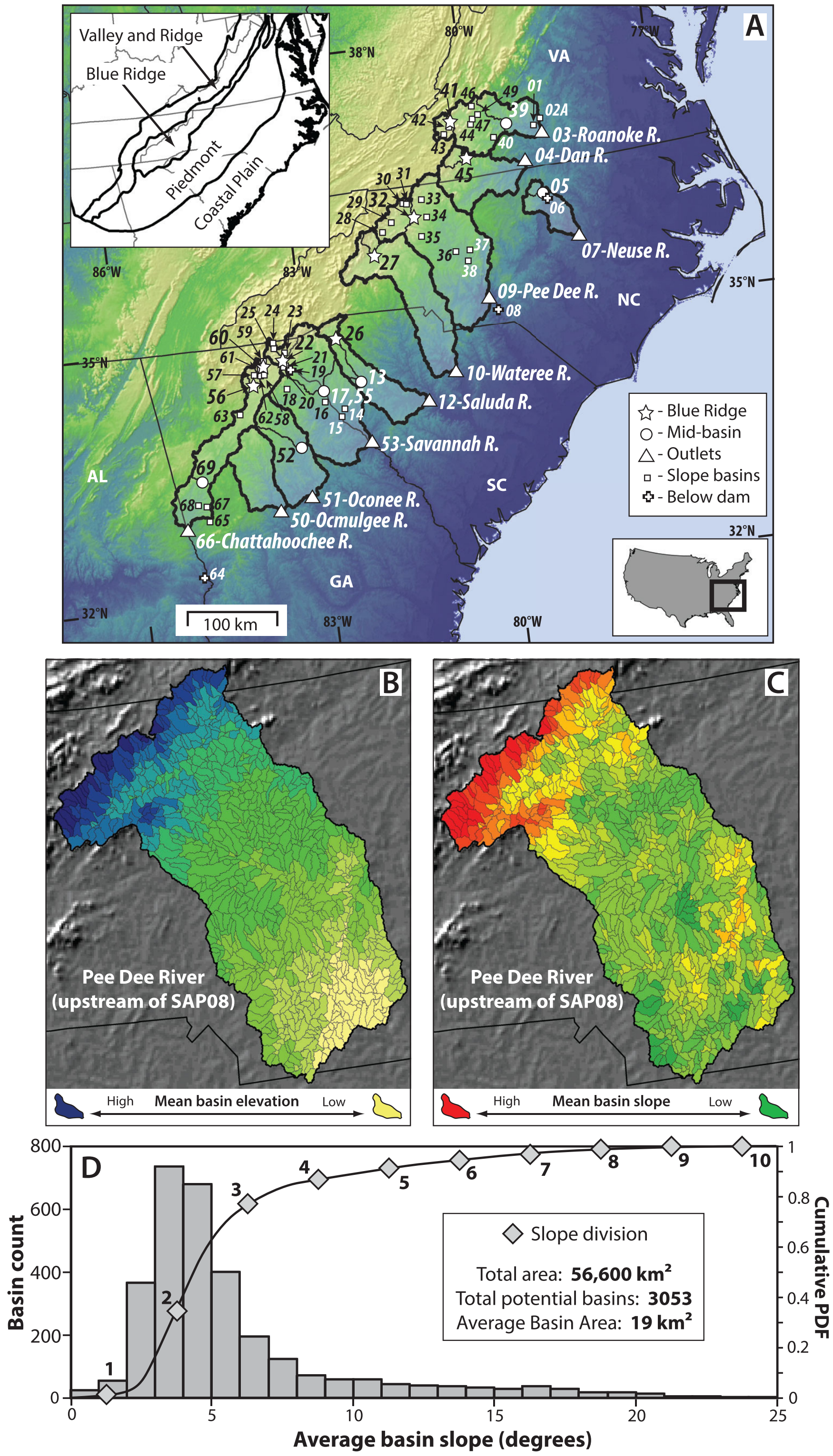

Figure 1. Basin selection. (a) Location map of samples used in this study including samples first presented in *Reusser et al.* [2015]. Numbers by basin are for sample identification with the prefix SAP. Inset shows field area in relation to the regional physiographic provinces. (b) Small subbasins within the large Pee Dee Basin (SAP09) mapped by average basin elevation. (c) Small subbasins within the large Pee Dee Basin (SAP09) mapped by average basin slope. (d) Frequency distribution (bars) and cumulative probability density function (PDF; solid line) of the average basin slopes for 3053 subbasins within the Roanoke, Pee Dee, Savannah, and Chattahoochee Rivers—all of which drain significant portions of both the Blue Ridge and Piedmont provinces. The skewed distribution of average basin slopes reflects the relative proportion of higher slope Blue Ridge subbasins (tail) and lower slope Piedmont (majority of subbasins). Diamonds represent the 10 slope divisions (2.5° widths) for which samples were collected.

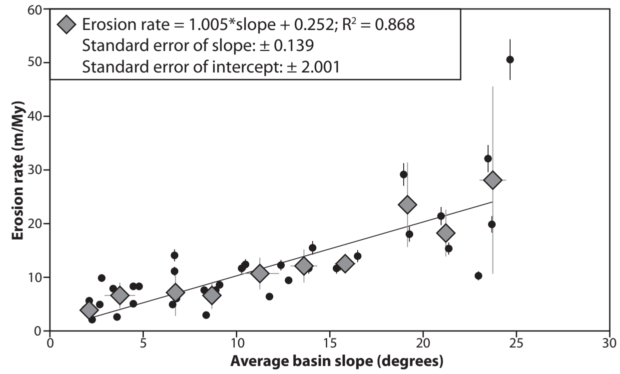

Figure 2. Average basin slope and ^{10}Be-derived erosion rates are well correlated for both the 36 small subbasins (small black circles) and also the average values for the ten slope divisions (filled diamonds with numbers) as shown in Figure 1d. Error bars on sample points represent erosion rate uncertainties from CRONUS (1 SD). Error bars on diamonds represent 1 SD of erosion rates and basin average slopes.

(Figure 2), which we used to predict erosion rates in 28 previously sampled [*Reusser et al*., 2015] basins in southeastern North America.

To determine if a more complex regression method would predict erosion rates better than the simple bivariate slope model, we employed additional multiple regression models using the statistical software packages JMP^{TM} Version 11 and a number of predictor variables generated with ArcGIS^{TM} for the same 36 small basin samples. First, we complied a database containing topographically derived and meteorological summary statistics for each of the 5104 subbasins contained within the 10 large-scale Piedmont drainages. For each sample, potential predictor variables included average basin elevation (m), basin relief (m), standard deviation of elevation (m), average basin slope (m), standard deviation of slope (m), basin area (km^2), mean annual temperature (°C), mean annual precipitation (mm), and physiographic province (supporting information Table S3). We constructed a multivariate correlation matrix to examine colinearity between variables, and reduced the number of variables accordingly prior to using them in a multiple regression model. Further, we performed a Principal Component Analysis using all of the variables listed above for the 36 training basin samples to test whether the resulting principal components might better explain erosion rates in a multiple regression model.

3. Results

Concentrations of ^{10}Be in the 65 samples (including one replicate) presented in this study and considered from *Reusser et al*. [2015] range from 1.44 to 14.2 $\times$ 10^5 at/g, yielding background erosion rates (E) ranging from 1.95 to 50.5 m/My, in agreement with previously published drainage-basin-scale ^{10}Be erosion rates for the southern Appalachian Mountains [*Duxbury et al*., 2015; *Matmon et al*., 2003a, 2003b; *Portenga and Bierman*, 2011; *Linari et al*., 2016] (supporting information Tables S1 and S2).

Results from temporal replication of a sampling site along the Savannah River (supporting information Table S1; SAP17, 2.81 $\pm$ 0.08 $\times$ 10^5 at/g; SAP55, 3.21 $\pm$ 0.09 $\times$ 10^5 at/g) suggest a temporal variance of ~14% (1 SD) in ^{10}Be concentration and resulting erosion rate estimates (supporting information Table S1; SAP17, 15.6 $\pm$ 1.2 m/My; SAP55, 13.4 $\pm$ 1.0 m/My). We consider this percentage to be an upper limit on temporal variability because the temporal replication site is located just downstream of a hydroelectric dam where sediment sourcing is uncertain and likely varies over time. The variability of the replicate samples is consistent with a compilation of resampling efforts by *Sosa-Gonzalez* [2016], which shows 112 pairs of temporal replicates that have a mode centered on 0% difference and one standard deviation of 7% difference; replicate variability is also consistent with variability within most of the 10 slope divisions (Figure 2).

Smaller basins ($n = 36$; 0.5–50 km^2), for which we present new data, are eroding at rates between 2 and 50 m/My with an area weighted average of 13 m/My. For these basins, basin average slope is positively related to the ^{10}Be-determined erosion rate (Figure 2). We find a significant linear slope-erosion rate relationship for 36 small basin samples (adjusted $R^2 = 0.580$, $p < 0.0001$). When the 36 samples are binned into ten discrete slope divisions that we used for experimental design (Figure 1), the resulting linear slope-erosion rate relationship is more statistically robust due to averaging scattered data within each division (adjusted $R^2 = 0.868$; $p < 0.0001$; Figure 2 and supporting information Table S2), but the

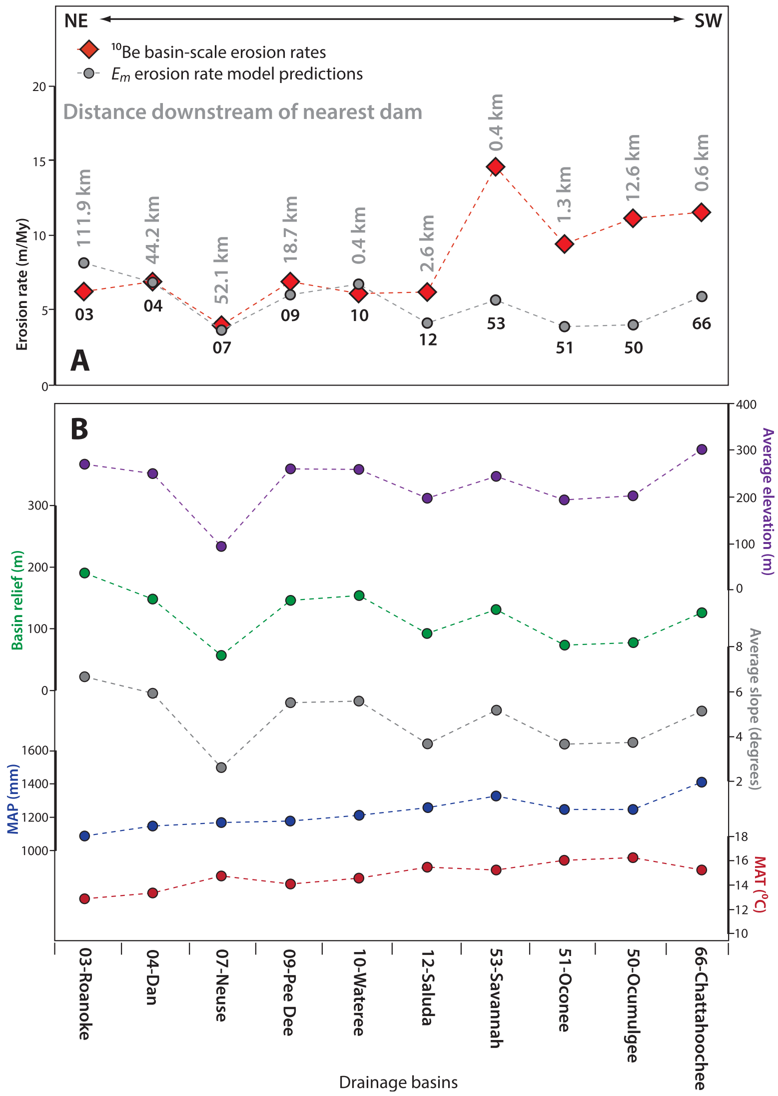

Figure 3. Compilation figure showing, basin by basin, all data relevant for interpreting the ^{10}Be erosion rates measured in this study as well as the erosion rates predicted with the slope-based model. Note, dashed lines connect data points for clarity and do not indicate continuous data. SAP sample designator is number before river name. (a) Larger diamonds are ^{10}Be erosion rates; smaller circles are erosion rates predicted with the slope model (equation (1)). (b) Basin-by-basin average values included in the multiple regression model (average elevation, basin relief, average slope, mean annual precipitation (MAP) and mean annual temperature (MAT)). Note that ^{10}Be-inferred erosion rates for the six NE basins (Roanoke to Saluda Rivers) track well with the model parameters in the lower panel; ^{10}Be erosion rates for the four basins to the SW (Savannah to Chattahoochee) deviate substantially from the modeled rates, likely due to the influence of numerous main stem river dams on sediment transport from upstream (see Figure 5).

regression coefficients are similar within error (Figure 2). The relationship between basin-averaged erosion rate and mean basin slope, when binned, yields the following model for erosion rates (E_m, m/My):

$$E_m = 1.005^* S + 0.252, \quad (1)$$

where S is the average basin slope (degrees). Note that the predicted erosion rates track well with the average values of elevation, slope, and relief but not with mean annual precipitation or temperature (Figure 3 and supporting information Table S3).

Results of a multivariate correlation matrix indicate that the only noncorrelated geographic variables are mean basin slope and latitude (at the centroid of each basin). This is logical as slope is a proxy for nearly every other morphometric variable entered into the multivariate analysis. When latitude is included to produce a multiple regression model, no predictive capability is gained (adjusted $R^2 = 0.57$, $p < 0.0001$).

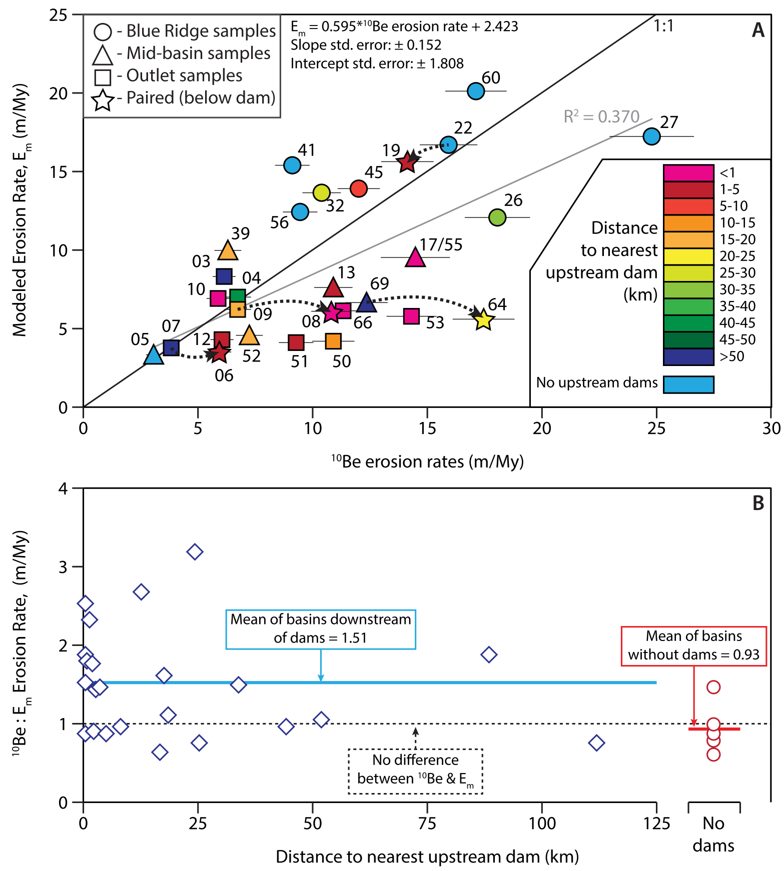

Figure 4. Comparison of model estimated and ^{10}Be-inferred erosion rates. (a) Relationship between erosion rates predicted with the slope model for outlet, Mid-basin, Blue Ridge, and paired dam samples reported in *Reusser et al.* [2015] and measured ^{10}Be erosion rates. Note that 7 of 10 outlet samples and 3 of 4 dam pairs lie below the 1:1 line. This likely reflects the influence of dams because samples collected downstream of dams contain some locally sourced material that may contain less ^{10}Be than material moving down the river upstream but now trapped in reservoirs behind dams. Dam pair samples connected by dotted line with arrow pointing to downstream point. (b) Ratio of ^{10}Be-inferred erosion rates to model erosion rates is higher for samples with dams upstream than for undammed basins.

Similarly, a multiple regression model generated with first five principal components yields a maximum adjusted $R^2 = 0.46$ indicating that we gain nothing by adding other variables. Therefore, for the rest of our analysis, we use the slope-only based predictive model (equation (1)).

The presence of dams, and the sediment trapping they cause, influences ^{10}Be concentrations in downstream sediment, upwardly biasing calculated erosion rates in many cases. For example, calculated ^{10}Be erosion rates for sample pairs, collected above and below dams at the outlets of the Pee Dee and Chattahoochee Rivers, yield apparent erosion rates that are greater downstream than upstream (SAP64, 17.6 ± 1.3 m/My versus SAP66, 11.4 ± 0.9 m/My, and SAP9, 10.9 ± 0.9 m/My versus SAP8, 6.8 ± 0.6 m/My, respectively; supporting information Table S1 and Figure 4d). The downstream/upstream difference is nearly twofold for the dam-pair collected approximately midway down the Neuse River (SAP6, 6.0 ± 0.5 m/My versus SAP5, 3.1 ± 0.3 m/My). Alternatively, in the much higher slope Blue Ridge, where the basins are substantially smaller than at the outlets, a dam-pair along the Savannah River is within the uncertainty of ^{10}Be erosion rate estimates (SAP19, 14.2 ± 1.2 m/My versus SAP22, 16.0 ± 1.2 m/My).

4. Implications of Our Results

4.1. Sampling Strategy and Model Estimation of Erosion Rates

Using a sampling strategy that represents the distribution of average subbasin slopes (Figure 1), a clear control on basin-scale erosion rates in eastern North American [*Portenga and Bierman*, 2011], we trained a linear model (equation (1)) that we then checked by predicting the erosion rate of previously sampled basins

(Figures 3 and 4). The linear model is appropriate because slopes in the basins we sampled (and in most of eastern North America) are subcritical.

When tested using the slope data from detrital fluvial sand ^{10}Be samples included in *Reusser et al.* [2015], the model (equation (1)) predicts erosion rates without bias for five samples collected from undammed channels (average difference, $(E_m - {}^{10}\text{Be})/E_m$, = 7%, average absolute difference = 25%). If samples collected >25 km downstream of the nearest dam are considered along with samples from undammed channels (total $n = 12$), the average difference is −6% and the average absolute difference is 28%. For samples ≤25 km downstream of a dam the results are different; the average difference between modeled and measured erosion rates is −71% and the average absolute difference is 80%. On average, proximity to dams correlates with increased discrepancy between model and ^{10}Be estimates of erosion, in most cases with an increase in the inferred ^{10}Be erosion rate.

The spatial domain over which this model applies is unknown; it may be useful for much of the southeastern North America but out of caution, we restrict its use to the area in which it was calibrated. The heterogeneity of erosion rates and the distribution of slopes in each field area will determine the number of samples needed to calibrate models such as we propose in other regions.

4.2. Influence of Dams on ^{10}Be Erosion Rate Estimates in Detrital Sediment

Large dams with high trap efficiencies [*Brune*, 1953] by design impede the flow of water and sediment; thus, the interpretation of ^{10}Be concentrations as basin-scale erosion rates, when measured in sediment collected from channels below such dams, is widely known to be uncertain [*Schmidt et al.*, 2016]. The uncertainty arises because the sampled material may not represent that carried into the reservoir from upstream. Although sediment deposited in reservoirs does remobilize and can be transported over dams during extreme flood events [*Meade*, 1982], it is not possible to determine if this were the case for any particular sample.

Sediment collected downstream of a dam is a mix of locally derived material, both from bank erosion and tributary contributions, as well as sediment transported from upstream. If the locally derived material is sourced from eroding river terraces deposited prior to dam construction (as suggested in some cases by data in *Meade* [1982]), then this alluvium will provide information about the long-term erosion rate upstream of the dam. However, if the eroding banks are saprolite, then at least some of the material sampled below dams is not representative of that carried down the river network. Although it is possible to sample only undammed tributaries, most main stem rivers around the world have dams in their watersheds (see: http://www.gwsp.org/products/grand-database.html) meaning that some samples collected previously for cosmogenic analysis have been influenced to an unknown degree by dam-induced sediment retention.

There are several lines of evidence that suggest dams have affected concentrations of ^{10}Be measured in sediments collected for model testing in southeastern North America (Figure 4a). Specifically, the presence of dams appears to result in an overestimate of the long-term erosion rate as shown by comparison to model-based estimates and an increase in the variability of erosion rate measurements for samples collected <25 km downstream of dams.

1. Considering the ratio of the erosion rate measured using ^{10}Be to that estimated by the model ($^{10}\text{Be}/E_m$ ratio), samples collected downstream of dams ($n = 23$) have an average $^{10}\text{Be}/E_m$ of 1.51 whereas those collected from undammed channels ($n = 5$) have an average ratio of 0.93 (Figure 4b). This is consistent with the observation that in general samples below the 1:1 line (Figure 4a) are closer to dams and include 7 of the 10 outlet samples (which in general reflect a larger number of dams upstream than the Blue Ridge and Mid-Basin samples). These data suggest that on average, collecting a sample <25 km downstream of a dam overestimates the long-term erosion rate by 1.5× although some samples appear unaffected and other have >3× differences from model-estimated rates. There is no clear trend between distance downstream of a dam and the magnitude of the bias effect; however, as pointed out in section 4.1, we do not detect an effect in samples collected >25 km downstream of dams.
2. The presence of dams near sample sites increases the variability of erosion rate estimates. For example, the standard deviation of the $^{10}\text{Be}/E_m$ ratio is 0.68 for samples collected with 5 km of a dam ($n = 18$) and 0.32 for samples collected >5 km from a dam ($n = 10$, Figure 4b). This observation suggests that sampling as far below dams as possible will minimize their effect on the variance of ^{10}Be-determined erosion rates.

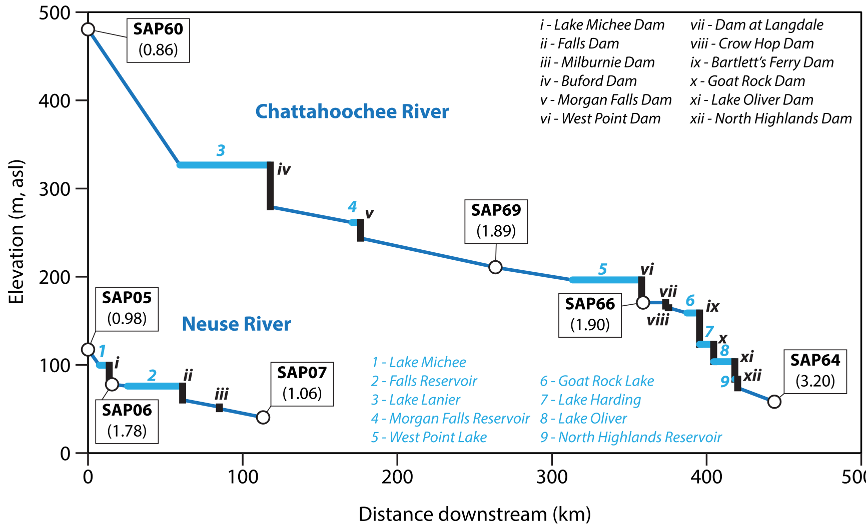

Figure 5. River long profiles for Neuse and Chattahoochee Rivers showing dams by Roman numeral (black), reservoirs by number (light blue), and river profile (dark blue). Sample locations and numbers shown with ^{10}Be/E_m ratio in parentheses below. Elevation and downstream distance determined from Google Earth. There are no dams above upstream samples, both of which have ^{10}Be/E_m ratio just below 1. With the exception of SAP07, which was collected nearly 50 km downstream of a large dam, all ^{10}Be/E_m ratios increase downstream as the number of dams and reservoirs increases.

3. Long profiles of large rivers exemplify how much of the channel length in the southeastern North America is impounded by dams and associated reservoirs (Figure 5). The ^{10}Be/E_m ratio increases directly below dams and for rivers such as the lower Chattahoochee, where impoundments are nearly continuous, the ^{10}Be/E_m ratio rises steadily downstream to >3.
4. If paired samples collected directly downstream of dams are interpreted as erosion rates under the assumption that the sediment was sourced from the entire upstream basin, samples from three of four rivers appear to overestimate background erosion rates relative to their upstream counterparts (supporting information Table S1 and Figure 4a). The dam-pair erosion rate estimates from the Pee Dee and Chattahoochee Rivers near their respective outlets differ by $\sim$60% and $\sim$54%, respectively. Erosion rates from the mid-basin dam pair differ by $\sim$93%. We measured no effect of a dam on the smaller, headwater, Blue Ridge basin.

Considering case 4 above, one can assume that material collected downstream of the dams was locally derived and use that information to alter assumptions in the erosion rate calculation. If one uses the corresponding local elevations (which are lower) to calculate nuclide production rates as opposed to the hypsometrically weighted elevations for the entire basins (which are higher), the differences in upstream versus downstream erosion rates decrease from an average of $\sim$69% for the four pairs to $\sim$35% because production rates decrease with elevation. Because less than half of the difference between upstream and downstream erosion rates is explained by using local nuclide production rates alone, the samples we collected below the dams must include locally derived material that is less well dosed by cosmic radiation than material originating upstream. Because downstream landscapes are less steep than upstream landscapes (Figure 1), downstream erosion rates should be lower (Figure 2). Thus, we infer that some of the sediment downstream of the dams is derived from incised bluffs of sediment or saprolite and thus must be sourced from below the landscape surface where cosmic-ray dosing, and thus ^{10}Be concentration, are less. It is possible that channels downstream of the dams, because they are starved for sediment, have incised into this material which covers much of the Piedmont, a phenomenon recognized by *Meade* [1992].

There are several strategies that could be used to improve data quality in catchments where dams trap sediment and influence downstream erosion rates. (i) Sampling could be restricted only to subbasins without dams and if there is a robust slope/erosion rate relationship, such as what we measure here; the erosion rate of dammed basins could be modeled rather than measured. (ii) Recent, but predam, terraces could be sampled downstream of dams [cf., *Cox et al.*, 2009]. (iii) Samples could be collected just before the channel enters the dam impoundment; downstream of the dam, undammed tributaries could be sampled. Measured erosion rates could then be combined mathematically (weighted according to calculated sediment flux, cf. *Granger et al*. [1996] and *Portenga et al*. [2015]) to estimate the erosion rate of the unsampled area below the dam. (iv) On the basis of data presented here, in humid-temperate, moderate relief landscapes, sampling >25 km downstream of dams is likely to minimize their impact on ^{10}Be-based erosion rate estimates. This distance could be established in other geomorphic and climatic settings.

Considering the regional drainage basins of southeastern North America [*Reusser et al*., 2015; *Trimble*, 1977], measured ^{10}Be and model-predicted rates agree better in the six northern basins (Roanoke to the Saluda Rivers) than in the four southernmost basins (Savannah, Oconee, Ocmulgee, and Chattahoochee Rivers; Figure 3). We suspect that dams (as illustrated in Figure 5 for the Chattahoochee River) likely affect the concentration of ^{10}Be measured in outlet samples collected from these four southernmost rivers. We base this conclusion on the deviation between erosion rates measured using ^{10}Be and those estimated by the model (^{10}Be/E_m ratio, Figure 3) and because there do not appear to be pronounced differences in the geology between the northern and southern basins [e.g., *Meade and Trimble*, 1974; *Trimble*, 1977]. Access to the river channels for the four southern basins limited sampling to sites in close proximity to dams (from several km downstream to immediately below dams). In cases, where samples were collected downstream of these large dams, the model erosion rates appear to be better estimators of average upstream erosion than sediment collected below the dam. Using model data rather than the overestimated ^{10}Be erosion rates in these four catchments means that the primary conclusion of *Reusser et al*. [2015], that humans have greatly increased sediment yield above background, is even more strongly supported because background erosion rates in these four rivers are likely lower by a factor of $\sim 2\times$ than the ^{10}Be-based erosion rates reported by *Reusser et al*. [2015].

5. Conclusions

The experimental design that we present here, of sampling undammed tributary basins with mean basin slopes that reflect the distribution of slopes of the larger parent basin, is easily applied elsewhere and can improve the accuracy of regional scale erosion rate estimates in areas where slope and erosion rate are correlated. Using this approach, we calibrate and test a simple regression model that can predict the erosion rate of unsampled basins. Because slope is the dominant control on basin-scale erosion rates in much of the world [*Portenga and Bierman*, 2011], our approach is widely applicable.

Although ^{10}Be has been used previously to estimate erosion rates for large river systems elsewhere around the globe [e.g., *Schaller et al*., 2001], the influence of dams on the concentrations of ^{10}Be measured in fluvial sediment, and in turn the calculated erosion rates, has until now, not been tested. By sampling in river systems where dams are ubiquitous, we provide data, that in concert with model results, indicate that large dams influence ^{10}Be concentration in sediment. Sampling sediment from young terraces can test for and obviate this effect as can sampling as far as possible downstream of dams. In our field area, samples collected >25 km below the nearest dam appear less affected by sediment retention in reservoirs than samples collected closer to dams.

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