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**Using *insitu* 10Be to revisit the “fallacy of stream equilibrium” in large**

**continental drainages**

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(2000 word limit. Includes intro graph and text. Excludes methods, refs and fig caps)

**Introduction paragraph:** (200 word limit)

**Introduction and setting:**

Quantifying natural, or background rates of sediment generation and landscape erosion is imperative to the design and implementation of realistic resource management strategies. In contrast to these background process rates, human activities, such as landclearance for agriculture, can dramatically elevate the pace at which sediments move across hillslopes and into river systems (e.g. Hooke, 1994, 2000). Traditional approaches used to quantify the mass of sediment moving through fluvial systems, such as contemporary sediment yield data, often fall short of capturing natural rates of erosion due to their limited duration and the underlying assumption that such records reflect the undisturbed sediment load of rivers (Meade, 1969; Trimble and Crosson, 2000; Wolman and Miller, 1960; Kirchner et al., 2001).

Trimble’s investigation of erosion along the southern Appalachian Piedmont demonstrated the errors associated with inferring rates of regional denudation from the present mass of sediment carried by large rivers draining continental landmasses (Trimble, 1977). By contrasting the degree of soil truncation resulting from cotton and tobacco production during peak agricultural use around the turn of the century with the sediment yields recorded at the Piedmont-Coastal Plain transition for 10 large-scale (104 – 105 km2) catchments (Figure 1), Trimble clearly established the discordance of hillslope erosion and sediment yields in large, low-gradient river systems. At the time, these findings challenged the long-held assumption that the mass of material eroded from hillslopes was in equilibrium with the mass of sediment carried by rivers, an assumption of landscape steady state (e.g. Judson and Ritter, 1964; Menard, 1961; Dole and Stabler, 1909). While Trimble’s argument was compelling and consistent with those of many others (e.g. Meade, 1969; Anhert, 1970; Walling, 1983) as well as unsettling, at the time there were no techniques capable of reliably quantifying background rates of erosion. In the absence of this information, there was no way to quantify the degree to which human landuse practices during the peak agricultural period increased erosion above natural, background rates.

Here, we present new *in situ* cosmogenic 10Be data (n=24) and use those data to infer natural drainage basin erosion rates from the same low-gradient southern Appalachian Piedmont catchments studied by Trimble (1977). These data allow us to quantify the erosive effects of human landuse practices and compare erosion rates calculated from sediment yields to long-term, background 10Be rates of erosion. The region has a profound and well-documented history of landscape disturbance resulting from land clearance for agriculture over the past several centuries (Dole and Stabler, 1909; Meade, 1969; Wolman, 1967; Costa, 1975; Trimble, 1977; Walter and Merritts, 2008). Consequently, our 10Be result provide a rare opportunity to compare directly background rates of denudation to estimate of human-induced erosion based on contemporary sediment yield data and measurements of upland erosion. These comparisons elucidate both the value of establishing “natural” rates of erosion as well as the potential pit-falls of inferring rates of denudation from contemporary methods of erosion rate measurements in humid, temperate environments such as the Appalachian Piedmont.

Concentrations of *in situ*-produced 10Be measured in fluvial sediments can be used to estimate spatially averaged, millennial-scale rates of sediment production and landscape erosion (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). The concentration of 10Be is homogenized in the upper ~1m of Earth’s surface as hillslope materials are stirred by bioturbation (Jungers, et al., 2009) making erosion rate estimates insensitive to all but the most deeply penetrating forms of mass wasting (Niemi, 2005). Thus, in most instances, erosion rates modeled from 10Be measurements still record the isotopic signature of a longer-term (103 – 106 years) exposure and erosion history than the post-colonial era, and constitute a useful metric for comparison to human-induced rates of erosion (von Blackenburg et al., 2004).

**Study Site:**

The broad low-slope southern Piedmont region of the Appalachian Mountains (Figure 1), with its subdued topography, humid temperate climate, and rich soils was subjected to intensive European agricultural practices beginning in the 1700’s (Trimble, 1974). The headwaters of the most large catchments (10,000’s km2) draining the Piedmont originate inland in the much higher slope Blue Ridge province. Prior to settlement, much of the sediment traveling through the Piedmont drainages originated from infrequent but geomorphically significant mass movements in the upstream regions (e.g. Neary, 1986). Beginning in the 1700’s and peaking in the early 1900’s, extensive clearance for cotton and tobacco production increased dramatically resulting in widespread erosion of Piedmont hillslopes (average erosion depth of ~180 mm; Trimble, 1977) and aggradation of river channels, valley bottoms, and toe slopes (Meade, 1974; Trimble, 1974 and 1977; Costa, 1975; Phillips, 1992).

Hillslope erosion and fluvial sediment transport during the time of intensive Piedmont agriculture were largely disconnected. For example, the degree of soil truncation in the ten studied basins (Trimble, 1975 and 1977) suggested an area-weighted erosion rate of ~950 m/My. In contrast, the area-weighted sediment-yield-derived erosion rates (~53 m/My) at the river outlets reflected a sediment delivery ratio (Walling, 1983) of only ~6 percent (Figure 2). Much of the hillslope soil eroded during the peak agricultural period is stored as alluvial and colluvial deposits along these low-gradient Piedmont river and valley systems (e.g. Meade and Trimble, 1974; Trimble 1977; Walters and Merritts, 2008).

In the decades following the early 1900’s, substantial reductions in the mass of sediment carried by these southern Piedmont rivers were largely the result of Soil Conservation efforts and the construction of hydroelectric dam reservoirs (e.g. Meade and Trimble, 1974). While the sediment yield data used to infer denudation rates here are short in duration (~1 year; Dole, 1909; Dole and Stabler, 1909), they presumably provide a reasonable estimate of the peak rate of sediment output from these ten large drainages during peak agriculture (Trimble, 1977). Deposition of sediment in the Lloyd Shoals Reservoir, completed in 1910 along a tributary of the Ocmulgee River in GA, between 1910 and 1934 infers an erosion rate of ~73 m/My (Meade and Trimble, 1974), in fairly good agreement with the average rate of ~53 m/My for the entire study area in 1909. Between 1967 and 1972, following extensive soil conservation improvements within the watershed, sediment deposition in the reservoir dropped by nearly 7 fold inferring an erosion rate of ~10 m/My. While the findings from this one focused study are encouraging, they tell us little of the larger-scale spatial distribution of the degree to which agricultural practices elevated erosion rates above natural rates.

**Sampling methods: (all lab methods are currently nested in data table footnotes).**

In December 2006 and June 2008, we returned to the ten Southern Piedmont drainages studied by Trimble. We collected and field sieved samples of active channel sediment or recent overbank deposits to a grain size fraction of 1000-250 µg for *in situ* 10Be analysis. To compare human-induced rates of erosion presented by Trimble (1977) to our 10Be background rates, we (1) sampled the outlets of the 10 Piedmont drainages (n=10) for comparison to post-colonial erosion rates and sediment yields, (2) sampled the higher-slope Blue Ridge portions of many of the same basins (n=8) to investigate the influence of slope at large spatial scales, and (3) sampled approximately mid-way down several of the trunk streams (n=6) to determine if sediments mix predictably downstream. Our sampling approach allows for a three-tiered spatial and temporal comparison of erosion along the southern Appalachian Piedmont. Resampling the basin outlets provides insight into the difference between human-induced and background erosion rates through time, while the spatial extent covered by the study area allows us to consider differences in erosion rates from north to south along the range. Sampling down the trunk streams provides us the ability to detect spatial differences in erosion within several of the ten large basins.

**Results discussion and conclusions:**

***Big picture findings:***

Our 10Be analyses indicate that the more steeply sloping Blue Ridge portions of the 8 basins sampled naturally eroded faster than the lower slope Piedmont-dominated outlets of the 10 basins (13.4 vs. 8.8 m/My respectively; Figure 3; Table 1 (supp. mat.)). Samples collected from mid-way down the trunk streams (n=6) suggest that, at large spatial scales (102 to 104 km2), sediments mix predictably as they travel from higher-slope headwater regions to their Piedmont outlets (Figure 3). While Trimble’s work did not parse human-induced rates of either hillslope erosion or sediment-yield-derived erosion from different parts of each basin, our 10Be erosion rates suggest that under pre-colonial conditions, the higher-slope Blue Ridge portions of the landscape naturally erode more quickly over millennial time-scales; a finding suggestive of theories of landscape evolution posited by Hack (e.g. 1960; 1975).

When compared to the data compilation presented in Trimble (1977), the true extent of landscape disturbance during the peak agricultural period becomes evident. Our results suggest that during peak agricultural disturbance in the early 1900’s, aerially averaged rates of hillslope erosion (~950 m/My) exceeded 10Be-derived background erosion rates (~9 m/My) by more than a hundred fold (Figure 2; Table 1 supp. mat.). Even with an aerially averaged sediment delivery ratio of only ~6 percent (Trimble, 1977), streams were yielding nearly 6 times their normal, or “equilibrium” sediment mass due to land clearance (Meade, 1969). These findings unequivocally demonstrate the devastating effects that human landuse practices have had on natural systems of sediment generation and erosion along the southern Appalachian Piedmont; a condition that has been studied extensively world wide, yet rarely quantified (e.g. Hicks, 2000; Gomez, 2003; Kirchner et al., 2001; Syvitski et al., 2005).

***Spatial and temporal patterning of erosion:***

Taken as a whole, the three datasets show a remarkably similar pattern between background and human-induced erosion rates across the nearly 100,000 km2 study area (Figure 2). We can draw several first-order conclusions about erosion through time for all 10 basins; (1) during peak agriculture, human-induced landclearance effectively elevated rates of hillslope erosion by more than 100 fold, (2) the rivers of the southern Piedmont were unable to transport the entire load of sediment fed to them from eroding hillsides. When compared to our aerially averaged 10Be background erosion rates (~9 m/My), sediment-yield derived erosion rates (~53 m/My) suggest that landclearance caused only a 6 fold increase in erosion. Clearly a large proportion of the eroded material remained on the landscape. While the exact differences between peak agricultural hillslope and sediment load inferred erosion rates, and our 10Be background erosion rates vary to some degree from the north to the south, the similarity in pattern from basin to basin provides strong evidence that the effects of human landuse practices were felt system wide across the entire southern Piedmont.

***Sources and sinks:***

With the discrepancy between rates of hillslope and sediment-yield-derived rates of erosion suggesting a sediment delivery ratio (Walling, 1983) of only ~6 percent, much of the sediment loosed during peak agriculture went into to storage across the landscape (Trimble, 1977; Meade, 1982). Presumably, over time, these legacy sediments relict of past erosional disturbances will work their way out of fluvial systems draining the Piedmont (e.g. Walter and Merritts, 2008). As a consequence, the load of sediment carried by many tributary and trunk streams will remain elevated (Phillips, 2003). Further complicating these systems lags, most piedmont drainages harbor any number of hydroelectric dams with sediment trap efficiencies of up to 95 percent (Brune, 1953). Thick sediment deposits within the dam reservoirs will likely remain trapped on the landscape for the lifespan of the hydroelectric stations (Trimble, 1977).

***Utility of 10Be for land management:***

The greatest utility of 10Be background erosion rates is that they provide the context from which to assess nearly all other measures of erosion germane to the human timescale. Understanding what constitutes “natural” rates of erosion in any region is prerequisite to designing realistic landscape management strategies. In the case of the southern Appalachian Piedmont, Trimble’s work and that of others clearly demonstrated that in the face of human-induced landscape disturbance, hillslope erosion is dislocated from the mass of sediment carried by fluvial systems. While these findings established the dangers inherent in inferring erosion rates from sediment yields, they were incapable of providing any information concerning background erosion rates or the ability to quantify to degree of landscape disturbance.

Due to effective soil conservation measures across the southern Appalachian Piedmont in the mid 1900’s, sediment yields in many tributary streams have indeed been substantially reduced (Meade and Trimble, 1974). The 7 fold decrease in sediment deposition rates in the Lloyd Shoals Reservoir following soil conservation improvements discussed above demonstrates the importance and effectiveness of landscape management. However, prior to our work with 10Be, no method was capable of determining just how effective. While the scales are vastly different, work from this reservoir study infer an erosion rate of ~10 m/My, in good agreement with our average rate of background erosion of ~9 m/My across the entire study region.

Due to the large size of the drainage basins presented in this study, our data constitute a wide-angle view of the degree to which peak agriculture elevated erosion rates above background. 10Be erosion rate studies can also be conducted at smaller spatial scales to investigate the variability in background erosion across a region for the purpose of generating targeted management strategies, or to inform TMDL levels in managed watersheds (e.g. Mukundan, 2011). NEED ONE FINAL WRAP UP SENTENCE…OR A REDO OF THIS GRAPH.

**References** – (I’ll add these once the MS is cleaned up to avoid Endnote hissy fits)

**Acknowledgements**

-Matt Jungers, William Hackett, Jane Duxbury for field assistance.

-LLNL for AMS measurement.

-Fundings…PAUL, hate to admit this, but can’t remember where the funding for the SAPS samples came from. USGS through Milan? NSF?

**Author contributions:**

L.J.R. and P.R.B. instigated and directed this research. L.J.R. designed the field sampling strategy. L.J.R. and field assistants conducted fieldwork for the project. L.J.R and P.R.B. carried out all sample processing at the UVM. D.R. conducted all AMS measurements at LLNL. All authors contributed to manuscript preparation.

**ADDITIONAL INFORMATION:**

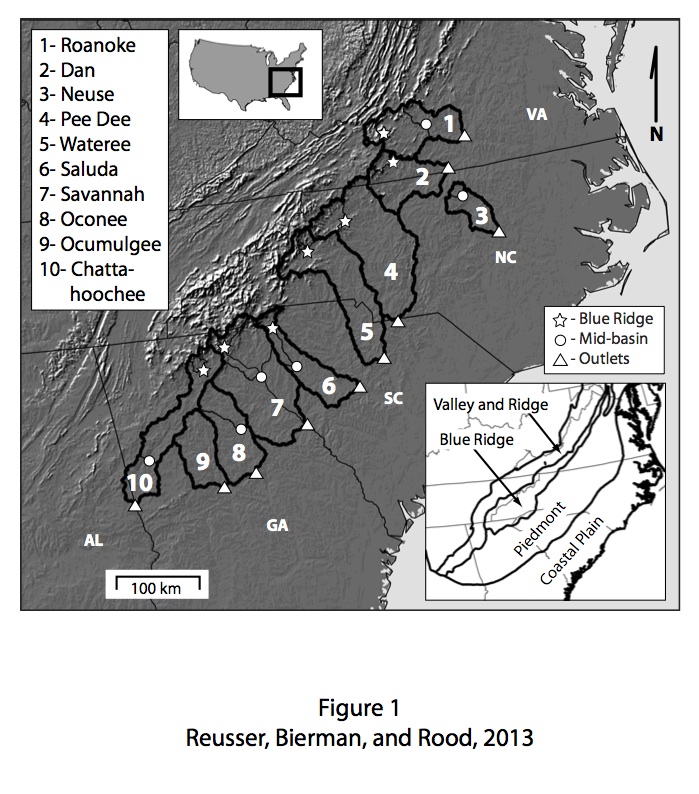
-Supplemental Material will include Table 1, and additional text if required.

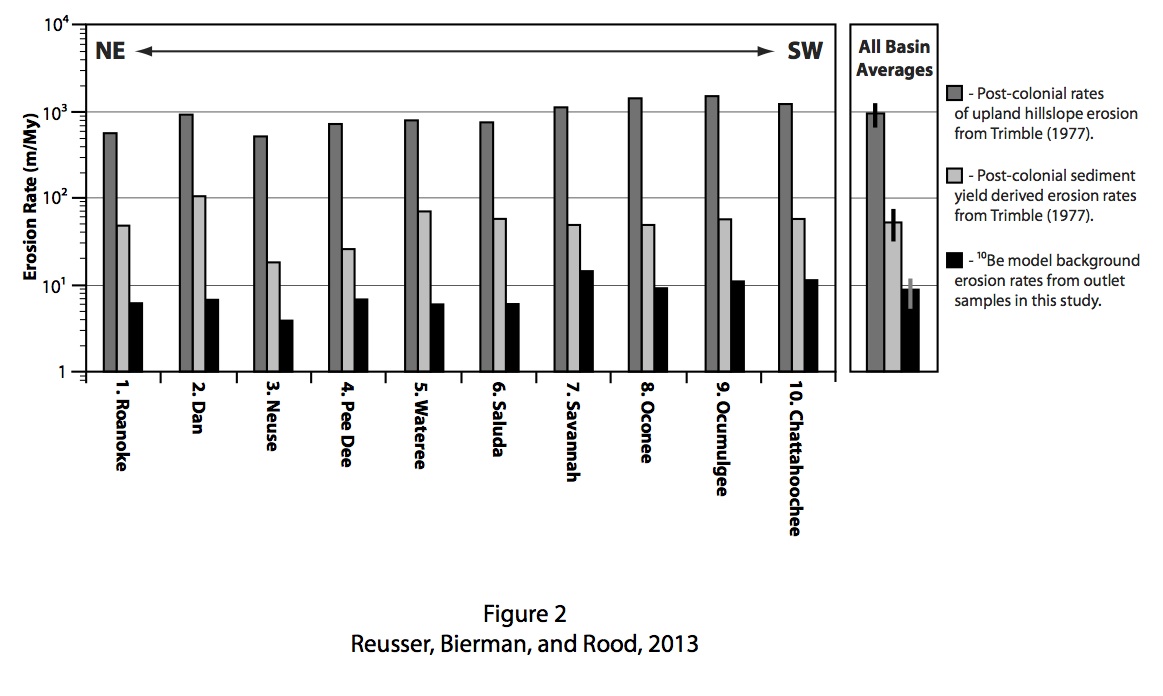
**Figure Captions:**

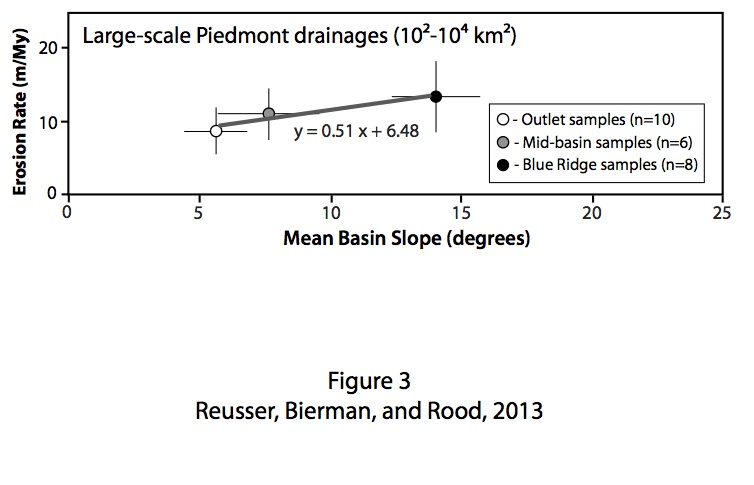
**Figure 1 -** Location map of the Southern Appalachian Piedmont field area along the southeastern seaboard of the United States. River basins 1 through 10 are the same basins studied and presented in Trimble (1977). “Blue Ridge,” “Mid-basin,” and “Outlet” denote the locations of *insitu* 10Be sample sites within each large-scale catchment. Figure modified from Figure 1 in Trimble (1977).

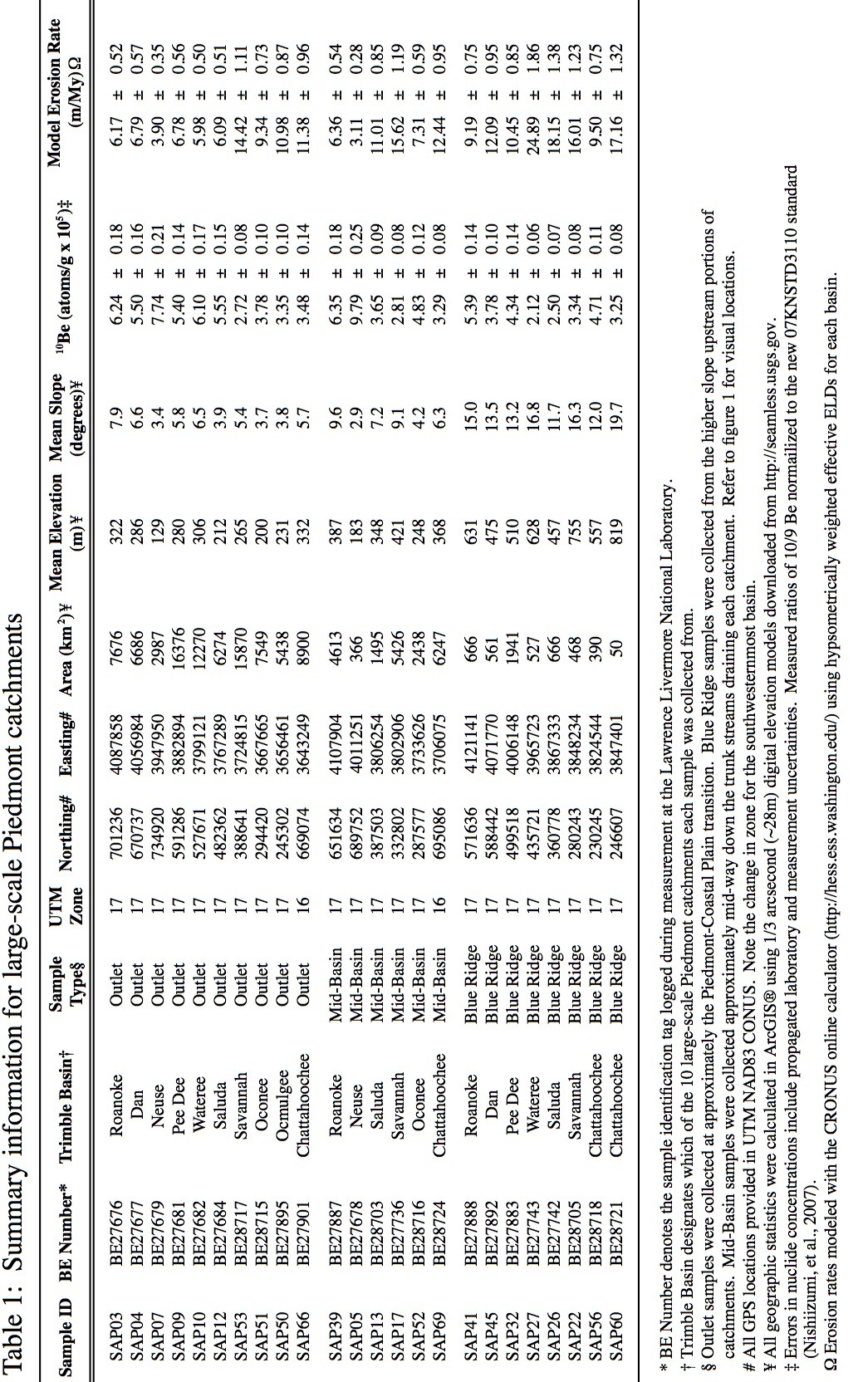
**Figure 2 –** Summary of all erosion rates for large-scale catchments presented and discussed in this paper. Refer to figure 1 for the location of each of the ten catchments. Dark and light grey bars are from data presented in Trimble (1977). Black bars represent *insitu* 10Be background erosion rate estimates.

**Figure 2 –** Mean basin slope – erosion rate relationships for all *insitu* 10Be samples presented in this study.

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