Quantifying Human Impacts on Natural Rates Of Erosion Along Continental Margins

A dissertation presented
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Landslides, Waipaoa Basin, NZ after cyclone Bola, 1988
Seminar outline

- **Overview of Research**
  - Landscape erosion – natural and human-induced
  - Methods of measurement
  - Background rates with $^{10}$Be vs. Short-term rates
  - Introduction to Study Sites

- **Primary Objectives**

- **In situ** and meteoric $^{10}$Be systematics

- Background erosion and erosion prediction along the southern Appalachian Piedmont, Atlantic Passive Margin

- Sediment mixing and background erosion in the active and non-uniformly eroding Waipaoa Basin, North Island, New Zealand

- **Summary and conclusions**
Why study erosion?

- Human activities elevate rates of erosion and change how sediment moves along hillslopes and in river channels.

- Can cause deposition on flood plains and in estuaries and bays and cause increased flooding.

- These changes have very real, and very costly repercussions.

- Need to know BACKGROUND rates of sediment generation and erosion for effective management strategies!

Important Questions to ask:

- How do you measure erosion?

- What are the best ways to compare natural and human-induced rates of erosion?
### Methods of measuring erosion:

**Short-term:** (years to decades)
- Reservoir Infilling Rates
- Water body infilling rates
- Sediment Yields (Delivery) from Rivers

**Intermediate Time Frame:** (Typically thousands to tens of thousands)
- **Cosmogenic Isotopes such as** $^{10}\text{Be}$
  - Erosion at discrete points
  - Spatially and Temporally Averaged Drainage Basin-Scale Erosion Rates
- Good for comparing natural and human-induced rates

**Long-term:** (millions to hundreds of millions)
- Thermochronometry
  - Fission Track
  - $(U-\text{Th})/\text{He}$
- Offshore Sedimentation Rates

**Limitations:**
- Very short integration periods (episodic delivery)
- Extreme sensitivity to landuse history

**Limitations:**
- Long integration time.
- Records reflect periods of vastly different climatic and potentially tectonic conditions
Study regions:

- Broad geographic regions along several well-characterized continental margins
- Widely **differing** tectonic and climate gradients, but share **similar** landuse histories (agricultural)

**Southern Appalachian Piedmont**
- Passive Margin Environment
- Intense agricultural disturbance between 1700 and ~1920

**Waipaoa River Basin**
- North Island, NZ
- Active subduction margin
- Widespread agricultural land-clearance. Modern afforestation efforts.

~9000 miles
Primary Objectives of Research:

1. **Comparison of natural long-term \textit{(in situ} $^{10}\text{Be})$, and modern-day, human-induced (sediment yield derived) rates of erosion.**
   - Potential implications for resource management.

2. **Investigate the sourcing and mixing of sediment in disturbed landscapes with meteoric $^{10}\text{Be}$.**
   - Primarily in the Waipaoa River Basin, NZ where quartz is scarce.
   - Apportion the relative contribution of sediment from different regions across a landscape.

1. **Explore relationships between tectonics, climate, and land-use history with one of the largest coherent $^{10}\text{Be}$ datasets collected to date.**
   - Provide $^{10}\text{Be}$ erosion rates in previously untestable environments
   - Compare and contrast $^{10}\text{Be}$ findings to other measures of landscape change.
   - Further develop relationships between erosion and physical landscape characteristics.
Production and accumulation of

• *In situ* $^{10}\text{Be}$
• Meteoric $^{10}\text{Be}$
**In situ production of $^{10}$Be:**

- Produced in upper several meters of rocks and sediment exposed at Earth’s Surface.

- Production rate: $\sim 5.2$ atoms per gram of quartz per year - measurable with AMS.

- Half-life of $\sim 1.36$ millions years – residence time of near surface materials much shorter meaning $^{10}$Be behaves as a stable nuclide over period of measurement.

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The concentration of cosmogenic nuclides produced in soil is often homogeneous over the top-most meter or so of soil. This homogeneity is the result of effective soil stirring by plants and animals (bioturbation).
**Accumulation of meteoric $^{10}$Be in soils:**

- **Produced in the** atmosphere **by the same processes as** in situ $^{10}$Be

- **Delivered** to soils across landscapes in rain, and to a lesser extent in NZ in dust.

- Accumulates over time in hillslope materials that eventually make their way to river channels.

- Accumulation rate: $\sim 1.7 \times 10^5$ atoms per cm$^2$ annually – easily measurable with AMS.

- Half-life of $\sim 1.38$ millions years – residence time of near surface materials much shorter meaning $^{10}$Be behaves as a stable nuclide over period of measurement.
Drainage basin-scale erosion rates with \textit{in situ} $^{10}$Be
And sediment sourcing meteoric $^{10}$Be:

\textbf{Production at Surface:}

\begin{itemize}
  \item Exponential decay with depth
  \item Production limited to upper several meters - \textit{Isolates near-surface process rates}
  \item Thorough mixing homogenizes $^{10}$Be inventory - relatively insensitive to Human Landuse Practices
\end{itemize}

\textbf{Steadily Eroding Landscape:}

\textbf{Sediment Sample:}

\begin{itemize}
  \item Rivers Mix millions Of sediment grains
  \item Each grain has unique history of Exhumation Erosion and Transportation To sample site
  \item Represents the spatially averaged history of erosion within a drainage basin
\end{itemize}
Erosion Along Continental Margins:


2. Waipaoa River Basin along the tectonically active eastern margin of New Zealand’s North Island.
1. Southern Appalachian Piedmont, USA

Relatively stable environment:
- Comparatively uniform erosion
- Long history of cosmogenic isotope study so we have a good foundation to start from.
Stretches more than 2500 km from Newfoundland, CAN to Alabama, USA

Largely stable environments. Tectonically quiescent for >200 My
Uplift driven by erosion - isostacy

Inspired more than a century of research into:
• The growth and decay of landscapes.
• The persistence of topography.
• The erosional consequences of human-landscape interactions.
• Modern different than background
Southern Appalachian Piedmont

Broad, low-relief surface. Drains east to the Atlantic Ocean

Rich Soils, humid climate, long growing season and subdued topography.

Intensive agriculture beginning in 1700’s through 1920’s. At peak, virtually entire piedmont cultivated for tobacco and cotton production.

Severe hillslope erosion and channel aggradation.
Area-averaged upland erosion rate
\(~950 \text{ m/My}\)

Area-averaged erosion rates inferred from sediment yield data
\(50 \text{ m/My}\)

Area-averaged delivery ratio
\(~5\%\)

Transport Limited System carrying capacity of streams

Implication: Sediment yield data are "dubious Indicators" of background or human-induced erosion rates in large humid region catchments
First testable hypothesis with $^{10}\text{Be}$:
Frist testable hypothesis with *in situ* $^{10}$Be:

- **Background** $^{10}$Be erosion rates from *large* Piedmont basins are lower than human-induced hillslope or sediment yield rates.
Sampling strategies – large basins

- Large Trimble Catchments
Conceptual models of long- vs. short-term erosion:

- Rates of hillslope erosion integrated from 1700 - ~1950.
  - Sediment yield inferred rates ~1 year (1909)

- \textit{In situ} \(^{10}\)Be rates provide much longer-term averaged background rates.
In situ $^{10}$Be results from this study compared to hillslope erosion rate and sediment yield-derived erosion rates from Trimble, (1977).

Our in situ $^{10}$Be background erosion rates
~9 m/My

Naturally, the Piedmont erodes >100 times slower than during peak agriculture
Where is all the sediment now?

Recovery from past landuse disturbances:

A: Measurement integration times

B: Land clearance through time

F: Storage of legacy sediment on landscape

Assumed limited storage of sediment across landscape prior to agricultural disturbance.
Testable hypotheses with $^{10}\text{Be}$ for small basins:

- Background rates of erosion in small sub-basins are related to their average basin slopes.

- The relationship between average basin slope and background *in situ* $^{10}\text{Be}$ erosion rates can be used to predict rates in drainage basins *without* $^{10}\text{Be}$ data.
Potential controlling variables of erosion
Rate tested in higher slope Appalachian terrain:
- Physiographic province
- Mean elevation
- Land cover and land use
- Mean basin slope

Only significant variable appears to be SLOPE

This Study:
Can the lower slope piedmont help us understand better erosion of the Appalachians?

~2° to ~20° degrees
Rationales' for testing slope-dependence

At small-basin scales:

- Represent the **full range of slope** conditions across the southern Piedmont.
- Generate a **statistically robust** relationship representative of the slope-erosion rate relationship at a **landscape-scale**.
- Avoid the influence of **dams** along rivers draining very large drainage basins.
Sampling strategies - small slope basins

[Map showing different regions with sub-basins highlighted in varying colors, each representing a mean slope degree range: 0 to 3, 3 to 3.5, 3.5 to 4.3, 4.3 to 5.2, 5.2 to 8, 8 to 25 degrees.]
Slope distribution of potential sample basins

![Graph showing the distribution of slope divisions with YELLOWS indicating desired slopes, REDS indicating selected basins, and GREEN indicating alternate basins. The x-axis represents mean slope (deg) ranging from 0.0 to 25.0, and the y-axis represents basin count. The graph also shows cumulative probability with values ranging from 0.0 to 1.0.]
What we find for the 37 small slope-test basins:

- Roanoke, Pee Dee, Savannah, and Chatahoochee basins
- Represent the NE to SW range across the entire study area

~3050 potential sample basins ~20 km² in size
What we find for the 37 small slope-test basins:

- **Slope division:**
  \[ y = 0.97x + 1.04 \]
  \[ R^2 = 0.88 \]
  \[ n = 10 \]

- **Individual samples:**
  \[ y = 0.98x + 1.05 \]
  \[ R^2 = 0.57 \]
  \[ n = 37 \]
Also generated a stepwise multiple regression model using these 37 small basin-test results:

Significant variables included in the model:

• Average basin elevation
  • Basin relief
• Average basin slope
  • MAP
  • MAT

Adj. $R^2 = 0.63$
$p<0.0001$
Predicted small-basin erosion rates made with both models:

Predicted erosion rates for all 5100 small basins within the 10 large Piedmont drainage basins.
Scaling up: Predicting large basin erosion rates from models:

Using lots of erosion rate predictions for small basins made with both models...

To predict an area-weighted amalgamated erosion for a large basin ($E_{ps}$ and $E_{pm}$).
Does it work?

Multiple regression model tracks the trends of all variables included well.

Amalgamated erosion rate predictions made with both models match each other well.

Implication:

Average basin slope alone is a powerful and robust predictor of erosion rates.
How do predictions compare to $^{10}$Be data for outlets?

Predicted and measured rates agree well in the northeastern basins.

But not so well for the southwestern basins.
Potential explanation for N vs. S differences:

No discernable differences in geology, climate, or landuse history, BUT...
Damn dams – (dam-pair sampling):

I collected samples up and downstream of dams
All southern rivers sampled below dams

Implication:
Samples collected downstream may reflect locally sourced material
Thus
Don’t represent basin-scale erosion

Dams impede flow of water AND river sediment
Never before tested assumption:

Very real implication for interpreting drainage basin background erosion rates made with \textit{in situ} $^{10}\text{Be}$ in large river basins.

Our \textit{small-basin in situ} $^{10}\text{Be}$-derived amalgamated erosion rates may be more reliable estimates of background erosion rates.
Scalability of small-basin slope-based model:

Amalgamated small basin approach

Whole-basin average slope

Simple slope model is fully scalable

Implication:
Potentially, we can predict a background Erosion rate at any point along a river network.
Summary of finding from the southern Piedmont:

- Human landuse practices on the Piedmont increased rates of hillslope erosion by more than 100-fold above background.

- Much of the sediment is still stored on the landscape and trapped in dam reservoirs.

- We can predict background erosion rates with simple statistical models.

- The influence of dams must be considered with using \textit{in situ} $^{10}$Be to infer background erosion in LARGE basins.
Real-world implications:

- Using the simple, and scalable average basin slope – based model we can predict erosion rates and mass fluxes of sediment at any point along a river network on the southern Piedmont.

- Could be used to establish realistic TMDL levels of sediment and associated pollutants.
Let's transition to an utterly different environment.
2. Waipaoa Basin, North Island, NZ

Very different from Appalachians:
- Episodic and non-uniform erosion
- Challenging environment for application of cosmogenic techniques.
Erosion in the Waipaoa Basin:

**Tectonically-active - Subduction Margin:**

- **1-10 mm/yr**
- **Area:**
  - **2200 km²**
- **Sediment yield:**
  - ~15 Million tons per year
- **Inferred short-term rate:**
  - **3 km/My**

One of the fastest on earth

**Appalachian Mtns:**

- **20 m/My**
- More than 100 times faster
Erosion in the Waipaoa Basin:

- Waipaoa Basin displays some of the most dramatic erosional features found anywhere in the world.
- Has attracted researchers from around the globe over the past several decades.
- Complex story of natural erodibility, extensive landclearance for agriculture, and subsequent reforestation efforts.

Natural Causes for Erosion:

**Temperate Maritime Climate:**
- Highly seasonal precipitation (1.3 to 2.5 m/yr)
- Periodic cyclonic activity (ENSO related)
- Frequent intense rainfall events
  - (29% chance every year, 99% every ten)
- Hydrologically triggered mass movements (landslides)
Region Primed For Erosion:

No More Trees!
Deforestation = massive erosion in the Waipaoa

- Mauri settlement ~700 yr BP.
- Commenced in early 1800’s with European settlement of NZ
- By 1880, downstream portions of basin cleared
- By 1920, upstream portions cleared
- Today, only 3% of basin remains covered in native vegetation
Variable response to land clearance:

Severe Gullying: weak rocks, faulted, fractured

Widespread Landsliding:

Channel Aggradation: deposition of upstream sediment

Only remaining Native Vegetation
Native Vegetation: what we think the Waipaoa used to look like
Native Vegetation:
what we think the Waipaoa used to look like
By 1910, the erosional effects of clearance were widespread.

Pervasive landsliding
- Hydrologically triggered
- Extreme rainfall events
- No trees to anchor hillslopes
By 1910, the erosional effects of clearance were widespread

- Rapidly eroding weak terrain
- Constant erosion and sedimentation

Rapidly eroding weak terrain
Constant erosion and sedimentation

River Channel
Gully
Fan
Temporary storage
Truck
Today, gully-derived sediment overwhelms material in the Waipaoa mainstem channel
Channel aggradation 1994
Rip Bridge
Channel aggradation late nineties
Rip Bridge
Channel aggradation 2002
No more bridge
Continual flood plain deposition of sediment increased rates of flooding in regions downstream (Poverty Bay Flats):
Testable hypothesis with meteoric $^{10}$Be:

- Concentrations of meteoric $^{10}$Be can be used to track the sourcing and mixing of sediment in the Waipaoa River Basin.
  
  - Isotopically distinct signatures of sediment from gullies vs. shallow landsliding dominated tributary basins.

- These isotopic signatures can be used to apportion the relative contribution of sediment from different parts of the Waipaoa Basin.
Accumulation of meteoric $^{10}\text{Be}$ in soils:

- Produced in the atmosphere by the same processes as in situ $^{10}\text{Be}$
- Delivered to soils across landscapes in rain, and to a lesser extent in NZ in dust.
- Accumulates over time in hillslope materials that eventually make their way to river channels.
- Accumulation rate: $\sim 1.7 \times 10^5$ atoms per cm$^2$ annually – easily measurable with AMS.
- Half-life of $\sim 1.38$ millions years – residence time of near surface materials much shorter meaning $^{10}\text{Be}$ behaves as a stable nuclide over period of measurement.
Chasing sediment in the Waipaoa Basin:

- Continuous and large
- Episodic and less
- Mix of both

**Map of Waipaoa River Basin**
- Mainstem Sample
- Tributary Sample
- Te Weraroa Stream (Tarndale Slip)
- Gully Prone Terrain
- Sample Numbers (10 = WA10met)
- Soil Pit Location

**Waipaoa River Basin**
North Island, NZ

Modern Sediment Yield:
\(~ 15 \text{ Mt yr}^{-1}\)  
\(~ 6800 \text{ t km}^{-2}\text{ yr}^{-1}\)  
(Hicks, et al., 2000)
Isotopic signatures of sediment:
Spatial distribution of meteoric $^{10}$Be concentrations:

- **Raw averages of data**
- **Vast majority of sediment in mainstem channel comes from gullies**

### A: within Waipaoa Basin

- **Western tributary samples (Waikohu Basin):** $\sim 2 \times 10^7$ at/g
- **Eastern tributary samples (Waihora and Totangi Basins):** $\sim 2.7 \times 10^7$ at/g
- **Southwestern tributary samples (Te Arai Basin):** $\sim 2.1 \times 10^7$ at/g
- **Headwater tributary samples (Te Weraroa, Mongarongo, Waimatau and Tikihore Basins):** $\sim 3 \times 10^6$ at/g
- **Mainstem and outlet samples:** $\sim 3.3 \times 10^6$ at/g
Mixing of sediment with different isotopic signatures:

Tarndale gully is the starting isotopic signature

Tarndale signal is augmented with higher concentration sediment from incoming tributaries.
Mixing model – apportioning relative contribution:

\[ [N_{up}] [m_{up}] + [N_{trib}] [m_{trib}] = [N_{down}] [m_{up} + m_{trib}] \]

and

\[ [m_{up}] + [m_{trib}] = 100 \% \]

Areas of the headwaters and the eastern and western tribs. combined are roughly equal

Gullied headwaters produce sediment at a rate

20 times

that of the east and west
Testable hypotheses with meteoric $^{10}\text{Be}$:

- We can track temporal changes in meteoric $^{10}\text{Be}$ concentration by resampling the same sites at different times.

- We can infer how source area change through time, and at different flow conditions.

  1. May 2004 – fluvial sediment
  3. August 2008 – fluvial sediment
  4. August 2008 – overbank flood deposit (event deposit)
Temporal variable in meteoric $^{10}$Be:

Not exactly sure why concentration are increasing through time in fluvial sediments?

Flood deposit likely reflects episodic input of shallow sediment with higher concentration landslide sediment from 7/31/2008 event.
Don’t see distinct temporal variability in the headwaters or gully dominate points along the mainstem channel.

Gullies continuously feed deeply-sourced, low concentration sediment to channels. These regions aren’t as sensitive to stochastic weather events like landslide-dominated basins.
Testable hypothesis with *in situ* $^{10}$Be:

- From a limited number of samples that actually contained quartz (18 out of 105) we can generate a reasonable estimate of background erosion in the Waipaoa Basin.
In situ and meteoric $^{10}$Be comparison samples:

A: In situ $^{10}$Be

Quartz only:
Only reflects the exposure
History of lithologies
That contain quartz.

B: Meteoric $^{10}$Be

Bulk sample:
theoretically reflects
entire drainage basin.
Reasonable estimate of background erosion:

Background rate $\sim 250$ m/My ($\text{in situ}^{10}\text{Be}$)

Just about **100 times slower** than contemporary sediment-yield-inferred erosion rate reflecting agricultural disturbance
Brings us full circle back to the Appalachians:

- Tectonically active
- Non-uniform erosion
- Event driven (cyclones)
- Intense human disturbance
  - Human ~100 >
  Background rates

-Largely passive
- Relatively uniform erosion
- Humid temperate climate.
  - Intense human disturbance
  - Human ~100 >
  Background rates
For the southern Appalachian Piedmont:

1. Background in situ 10Be rates are ~100 times slower than agricultural rates of hillslope erosion.

2. At peak disturbance, streams were incapable of transporting the majority of sediment fed to them. Even today, most of it is stored across the landscape in valley bottoms, toe-slopes and impounded in dam reservoirs.

3. Generated a statistically robust dataset and predictive model from the slope-erosion rate relationship for small-basins.

4. Model is scalable and can be used to predict erosion at any point along a river network in the southern Piedmont.
For the Waipaoa River Basin, NZ:

1. Proof of concept: Meteoric 10Be can be used to track fluvial sand within a tectonically active river network, severely disturbed by past human landuse practices.

2. Simple mixing models allow us to assess the relative contribution of sediment from different regions within a watershed.

3. Temporal replicates demonstrate how source areas, and erosion style change through time and as a function of flow conditions.

4. As for the southern Piedmont, human landuse practices appear to have increased inferred erosion rates by 100 times above background.
For the southern Appalachian Piedmont:

- With the scalable slope-based model, we can predict a background erosion rate at any point along the southern Piedmont.
  - These predictions could be used to inform TMDL levels for sediment and associated pollutants in waterways and water bodies.

For the Waipaoa River basin, New Zealand:

- Can apportion the relative contribution of sediment from different tributary basins within a watershed using a simple mixing model.
  - Gully-sourced sediment in the Waipaoa systems is visibly obvious, but a similar approach could be used in other, less disturbed basins where the contribution from various regions is less obvious.
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  Geology faculty

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And for tallying the number of Waffle Houses by region
And of course Paul Bierman for providing endless help and guidance over many many years!!
Questions?
In situ production of $^{10}\text{Be}$:

- Produced in upper several meters of rocks and sediment exposed at Earth’s Surface.

- Production rate: 5.2 atoms per gram of quartz per year - measurable with AMS

- Half-life of 1.5 millions years - residence time of near surface materials much shorter meaning $^{10}\text{Be}$ behaves as a stable nuclide over period of measurement.
Equilibrium Stream Concept

Primary motivation for this project:

“There is a balance between the material transported by the stream and that produced on the hillslopes” (Judson and Ritter, 1964)

- Steady-state between hillslope erosion and sediment leaving a catchment
- Essential requirement when modeling denudation rates from sediment yields

SELDOM TRUE TODAY...Especially when humans get involved!

Stream “Un” Equilibrium Along the Southern Piedmont
(Trimble, 1977)

- Ten large catchments draining the majority of the southern Piedmont (2,000 - 20,000 km²)
  - Sediment yield data reflecting peak agricultural disturbance.
  - Sediment yield vs. hillslope erosion vs. rates of denudation.
    - Does Stream Equilibrium hold??
Background \(^{10}\text{Be}\) vs. short-term (sed. yields)

**Drainage basin-scale Erosion Rates**

**Sediment Yield Derived Rates of Erosion:**
- Typically short - decades
- Sensitive to land-use practices - good for human-induced modern rate
- Sensitive to sediment delivery regime - episodic delivery

**Background Erosion Rates Estimated with \(^{10}\text{Be}\):**
- Integrates over \(10^4\) to \(10^5\) years
- Insensitive to land-use disturbances
- Episodic sediment delivery reflected in \(^{10}\text{Be}\) Rates

**Sri Lanka:**
- Short-term >100 \(X\) background
- Pervasive deforestation
- Tropical, monsoon dominated climate

(Hewawasam, etal, 2003)

**Idaho Mountain Streams:**
- Background \(~20\ \text{X}\) short-term
- Large infrequent events missing from record.

(Kirchner, etal, 2001)
A: Measurement integration times

Hillslope erosion rate integration time presented in this study; data sourced from Trimble (1977) (up to 1950)

Sediment yield-derived erosion rate integration time presented in this study; data sourced from Trimble (1977) (~1 year)

B: Land clearance through time

Long-term background conditions

~10 ka

Time Line

Assumed variability in natural long-term landcover conditions.

Assumed variability in hillslope erosion rates. Over long-periods, mass flux off hillslopes in approximate equilibrium with mass of sediment carried by streams.

Assumed variability in hillslope erosion rates. Over long-periods, mass flux off hillslopes in approximate equilibrium with mass of sediment carried by streams.

Assumed limited storage of sediment across landscape prior to agricultural disturbance.

C: Landcover conditions

Pervasive agricultural land clearance.

Increased soil conservation.

Maximum hillslope erosion.

Decreased hillslope erosion.

Maximum load limited by capacity of streams.

Reduced sediment loads.

D: Hillslope conditions

Sediment loads.

Vast quantities of sediment stored in valley bottoms.

Some legacy sediment now stored in reservoirs.

E: Sediment loads carried by streams

F: Storage of legacy sediment on landscape
The bar chart illustrates the rates of upland hillside erosion in various drainage basins. The rates are quantified in meters per year (m/My), showing a range from 1 to 10^4. The chart is oriented with NE on the left and SW on the right, indicating a directional variation across the drainage basins.

The data is categorized by drainage basins, each labeled from 1 to 10:
1. Roanoke
2. Dan
3. Neuse
4. Pee Dee
5. Wateree
6. Saluda
7. Savannah
8. Oconee
9. Ocmulgee
10. Chattahoochee

The chart includes different bars representing:
- Post-colonial rates of upland hillside erosion from Trimble (1977).
- Post-colonial sediment yield rates from Trimble (1977).
- "^10Be model background erosion rates from outlet samples in this study."
Amalgamated predictions ($E_{pm}$ vs. $E_{pnm}$) vs. $^{10}$Be rates for large basins

**A**

$E_{pm} = 0.5 (^{10}$Be$) + 3.9$

$R^2 = 0.35$

$E_{pnm} = 0.5 (^{10}$Be$) + 3.7$

$R^2 = 0.39$

- $E_{pm}$ vs. $^{10}$Be
- $E_{pnm}$ vs. $^{10}$Be

Amalgamated predictions ($E_{ps}$ vs. $E_{pnm}$) for large basins

**B**

$y = 1.0x + 0.4$

$R^2 = 0.89$

- Blue Ridge samples
- Mid-basin samples
- Outlet samples
Figure A: 

- 10Be basin-scale erosion rates
- Amalgamated $E_{ps}$ erosion rate predictions
- Amalgamated $E_{pm}$ erosion rate predictions

Figure B: 

- Basin relief (m)
- Average slope (degrees)
- MAP (mm)
- MAT (°C)

Drainage basins:
1. Roanoke
2. Dan
3. Neuse
4. Pee Dee
5. Waccamaw
6. Saluda
7. Savannah
8. Oconee
9. Ocmulgee
10. Chattahoochee

Chattahoochee outlet

Pee Dee outlet

Downstream of dam

Uphill of dam
Slope model ($E_{pm}$) predicted erosion rates

A

$y = 0.99x - 0.02$

$R^2 = 0.999$

Multiple regression model ($E_{pm}$) predicted erosion rates

B

Percent difference between amalgamated and whole-basin predictions (relative to amalgamated) as a function of basin area

C

$R^2 = 0.71$
Multiple regression model erosion rate predictions for all 5104 sub-basin along the southern Appalachain Piedmont displayed over the 37 sample used to generate the slope model.

- **Slope division:** $y = 0.97x + 1.04 \quad R^2 = 0.88 \quad n = 10$
- **Individual samples:** $y = 0.98x + 1.05 \quad R^2 = 0.57 \quad n = 37$
- **Multiple regression model predictions:** $y = 0.99x + 1.04 \quad R^2 = 0.88 \quad n = 5104$
Percent difference between erosion rates predicted with the simple slope model and the multiple regression model for all sub-basins along the southern Appalachian Piedmont.
Meteoric $^{10}\text{Be}$ in hillslope materials

**Figure 10:**

**Key:**
- Depth profile samples from a relatively stable "nose" on the Waimata hillslope.
- Individual soil horizon samples collected across the entire Waimata hillslope from more actively eroding hillslope material.
- Fluvial samples in close proximity to the Waimata hillslope collected to investigate the potential source depth of material carried by streams.
In situ $^{10}$Be laboratory replicates

~8% reproducibility (excluding wa54)

At AMS detection limit

Figure 2:
Figure 3:

Meteoric $^{10}$Be laboratory replicates by region

A: within Waipaoa Basin

- Forested (native vegetation)
- Heavily gullied headwater basin
- More stable eastern and western tributaries
- Outlet

B: Basins to the N and S

- Independently prepared and measured replicate samples
- Average of meteoric $^{10}$Be laboratory replicates

~6% reproducibility (excluding outlet wa12)
**Figure 6:**

**A**

In situ $^{10}$Be temporal variance

- 31% (eastern Waikura Basin outlet)
- 44% (Waipaoa basin outlet)

**B**

Inferred erosion rate (m/My)

- -31% (wa02/23)
- -44% (wa12/24)

- Collected on 5/20/2004
- Collected on 3/14/2005
Meteoric $^{10}\text{Be}$ temporal variance along mainstem Waipaoa River

**Key:**
- $\blacklozenge$ May 2004 - river sediment samples
- $\blacklozenge$ March 2005 - river sediment samples
- $\blacklozenge$ August 2008 - river sediment samples
- $\blacklozenge$ August 2008 - overbank flood deposits

**Equation:**
$$y = 2.0E+6^{0.0005(10)\text{Be}}$$
$$R^2 = 0.78$$

Figure 9:
In situ - meteoric $^{10}\text{Be}$ comparison samples from the Waipaoa Basin

Relative enhancement of meteoric $^{10}\text{Be}$

- Waterworks Bush (never been cleared)
- Te Arai outlet
- Eastern and western tributaries
- Heavily gullied headwaters
- Mainstem and outlets

Relative enhancement of in situ $^{10}\text{Be}$

Figure 12:
Erosion rate proxies for the Waipaoa Basin

Key:
- **Background rate** - Sediment modeling (Kettner, et al., 2007)
- **Post Polynesian arrival (~700 ybp)** - Sediment modeling (Kettner, et al., 2007)
- **Post European arrival (~1820)** - Sediment modeling (Kettner, et al., 2007)
- **Modern rates inferred from sediment yields** - (Hicks, et al., 2000)
- **In situ $^{10}$Be inferred background rate** - This study

In situ $^{10}$Be data suggest a background erosion rate of ~250 m/My

Figure 13: