EROSION RATES IN (SUB) TROPICAL, RAPIDLY DEVELOPING COUNTRIES: AN ISOTOPIC APPROACH TO MEASURING BACKGROUND RATES OF EROSION IN BRAZIL AND CHINA

A Graduate Research Proposal

January 2015

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In Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy in

Natural Resources

University of Vermont

Abstract

My proposed research will use measurements of the rare isotope ^{10}Be in sand collected from rivers in Santa Catarina and Rio de Janeiro States, Brazil and Yunnan, China to quantify long-term, background rates of erosion and thus sediment supply. In Brazil, I will also investigate the effect of mass movement events on material sourcing to rivers, by comparing the isotopic concentration of active channel sediments, river cobbles, and debris flow material. In China, I will investigate the difference in material transport between dry and monsoon seasons by comparing the isotopic concentration of overbank (deposited during monsoonal floods) and in-channel sediment. Additionally, in China, I will quantify the erosion index, a ratio between ^{10}Be deposition and export, for the sampled basins using both *in situ* ^{10}Be concentrations and measured sediment yields to calculate mass loading of our drainage basins. The erosion index compares the ^{10}Be delivered to the watershed, with that leaving it to assess if a watershed is in steady state. For samples in both of the countries, I will assess the relationship between erosion and landscape-scale geographic variables (such as precipitation, slope, and land use). Quantifying background erosion using ^{10}Be in Brazil and China will increase the frequency of such measurements in tropical and subtropical climates. Both Yunnan and Santa Catarina State have economies that rely on agriculture to provide a great amount of revenue for their respective countries. Knowledge of background erosion rates will be helpful for land management and agriculture, because such rates serve as a benchmark to compare current erosion rates. Agriculture activities can be planned better with a knowledge of background erosion rates, potentially decreasing soil losses in highly erodible watersheds.

Introduction and background

Erosion is a natural processes, but its rate has been increased dramatically by humans (Enters, 1998; Hooke, 1994; Hooke, 2000; Reusser et al., 2015). Natural resources and many aspects of our livelihoods can be impacted by erosion including, water quantity and quality (Bilotta and Brazier, 2008), reservoir lifespan (Harden, 2006, Owens et al., 2005), aquatic ecology (Owens et al., 2005), and agriculture (Pimentel et al., 1995; Pimentel, 2006). The magnitude of these effects can be reduced with efficient environmental management. To craft such effective management techniques, knowledge of background erosion rates and dominant landform processes is necessary.

Cosmogenic ^{10}Be

Cosmogenic nuclides were first suggested as a method to determine background erosion rates in the 1990's (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). *In situ* cosmogenic isotopes (I will use ^{10}Be) are formed when rocks and sediment are exposed to secondary cosmic rays at and near Earth's surface (Lal and Peters, 1967); such isotopes accumulate over the exposure time. The formation of these isotopes decreases with depth, and is generally insignificant below a depth of 2 meters (Lal and Peters, 1967). Because of this formation process, the concentration of ^{10}Be is a good indicator of near-surface residence time, and of denudation rates which are inversely related to isotopic concentrations. The method to derive denudation rates from cosmogenic isotope concentrations in river sediment assumes that the rate of erosion is steady over the time period integrated, that sediment sourcing is steady, and that sampled sediment is representative of the erosion of the entire basin (see Brown et al., 1995, Bierman and Steig, 1996 and Granger et al., 1996 for the assumptions of the method). The integration time depends on erosion rate: for fast erosion rates, sediments spend little time in the upper meters of the soil (*in situ* ^{10}Be production zone), whereas in a slowly eroding watershed, sediments spend more time in the nuclide production zone. Background erosion rates can be used to address issues raised in policy, land management, and ecological economics debates. Considering geologic (background) erosion rates when designing policy and land management regulations will make these approaches realistic. In terms of agriculture, these erosion rates can be used to plan where the fields will be located or what will be grown. Growing crops that cause less loss of the top soil, and locating fields in areas that are less prone to erosion can save both money and time.

Meteoric ^{10}Be forms in the atmosphere as the result of the spallation (splitting) of nitrogen and oxygen atoms (Lal and Peters, 1967). Once formed in the atmosphere, the isotope adheres to aerosols and is delivered to the surface typically in rainfall, but can also fall as dry precipitation (McHargue and Damon, 1991). The concentration of meteoric ^{10}Be in precipitation is a function of latitude and movement of the isotope from the atmosphere to the troposphere (McHargue and Damon, 1991). Graly and others (2011) published a method to calculate the meteoric ^{10}Be delivery rate, accounting for mean annual precipitation and latitude. Most meteoric ^{10}Be can be found in the upper few meters of the soil (Pavich et al., 1984; Pavich et al., 1985). It has been used as a sediment tracer at the watershed level (see Reusser and Bierman, 2010) and to estimate the rate of soil transport (see Jungers et al., 2009) among other uses.

Sediment yield data

The Ministry of Hydrology of the People's Republic China has been collecting data daily on water quality parameters in the International Rivers of Yunnan and Tibet region since the 1950s (Schmidt et al., 2011). Such a complete record of sediment loading is very rare, and provides a strong underpinning to erosion and water quality research in the region. Two measured parameters are total suspended sediment and discharge, which can be used to calculate sediment yield for the river. These data were collected from 1953 to 1989, but we will use data from up to 1987. Data after 1987 is not publicly available, and some stations have sediment data starting in 1958 or later, so we will use the years available for each station. The data was compiled from the government documents, translated, and compiled in a database described by Henck et al (2010), and published at: http://depts.washington.edu/shuiwen/

Payment for Ecosystem Services

One approach to environmental conservation adopted in recent years is to share the costs of conserving the land; those who benefit from the ecosystem services rendered by the conserved land pay a fee to the land owner. Pfaff and others (2008) define payment for environmental services as an effective way to induce conservation while compensating those who incur its costs.

The need to shift conservation (and conservation policy) approaches from experience-based to knowledge-based has been discussed by several authors (e.g. Ferraro and Pattanayak, 2006; Pullin and Knight, 2001; Sutherland et al., 2004; Pfaff et al., 2008). They all agree on the need for evaluation and a more scientific (data-based) approach to conservation practices. It is here where geomorphology, through cosmogenic nuclides, can be integrated with conservation. Quantifying background erosion rates for places where a Payment for Ecosystem Services (PES) scheme will be installed, will serve as a benchmark to assess policy effects on contemporary erosion rates. These data will be useful when monitoring the ecosystem and assessing the effects of the PES on the overall health of the ecosystem.

Erosion Index

Another approach to study surface material transport is to look at the erosion index of a watershed. Brown and others (1988) defined the erosion index as the ratio of meteoric ^{10}Be leaving the basin to that deposited on it. The equation to calculate erosion index is

$$I = \frac{M\eta'}{Aq} \qquad \textit{Equation 1}$$

Where M is the annual sediment load, η' is the ^{10}Be concentration in the material leaving the basin, A is the basin area, and q is the atmospheric deposition rate of ^{10}Be in the watershed. I calculate the q value for each watershed, using the equation published by Graly and others (2011):

$$q = P \cdot \left(\frac{1.44}{1 + \frac{EXP(30.7 - L)}{4.36}} + 0.63 \right) \qquad \textit{Equation 2}$$

Where L is the latitude in which the watershed is located and P the mean annual precipitation rate.

If a basin is in steady state (erosion and soil formation), then the amount of ^{10}Be leaving the basin is similar to that being deposited (Brown et al., 1988). If on the other hand, the index has a value over one, it means the basin is eroding more quickly than soil is being produced, in other words, more ^{10}Be is leaving the basin, than it is being deposited by precipitation. The erosion index provides an important piece of information for evaluating land management practices, because it informs us about the balance between soil formation and erosion. This information is key when considering restoration projects, conservation and future land uses that could tip the erosion index either way (greater or smaller than one).

Study areas

BRIC was a term used for the first time in 2001 by Goldman Sachs to refer to Brazil, Russia, India, and China; rapidly developing economies, expected to have an increasing weight in the global economy in the decade to follow (O'neill, 2001). While becoming major players in the world economy and trade, these countries have become resource users and polluters in magnitudes comparable to those of the largest developed nations (Söderbaum and Tortajada, 2011). Agriculture is one the main economic drivers in these countries, to the extent that 25% of the world's agricultural land area is situated in BRIC nations (Brosig et al., 2013). Brazil and China are located in tropical and subtropical regions. In 2001, the Food and Agriculture Organization of the United Nations estimated that tropical forests were being cleared at an alarming rate of ~29 ha/min (FAO, 2001). Agriculture and deforestation are tightly linked to erosion (Pimentel et al., 1987), and because agriculture is growing at an accelerated pace in BRIC countries (Brosig et al., 2013), the information obtained from our studies in Brazil and China will have many applications to economy and land management.

Rio de Janeiro and Santa Catarina states have escarpment topography – associated with a passive tectonic margin – parallel to the Atlantic coast that divides the coastal plains from the interior plateau (Ollier, 2004; Domínguez, 2009; Hesp et al., 2009; Angulo et al., 2009). The state of Rio de Janeiro is mostly mountainous, composed of gneiss overlain by lower Paleozoic rocks (Hartt, 1870). The eastern part of Santa Catarina state is occupied by Atlantic lowlands and the southern Brazilian highlands (Behling, 1995). The Brazilian Atlantic forest originally stretched between the Rio Grande do Norte to Rio Grande do Sul states (Chiarello, 1999) and supported some of the highest biodiversity in the planet; however, the forest is being reduced at an alarming rate (Lira et al, 2012; Rebollar et al., 2012). Most of our Santa Catarina samples are located inside or in close proximity to the Atlantic Forest. Rio de Janeiro and Santa Catarina experience high humidity and temperatures along the coast, and more stable and lower temperatures in the highlands (Williams, 1962). Temperatures in Rio de Janeiro reach their maximum between June and July (29°C), and their minimum temperature in January and February (21°C) (Brickus et al., 1998). Rio receives between 1,200 and 1,500mm rainfall annually (de Sherbinin and Hogan, 2011). In Santa Catarina, mean temperatures range from 14°C in the winter to 23°C in the summer (annual mean of 19°C), and precipitation between 1,250 and 1,400 mm (Hesp et al., 2009).

Yunnan province is located in southwestern China. Morphologically, the province is a mountainous region that connects with the Tibetan highlands in the northwest, and forms a broad plateau on the eastern side of the province (Leloup et al., 1995). Due mostly to its mountainous terrain, a small percentage of land in the province has been classified as suitable for agriculture (Thomas, 1992). However, rice paddies are widespread in the region (Xiao et al., 2005). Even if at small-scale, agriculture is widespread in Yunnan. Climate in Yunnan is controlled by its high elevation, with mean annual temperatures ranging between 14.7 and 18.7 °C; between 800 and 1100mm of precipitation falls annually (Jin et al., 1990). Yunnan's climate is dominated by the interaction between the East Asian Summer monsoon and the Indian Summer monsoon, as well as by surface orography (Hui et al., 2013). During this monsoon season (May to October), 85% of the annual precipitation falls, and the rivers transport 62% of the annual discharge (Henck et al., 2010; Hui et al., 2013). Soil erosion and flooding events are intensified during the monsoon months (Zisheng et al., 2010).

More specifically, our field sites are located within the International Rivers of Yunnan and Tibet region. The region hosts part of the Three Parallel Rivers UNESCO World Heritage Site, where multiple dams are proposed for both the Salween and Mekong rivers (Feng and He, 2004; Magee, 2006). Yunnan is a region of great biodiversity (Ying-shan et al., 2007); however dam construction, agriculture and other land use changes pose a threat to the province's environment.

Objectives:

My field areas are located in tropical and subtropical regions of Brazil and China. Because the objectives for each project are different, I will consider the objectives for each project separated by country in this section. Quantifying background erosion rates in both Brazil and China will increase the number of cosmogenic nuclide measurements in tropical and subtropical climates. As noted by Portenga and Bierman (2011), although cosmogenic nuclides have been widely used as a method for background erosion rates, their use on tropical environments has been limited. Out of the 1149 sample included in their compilation, only 98 were from tropical watersheds. Since then, studies using cosmogenic nuclides with field sites in Puerto Rico (Brocard et al., 2014a; Brocard et al., 2014b), Brazil (Salgado et al., 2006; Salgado et al., 2007; Salgado et al., 2008; Salgado et al., 2013; Cherem et al., 2012a; Cherem et al., 2012b; Barreto et al., 2013, Barreto et al., 2014; Rezende et al., 2013), and the tropical regions of Africa (Hinderer et al., 2013) and Australia (Lal et al., 2012) have been published.

Brazil:

Using *in situ* ^{10}Be concentrations of active channel sediments in Rio de Janeiro and Santa Catarina, Brazil, I will constrain background erosion for 14 basins (see Figure 1 for sampled watersheds locations). I will assess the relationship of erosion rates to landscape scale variables (see variables in Table 1). With this information, I will place erosion rates of the Atlantic Forest of Brazil in the context of other tropical places and passive margin areas, where cosmogenic ^{10}Be has been used as an erosion rate monitor. I expect this data to be used to inform the establishment of a payment for ecosystem services (PES) program in Santa Catarina State. This is a novel application of cosmogenic geomorphology to the environmental conservation field.

Table 1: Landscape level variables and data sources

Variable	**Data sources**	**Website**
Brazil		
Land use	Global Land Cover – GLC30	http://www.globallandcover.com/GLC30Download/index.aspx
Rainfall	WorldClim – Global Climate Data	http://www.worldclim.org/
Area Elevation Slope	Instituto Nacional de Pesquisas Espaciais – Topodata 30m DEM	http://www.webmapit.com.br/inpe/topodata/
Lithology	Serviço Geolófico do Brasil	http://geobank.sa.cprm.gov.br/
China		
Land use	Global Land Cover – GLC30	http://www.globallandcover.com/GLC30Download/index.aspx
Elevation Slope Relief Rainfall	APHRODITE	http://www.chikyu.ac.jp/precip/cgi-bin/aphrodite/script/aphrodite_cgi.cgi/register

I will measure the isotopic concentration of debris flow material in 7 basins in Rio de Janeiro and 1 basin in Santa Catarina, and compare to the concentration of active channel sediments. The rationale is that because residence time is inversely proportional to the isotopic concentration (Portenga and Bierman, 2011), if the sediments have been exposed at the surface for a long time, their concentration will differ greatly from that of river sediments. Comparing these concentrations, I will get insight into the mechanisms that control the source of sediment to streams in Southern Brazil.

In order to understand the difference in material transport to the river during mass movement and rainy events, I will compare the isotopic concentration of river channel sediment and river cobbles in 3 sites in Rio de Janeiro. If the concentration do not differ greatly, the supply of material to the river is not greatly affected (nor dominated) by high flow events and landslides.

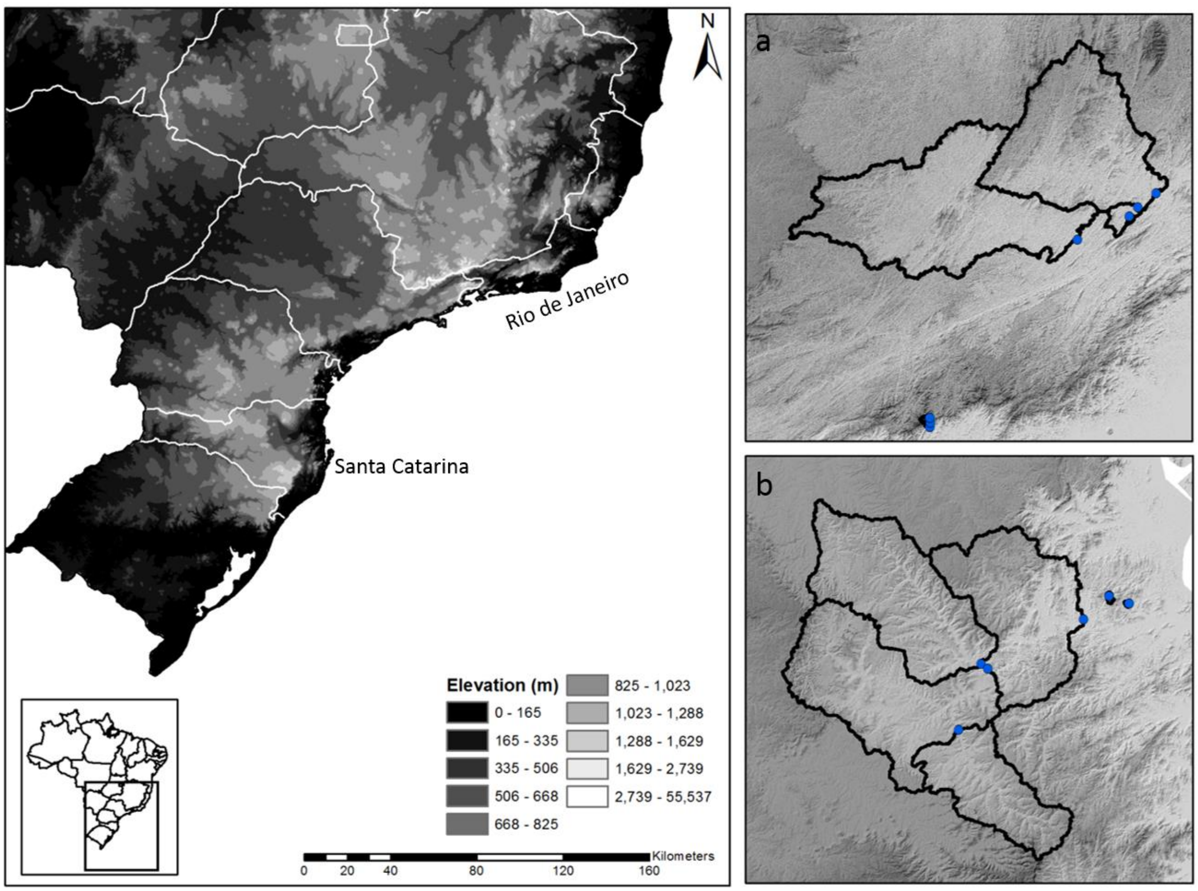

Figure 1: Location of Santa Catarina and Rio de Janeiro states in southern Brazil. Sampled watersheds in Rio de Janeiro (a) and Santa Catarina (b), Brazil. Sample locations are indicated with the blue dots.

<u>China</u>:

I will measure *in situ* and meteoric ^{10}Be in 70 samples from Yunnan, China (see Figure 2 for sampled watersheds locations); of these samples 40 are from active river channel sediment and 30 are from overbank samples and two were supplied from previous sampling campaigns (see Appendix 1). Using the *in situ* isotopic concentration, I will estimate background erosion rates in all the basins we sampled (see Lal, 1991), and assess the relationship between erosion and landscape level variables (see variables on Table 1). We will measure meteoric ^{10}Be for these samples, and use these isotopic concentration to calculate the erosion index for each watershed.

The erosion index and atmospheric deposition of ^{10}Be for each basin will be calculated using Equation 1 and Equation 2 explained above. To calculate the index, we need to know the sediment yield of the basin. We will calculate the index using two sediment yields for each watershed: the sediment yield derived from isotopic concentration which integrates over thousands of years, and using official data from the Chinese Government which integrates over decades. Water quality parameters, including sediment yield, have been measured daily for at least 5 years in the sampled watersheds, by the Ministry of Hydrology of the People's Republic of China. In doing this, I will attempt to compare how the erosion index has changed over time, a novel approach to erosion index calculations. For each watershed, we will calculate the erosion index using both the overbank and in-channel samples, using both the sediment yield calculated from sediment load, and the one calculated from isotopic concentration.

Two of the fundamental assumptions of the method to constrain erosion rates using isotopic concentrations will be evaluated in my work. One of these assumptions is that the erosion is representative of the entire basin. Comparing the isotopic concentration, and derived erosion rate, of material deposited during high flow events (overbank samples deposited in the last monsoon) with samples from the active river channel, I will understand changes in material supply to the river. If the values vary greatly, two things can be inferred: that the source of the material is different during seasons, and that the erosion rates measurements are sensitive to seasonal changes. The method also assumes that the erosion rate is steady over the time period integrated. I resampled sites that have been measured for ^{10}Be in 2005, 2006 and 2013, and will compare the concentrations to assess temporal changes and the validity of this assumption. Twelve of our samples were collected in locations that were sampled in 2013 (CH-0XX's), and thirteen from sites that were sampled in 2005 (TRR's).

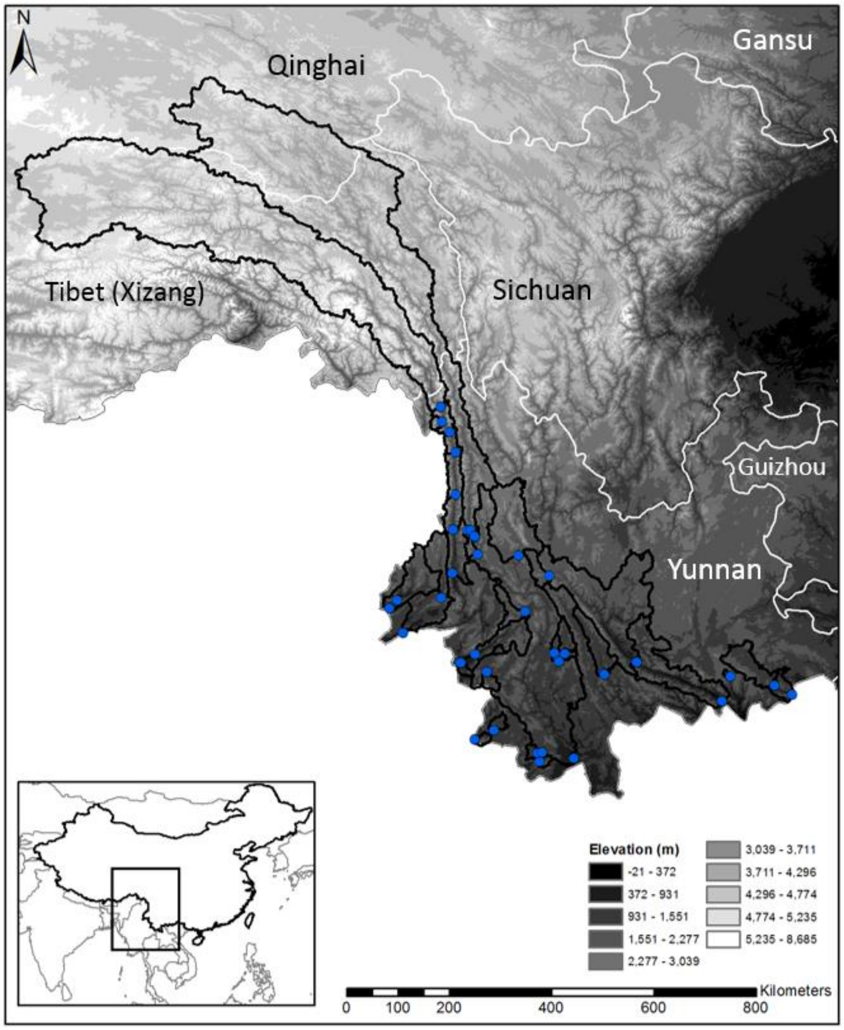

Figure 2: Location of the sampled watersheds in Yunnan, China. Sample locations are indicated with the blue dots. The inset shows the location of our samples within China.

Methods

To address my objectives, I will measure the *in situ* ^{10}Be concentration in active channel sediments, debris flow material, and river cobbles for the Brazil samples. Because river cobbles are bigger than the sediment transported by base flow in the river, it is assumed that this heavier material was transported during an episode of higher input of sediment to the river (mass wasting event or high water flow). Under this assumption, I will measure and compare the ^{10}Be concentration of river cobbles and channel sediments to assess differences in material sourcing.

For the China samples, I will measure meteoric and *in situ* ^{10}Be concentrations in our active channel and overbank samples. In both Brazil and China active channel sediments, I will calculate background erosion rates using CRONUS, a method to calculate surface erosion rates based on cosmogenic ^{10}Be and ^{26}Al measurements (see Balco et al., 2008), available at http:// hess.ess.washington.edu/. Landscape level variables will be quantified for each basin, and their relation to erosion rate will be quantified using JMP for parametric analyses, using regression and multivariate analysis. For the China samples, I will calculate the erosion index and atmospheric deposition rate for each watershed using Equations 1 and 2 (shown above) respectively. The sediment yield for the erosion index will be calculated using *in situ* ^{10}Be derived sediment generation rates and modern sediment data. Table 1 shows the data source for these landscape variables. In Table 2, I summarize how each research objective will be addressed methodologically. A complete list of samples and which isotopic analysis I will perform on each can be found on Appendix 1, and detailed methods for these analyses can be found in Appendix 2.

Table 2: Summary of methods to address each objective

Objective	**Methodology approach**	**Analysis**
Brazil		
Background erosion rates	*In situ* ^{10}Be on river channel material and CRONUS calculator	
Erosion controls	Erosion rate and landscape variables	Regressions and multivariate analyses between erosion rate and landscape variables using JMP
Erosion mechanisms	*In situ* ^{10}Be on material from river channel and debris flow	Compare concentrations
Material transport	*In situ* ^{10}Be on from river sand and river cobbles	Compare concentrations
China		
Background erosion rates	*In situ* ^{10}Be on river channel material and CRONUS calculator	
Erosion controls	Erosion rate and landscape variables	Regressions and multivariate analyses between erosion rate and landscape variables using JMP
Changes in sediment transportation	*In situ* ^{10}Be on river channel material	Calculate atmospheric deposition and erosion index, using the sediment yield data from the Ministry of Hydrology and sediment yield derived from *in situ* ^{10}Be data
Soil loss	Meteoric ^{10}Be	
Test method assumption: Is the erosion rate representative of the entire basin?	*In situ* ^{10}Be on overbank and in-channel sediments at the same location	Compare concentrations
Test method assumption: Is the erosion rate steady over the integrated time?	*In situ* ^{10}Be on resample locations	Compare concentrations

Preliminary Results

In situ produced ^{10}Be concentrations for the 14 Brazilian watersheds we sampled range between 7.56 ± 0.29 x 10^4 to 2.49 ± 0.06 x 10^5 atoms/g. The erosion rates derived from these concentrations range between 11 and 47 m/Myr, with an average of 22 m/Myr, and a median of 16 m/Myr. There is no significant difference in the erosion rate of basins in Rio de Janeiro and Santa Catarina States. Although these erosion rates are fairly low, they are higher than those published (using cosmogenic ^{10}Be) for watersheds also located in passive margins including Namibia, Madagascar and southeastern North America (Bierman and Caffee,2001; Bierman et al., 2007; Cox et al., 2009; Sullivan, 2007; Duxbury, 2009). However, published cosmogenic-derived erosion rates for Sri Lanka (Hewawasam et al., 2003; Vanacker et al., 2007; von Blanckenburg et al., 2004) average 22 m/Myr, similar to my Brazilian watersheds.

Annual precipitation and mean basin slope are the strongest predictors of erosion in the basins we studied. Precipitation has a stronger relationship with erosion (R^2=0.55, $p<0.01$) than slope (R^2=0.45, p=0.01). When combined, their relationship to erosion increases (R^2=0.70, p=0.01).

Timeline

Date	Task
September 2011	Rio de Janeiro, Brazil – Field season
May 2012	Santa Catarina, Brazil – Field season
May-June 2013	Yunnan, China – Field season 1
January 2014	Yunnan, China – Field season 2
Spring 2014	Completion of graded credit hours
Summer – Early fall 2014	Preparation of quartz for in-situ ^{10}Be extraction Extraction of meteoric ^{10}Be from samples Preparation for Teaching Requirement
Fall 2014	GEOL 352 – Teaching requirement August 2014 – complete extraction of meteoric November 2014 – complete extraction of *in situ* ^{10}*Be* Brazil data analysis October 2014 – present research, Geological Society of America annual meeting, Vancouver, Canada

Winter 2014	Literature review and method chapters of thesis Start analyzing China data Comprehensive exams
Spring 2015	Visit to Oberlin College Data analysis and paper (thesis) writing
August 2015	Thesis defense

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APPENDIX 1 – Sample list

Sample ID	Sample type	Analysis to perform		Notes
		Meteoric ^{10}Be	*In situ* ^{10}Be	
Brazil – Rio de Janeiro				
BRA-01	river cobbles		X	
BRA-01S	river sand		X	
BRA-02	river cobbles		X	
BRA-02S	river sand		X	
BRA-03	river cobbles		X	
BRA-03S	river sand		X	
BRA-04	debris flow boulder		X	
BRA-05	debris flow boulder		X	
BRA-06	debris flow boulder		X	
BRA-07	debris flow boulder		X	
BRA-08	debris flow boulder		X	
BRA-09	debris flow sediment		X	
BRA-10	debris flow boulder		X	
BRA-11	debris flow boulder		X	
BRA-12	debris flow boulder		X	
BRA-13	debris flow boulder		X	
BRA-14	debris flow boulder		X	
BRA-15	debris flow boulder		X	
BRA-16	debris flow boulder		X	
BRA-17	debris flow boulder		X	
BRA-18	debris flow sediment		X	
BRA-19	river sand		X	
BRA-20	river sand		X	
BRA-21	river sand		X	
BRA-22	river sand		X	
Brazil – Santa Catarina				
BRA-40	river sand		X	
BRA-41	river sand		X	
BRA-42	debris flow sediment		X	
BRA-43	river sand		X	
BRA-44	river sand		X	
BRA-45	river sand		X	
BRA-46	river sand		X	
BRA-47	river sand		X	

China – Yunnan				
CH-073	river sand	X	X	Station 6, 2013 sample
CH-074	overbank deposit	X	X	Station 6, 2013 sample
CH-101	river sand	X	X	Station 91
CH-102	overbank deposit	X	X	Station 91
CH-103	river sand	X	X	Station 90
CH-104	overbank deposit	X	X	Station 90
CH-105	river sand	X	X	Station 108
CH-106	overbank deposit	X	X	Station 108
CH-107	river sand	X	X	Station 106
CH-108	overbank deposit	X	X	Station 106
CH-109	river sand	X	X	Station 103
CH-110	overbank deposit	X	X	Station 103
CH-111	river sand	X	X	Station 103
CH-112	overbank deposit	X	X	Station 103
CH-113	river sand	X	X	Station 87
CH-114	river sand	X	X	CH-056 resample
CH-115	river sand	X	X	CH-058 resample
CH-116	river sand	X	X	CH-043 resample
CH-117	river sand	X	X	Station 49; CH-060 resample
CH-118	overbank deposit	X	X	Station 49; CH-044 resample
CH-119	river sand	X	X	Station 6; CH-073 resample
CH-120	overbank deposit	X	X	Station 6; CH-074 resample
CH-121	river sand	X	X	CH-070 resample
CH-122	river sand	X	X	CH-071 resample
CH-126	overbank deposit	X	X	Station 11; CH-076 resample
CH-127	river sand	X	X	Station 11; CH-075 resample
CH-128	overbank deposit	X	X	Station 109
CH-129	river sand	X	X	Station 109
CH-130	overbank deposit	X	X	Station 94
CH-131	river sand	X	X	Station 94
CH-132	overbank deposit	X	X	Station 32
CH-133	river sand	X	X	Station 32
CH-134	overbank deposit	X	X	Station 93
CH-135	river sand	X	X	Station 93
CH-136	overbank deposit	X	X	Not a station
CH-137	river sand	X	X	Not a station
CH-138	overbank deposit	X	X	Not a station
CH-139	river sand	X	X	Not a station
CH-140	overbank deposit	X	X	Station 99

CH-141	river sand	X	X	Station 99
CH-142	overbank deposit	X	X	Station 85
CH-143	river sand	X	X	Station 85
CH-144	overbank deposit	X	X	Station 84
CH-145	river sand	X	X	Station 84
CH-146	overbank deposit	X	X	Station 100
CH-147	river sand	X	X	Station 15
CH-148	overbank deposit	X	X	Station 15
CH-149	overbank deposit	X	X	TRR 13b resample
CH-150	river sand	X	X	TRR 13b resample
CH-151	river sand	X	X	Station 4
CH-152	overbank deposit	X	X	Station 4
CH-153	river sand	X	X	TRR 14b resample
CH-154	river sand	X	X	TRR 14b resample
CH-155	river sand	X	X	Station 86
CH-156	overbank deposit	X	X	Station 86
CH-157	river sand	X	X	Station 97
CH-158	overbank deposit	X	X	Station 97
CH-159	river sand	X	X	Station 101
CH-160	overbank deposit	X	X	Station 101
CH-161	river sand	X	X	TRR 9 resample
CH-162	overbank deposit	X	X	TRR 9 resample
CH-166	overbank deposit	X	X	TRR 10 resample
CH-167	river sand	X	X	TRR 10 resample
CH-168	river sand	X	X	TRR 11a resample
CH-169	river sand	X	X	TRR 11a resample
CH-170	river sand	X	X	TRR 11b resample
CH-171	river sand	X	X	TRR 12 resample
CH-172	overbank deposit	X	X	TRR 12 resample
Y13-01-DM	river sand	X	X	Station 87 – Devin McPhillips sample
TRR-5	overbank deposit	X	X	2005 sample
TRR-6	overbank deposit	X		2005 sample
TRR-8	overbank deposit	X		2005 sample
TRR-9	overbank deposit	X		2005 sample
TRR-10	overbank deposit	X		2005 sample
TRR-11b	overbank deposit	X		2005 sample
TRR-12	overbank deposit	X		2005 sample
TRR-13b	overbank deposit	X		2005 sample
TRR-14b	overbank deposit	X		2005 sample

TRR-28	overbank deposit	X		2006 sample
TRR-36	overbank deposit	X		2006 sample

APPENDIX 2 – Detailed Methodology

Field methods

In order to address my objectives, I sampled river sediments and debris flow sediments in Rio de Janeiro, river sediments in Santa Catarina, both in Brazil, as well as river sediments in Yunnan, China. Unless noted otherwise, in all cases where active channel sediments were sampled, they were field sieved to the sand fraction (250-850μg).

Rio de Janeiro, Brazil:

Twenty five (25) samples were collected in September 2011 in Rio de Janeiro, Brazil. Seven of these samples were active channel sediment. In three of the sites where river sediment were sampled (BRA-01,-02 and -03), river cobbles were also sampled and analyzed for ^{10}Be to assess differences in material sourcing to the river. Three of the basins in Rio de Janeiro that were sampled, mostly drain the Serra do Mar escarpment.

A series of samples associated with debris flows were collected to assess the recurrence interval of these events. At 8 sites, sediment material of an older debris flow were collected; 5 samples were collected from the 2011 debris flow. Two additional sediment samples were collected from another debris flow event.

Santa Catarina, Brazil:

In May 2012 eight samples were collected in Santa Catarina, Brazil. Seven of these are active river channel sediments. Samples BRA-41 and BRA-43 are nested. Samples BRA-44 to BRA-47 are all nested, and will be analyzed as a network. I sampled sediments from a debris flow adjacent to the location of BRA-41; the debris sediment samples is BRA-42.

Yunnan, China:

In January 2014, I did an extensive sampling in Yunnan, China. Unless otherwise noted, or where it was not possible due to access to the river, I sampled sediments from both the active river channel and from material deposited overbank during the monsoonal flood. I assumed that material in the overbank was deposited during the last high flow event, which was the summer of 2013 monsoon season. Comparison of overbank and in channel sediments will help assess the difference in material sourcing and transportation between the dry and monsoon season.

I sampled 22 rivers near – within a few kilometers of – Chinese government hydrology stations. Suspended sediments, among other parameters, are measured daily in these stations. The sites chosen for my sampling have daily suspended sediment data for at least 5 years.

During the summer 2013, we had a field season in Yunnan for another project funded by the same National Science Foundation grant (Award # 1114166) that studied the dynamics between land use and erosion at the sub-basin and whole basin level in three watersheds. Twelve sites sampled in

2013, were resampled in January 2014 for my project. Comparing these measurements from samples taken at the same spot, six months apart and in different weather conditions will help assess material sourcing and evaluate the assumptions of the *in situ* ^{10}Be method.

I resampled 7 sites in the main stem and tributaries of the Mekong and Salween that had been previously analyzed for *in situ* ^{10}Be, and published in Henck and others (2011). Comparing the results from our samples to the previously measured will help evaluate the assumptions of the *in situ* ^{10}Be method, and assess the temporal variation of the isotopic concentration.

In all the Yunnan samples, I measured *in situ* ^{10}Be and meteoric ^{10}Be to quantify background erosion. For the samples adjacent to hydrologic stations, we will also use suspended sediment data to quantify modern erosion rates and compare to long-term rates.

<u>Laboratory methods</u>

In situ ^{10}Be:

Sediments analyzed for *in situ* ^{10}Be were processed to isolate and purify the quartz fraction, following the method published by Kohl and Nishiizumi (1992). Samples had two – three whenever needed – etches with 6N Hydrochloric acid (HCl) to dissolve the carbonates and remove all meteoric ^{10}Be. Samples that reacted with HCl because of their high carbonate content were left in acid overnight without heating; if there was no reaction, samples were sonicated overnight (heat and vibration applied to the samples). Most of the Yunnan samples reacted with HCl. After the HCl etches samples were rinsed and dried. If magnetic material was present after etching, the samples were placed in a magnetic separator and the non-magnetic phase was used for further sample preparation.

Samples were then weighed into 4-liter bottles and etched in 1% Hydrofluoric acid (HF) and Nitric acid (HNO_3); they had three overnight etches in the sonicator. This combination of acids dissolves a vast amount of material, but quartz is more resistant, so it is an efficient way to isolate and purify the quartz. Afterwards, samples were rinsed and dried. Once dry they were weighted to quantify quartz yield of each sample.

A set of two long etches (72 hours and a week long) in weak Hydrofluoric and Nitric acids helped further purify the quartz fraction. Samples that had less than 20 grams of quartz before the long etches, were etched with 0.25% HF/HNO_3; otherwise, they were etched in 0.50% HF/HNO_3. Once rinsed and dried after long etches, quartz purity was tested in the Cosmogenic Laboratory Meteoric Laboratory. During purity test, the impurity content of the sample was also quantified. If the quartz was clean, samples had a final etch in weak acid (HF/HNO_3) in the clean ^{10}Be extraction laboratory. This etch reduced the chance of introducing dust and contamination to the clean laboratory facilities used for extraction.

Once the quartz was purified for each sample, about 20 grams of sample were weighed in into Teflon bottles and spiked with Be and Al carrier, to reach desirable concentrations for Accelerator

Mass Spectrometer (AMS) measurements. Hydrofluoric acid was added in 5:1 acid to sample mass ratio, to dissolve the quartz. Samples were heated to 135°C to dissolve completely. Once dissolved, samples had three perchloric ($HClO_4$) drydowns followed by two drydowns in concentrated hydrochloric (HCl) acid, to prepare them for chromatography columns. Two sets of chromatography columns separated the ions in the samples. Be and Al ions from each sample were isolated during columns, and precipitated as gels after titrating with ammonium hydroxide (NH_4OH), using methyl red as an indicator. Once the gels were clean and dry, they were packed into targets for AMS analysis at the Scottish Universities Environmental Research Centre (SUERC) to measure their isotopic ratios. Ratios were corrected using the fully processed lab blanks I processed in each batch.

Corrected ratios, along with some watershed-level data obtained from GIS and Matlab, were used to calculate erosion rates for each watershed. I chose the constant erosion rates that used the Lal (1991) and Stone (2000) spallation scaling scheme calculated from CRONUS Earth calculator (http://hess.ess.washington.edu/). I will also use the corrected ratios to calculate the sediment yield needed to calculate the erosion index for each watershed using the Equation 1 discussed above. The atmospheric deposition for each watershed will be calculated using Equation 2.

Meteoric ^{10}Be:

Sediments analyzed for meteoric ^{10}Be were pulverized to a powder before processing in the meteoric extraction lab to homogenize the material. Unlike for *in situ* measurements, no acid etches or separations are required for meteoric.

Powdered samples were weighed into platinum crucibles, and spiked with Be carrier to desirable concentrations for AMS measurements. After the carrier was dried, solid potassium hydrogen fluoride (KHF_2) and sodium sulfate ($NaSO_4$) were added to the crucibles as reagents before fluxing. Samples were then melted in a natural gas flame intensified with oxygen. The flux resulting from this step (contained inside the platinum crucibles) was placed in Teflon beakers containing MilliQ® water, and left leaching into the water at 95°C for 48-72 hours. After this period, most of the water was evaporated and concentrated perchloric acid was added to precipitate out undesired ions in the samples and keep the ions of interest in the solid phase. Chromatography columns isolated the Be ions in the sample for further processing. Samples were precipitated to gels by titration with ammonium hydroxide (NH_4OH), using methyl red as an indicator and dried down. Once dry, the samples were packed into targets for AMS analyses at SUERC.

Data processing and analysis:

Suspended sediment data- Yunnan:

Suspended sediment data for 27 hydrologic stations, located within a mile of our sampling sites, collected by the Ministry of Hydrology of the People's Republic of China was manually entered from the government records to a spreadsheet. Data was quality controlled and the location of the station was confirmed before the data was used for analysis. I will use this sediment yield data to calculate the erosion index of each basin and compare to the sediment yield derived from isotopic concentrations.

GIS and Matlab:

I used GIS to quantify all the landscape level variables for our analyses – see Table 1 for variables calculated and data sources. Unless otherwise noted, I quantified these variables with the Zonal Statistics tool on the data layer of interest, and using the outline of watersheds as the zone to calculate within. A custom-made ArcGIS tool was used to prepare the data to be used in Matlab. I used a Matlab script to calculate the effective elevation of each watershed.

Statistical analyses:

JMP 10 was used for statistical analyses. I used linear regressions and multivariate analyses to assess the relationship between isotopic measurements, suspended sediments, and the landscape level variables I quantified for each watershed.