Detecting landscape response to perturbations by climate and baselevel in central Pennsylvania using *in-situ* ^{10}Be and ^{26}Al

A Thesis Proposal Presented

by

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to

The Faculty of the Geology Department

of

The University of Vermont

April 15th, 2015

Submitted to the Faculty of the Geology Department, the University of Vermont, in partial fulfillment of the requirements for the degree of Master of Science specializing in Geology.

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Abstract

I will use measurements of *in-situ* produced cosmogenic ^{10}Be and ^{26}Al, isotopes produced in terrestrial materials through bombardment by cosmic rays (Lal, 1991), to investigate the landscape evolution of Pennsylvania. I will examine small scale landscape evolution by investigating the blockfields of Hickory Run State Park (near Penn Forest, PA) and the talus slopes of Garner Run (near State College, PA) in order to understand better the timing and the influence of periglacial activity on the generation and movement of sediment. My research will then examine the larger-scale by studying the control of sediment generation rates as a function of channel incision from a change in base level in Young Womans Creek watershed, a 106 km^2 tributary of the West Branch Susquehanna River in the southeastern corner of Potter County, PA. My work is part of the NSF Shale Hills CZO project designed to better understand the origin and behavior of soils.

1. Introduction

Geomorphologists use the term 'landscape evolution' to describe the tectonic, climatic, topographic, geologic, and biotic processes that drive landscape change over time (Bierman and Montgomery 2013). The evolution of the Appalachian landscape has been a source of debate amongst geomorphologists since the late 1800's (Davis, 1889), and today glacial/interglacial cycles (Braun 1989) and changes in the 'baselevel' of the landscape (Hancock and Kirwan 2007), the elevation to which a landscape would erode if given enough time, are recognized as two important drivers of Appalachian landscape change. This study will employ cosmogenic isotope measurements to investigate the influence of climate and baselevel as they relate to the evolution of three sites just south of the last glacial maximum boundary in the northern Appalachians. Two sites will focus on the influence of climate, and the other will focus on baselevel.

The first site, a 'blockfield' (field of boulders) at Hickory Run State Park, is thought to have developed from frost-induced weathering processes during the last glacial maximum, but no data exist on the age of this feature or how the field developed. Mine will be the first quantitative attempt at constraining the exposure age of Appalachian blockfields and will contribute to the Pennsylvania Department of Conservation and Natural Resources' knowledge of this important natural landmark. The second site, Garner Run, is a collaborative effort with researchers from the Shale Hills Critical Zone Observatory (SHCZO) and will expand the observatory from a predominantly shale-underlain watershed to a new site with a different lithology (Brantley et al., 2013). Research here will be focused on understanding the generation and movement of sediment over time, which has likely been influenced by climatic processes that are no longer active, and will contribute to the greater knowledge base of the geomorphology at this new site. The third site, Young Womans Creek, is where I will collect stream sediment samples from a small drainage network to investigate the control of sediment generation rates by channel incision, which has been driven in this region by changes in baselevel over time (Hancock and Kirwan 2007). Miller et al. 2013 studied channel incision in a generalized fashion over a much larger area of the central Appalachians, and my study adds to this by creating the first detailed analysis of incision rates and distribution in a small Appalachian watershed. The lithology of all three sites is predominantly sandstone (Miles et al., 2001) and thus they all contain ample amounts of quartz, the mineral necessary for my method of isotopic analysis (Nishiizumi et al., 1986). Locations are displayed below in figure 1.

2. Background

2.1 Cosmogenic Nuclides

In-situ 'cosmogenic' isotopes are produced in the uppermost several meters of rock and soil where quartz grains are bombarded by neutrons created by the interaction of cosmic rays with the atmosphere (Lal, 1988; Granger and Muzikar, 2001; Gosse and Phillips 2001). Quartz is used in this method because it contains ample amounts of ^{16}O and ^{28}Si, which transform into

^{10}Be and ^{26}Al, respectively, when struck by cosmic rays (Lal, 1991). Production rates of cosmogenic isotopes are highest at the surface of the Earth and decrease with depth, and they also vary with elevation, latitude, and changes in Earth's magnetic field strength (Lal, 1991; Nishiizumi et al. 1991; Granger and Riebe 2014).

The accumulation of cosmogenic isotopes in bedrock and sediments allows us to estimate exposure times and erosion rates at two different scales, (1) at discrete locations on bedrock surfaces (Lal, 1991), and (2) for an entire drainage basin (Granger et al., 1996; Brown et al., 1995). When measured in bedrock, nuclide concentrations represent an apparent surface exposure age, the effective number of years over which the measured concentration of this nuclide would build up in a sample exposed at the surface (Lal, 1991). When measured in stream sediments, nuclide concentrations indicate spatially averaged rates of erosion in the area of the basin upstream of the sample site (Bierman and Steig, 1996).

Using two cosmogenic nuclides with different half-lives in conjunction with each other, such as ^{10}Be and ^{26}Al, allows one to investigate the burial history of a sample. The method, called cosmogenic burial dating, depends on different isotopes decaying at different rates (Lal, 1991; Granger and Muzikar 2001, Corbett 2013). ^{26}Al and ^{10}Be are produced at a rate of 6.75:1, and when a sample is buried the ratio of $^{26}Al/^{10}Be$ decreases as the half-life of ^{26}Al (0.71 m.y.) is shorter than that of ^{10}Be (1.36 m.y.) (Nishiizumi et al. 1991; Nishiizumi et al. 2007). If a sample is re-exposed, then production begins again, and the ratio increases. Burial dating has many different applications, including for research on glacial retreat and readvance (Bierman et al., 1999; Corbett et al., 2013), deposition of deeply buried cave deposits (Granger and Muzikar, 2001), and in profiles of buried alluvial deposits (Granger and Smith 2000).

2.2 Past Climate of the Northeast United States

The climate of Pennsylvania oscillated in response to repeated cycles of ice sheet retreat and advance through the Pleistocene (Braun, 1989). In the late Pleistocene, the Laurentide ice sheet extended into the northern Appalachians at least eight times, causing areas just south of the glacial boundary to develop a 'periglacial' climate, a cold environment usually containing permafrost with landforms produced by strong frost action, intensive mass wasting, and eolian activity (Clark and Ciolkosz, 1988). At its maximum extent, the Laurentide ice sheet extended just south of the state border in northeastern Pennsylvania (Braun, 1989).

Studies of glacially transported boulders off the coast of Massachusetts indicate that the southeastern margin of the ice sheet reached its maximum extent 23.2±0.5 ka BP (Balco et al., 2002), and studies of the global glacial maximum indicate that the onset of maximum ice extent was ~30 ka BP, experiencing only minor decreases until 21 ka BP (Lambeck et al., 2014). Shortly afterwards (18.2 ka BP) the ice sheet began to retreat, ablating rapidly until 13.8 ka BP at which point it receded from what is now northern New England (Ridge et al., 2012). With the retreat of the ice sheet, periglacial weathering processes became inactive. Today, relict landforms from these cold glacial periods can be found throughout Pennsylvania (Clark and Ciolkosz, 1988). Blockfields (also referred to as boulder fields and felsenmeer) are a particularly common type of periglacial feature, and are characterized by low-angle, sheet-like accumulations of large rock fragments over bedrock or weathered rock. The blockfields at Hickory Run State Park were first recognized as such in the 1950's (Smith, 1953; White, 1976).

2.3 The Appalachian Mountains

The Appalachian Mountains run SW-NE through Pennsylvania, and their evolution has been a source of heated geomorphological debate since 1899, when Davis proposed his geographic cycle model, which states that if a landscape is undisturbed, relief will decrease until only a flat peneplain is left (Davis, 1899). An alternative 'dynamic equilibrium' theory was argued by Hack, who postulated that a landscape that is subjected to uniform conditions over time will develop a 'steady-state' in which slope adjusts to the lithology and the landscape erodes at a uniform rate (Hack, 1960). The nature of the evolution of the Appalachians is still debated, especially because the mountains persist despite the end of orogenic activity millions of years ago (Baldwin et al., 2013).

A growing body of researchers have used cosmogenic nuclides to study landscape evolution by evaluating long-term erosion rates in the Appalachians (e.g. Matmon et al., 2003; Reuter, 2005; Hancock and Kirwan, 2007; Portenga et al. 2013; Miller et al., 2013; Duxbury et al. 2015; Reusser et al., 2015). Cosmogenic nuclides such as ^{10}Be are useful for studies on a 10^3–10^6 year time scale, long enough to reflect changes in climate, and can help distinguish landscapes in a transient state of relief (a landscape with decreasing relief, like Davis' theory) versus those in the 'dynamic equilibrium' that Hack postulates (Bierman and Steig, 1996; Granger et al., 1996; Riebe et al., 2004; von Blanckenburg, 2005; Miller et al. 2013).

Today, researchers have recognized that the Appalachian landscape is not in equilibrium and that for some reason, whether tectonic or climatic, the baselevel of the Appalachian landscape has changed over time (Pazzaglia and Gargner, 1993; Miller et al. 2013). This perturbation has propagated up the watersheds as a series of 'knickpoints', or sudden changes in gradient, in river and stream channels. Miller et al. (2013) used cosmogenic nuclides and topography analysis to understand the landscape scale effect of knickpoints in the Susquehanna Basin, comparing erosion rates above and below knickpoints in a collection of large drainage basins sampled by Reuter (2005).

3. Description of Study Sites

This section contains information on the locations and lithology of my study sites. The portion on Hickory Run is expanded to illustrate the current debate on the development of the blockfield and periglacial features in general.

3.1 Hickory Run

The blockfield at Hickory Run is the largest of its kind in the eastern United States (roughly 150 by 700 m), and is a designated National Natural Landmark. It is comprised of sandstones of the Ducannon Member of the Catskill Formation and is located in northern Carbon County, Pa, in the Pocono Plateau of the Appalachian Plateaus physiographic province (Sevon, 2000). The first major study of the blockfield was by H.T.U Smith in 1953, who proposed four potential modes of origin for the blockfield (Smith, 1953). A simplified version of Smith's hypotheses is presented here:

1. The boulder deposits resulted from direct glacial or glaciofluvial deposition.
2. The blocks accumulated in-situ as a residual weathering product.
3. The blocks formed in-situ by more or less vertical settling of boulders during the erosional development of the valley—the most resistant boulders are the only ones left.
4. The blocks have accumulated from a mass movement from the valley sides next to the field.

Ultimately Smith concluded that hypothesis #4, a mass movement from adjacent valley sides, was the most likely formation mechanism, and this remains the favored hypothesis today (Wedo, 2013). However, despite the passage of time since Smith's work and the considerable interest that this blockfield and others have generated amongst Quaternary geologists, no studies have confirmed or disproved that it did, in fact, migrate downslope (Potter and Moss, 1968).

In her 2013 M.S. thesis, Andrea Wedo used the Schmidt Hammer, an *in-situ* non-destructive test for rock hardness, to obtain relative age data by analyzing the weathered surfaces of the boulders (Wedo, 2013; Goudie 2006). However, her results displayed no particular age distribution downslope and were questionable as it has been suggested that the Schmidt hammer may have many limitations—rocks with long-term surface exposures may have weathering difficult to discern from each other, the instrument itself is difficult to calibrate, and even slight variations in texture can be a potential source of error (McCarroll, 1989).

3.2 Garner Run

Garner Run is located in the Ridge and Valley Province in Huntingdon County, 15 km southwest of State College, PA. The site consists of a low-order drainage bordered by a ridgeline of talus, coarse-grained material colluvial material, shed from the slope above. The bedrock at the top of the ridge is from the Juniata Formation (predominantly sandstone), and transitions through the Tuscarora Formation (quartzite) to the Clinton Group (shale and sandstone) downslope (Miles et al., 2001).

3.3 Young Womans Creek

Young Womans Creek is a 106 km^2 watershed that drains into the West Branch Susquehanna River. The basin sits at the corner of Potter, Lycoming, and Centre Counties in the Appalachian Plateau physiographic province, and is comprised of 5 formations including the Burgoon, Catskill, Huntley Mountain, and Pottsville Formations, which are all sandstone, and a small strip of the Mauch Chunk Formation in the SE corner of the basin, which is shale.

4. Research Hypotheses

Garner Run is a new project run through the Shale Hills CZO; no publications and very little data exist for this site. Because of the collaborative nature of my research there, I must wait to form hypotheses and a sampling strategy until we visit the site with others, discuss its geomorphology, and articulate the CZO goals there. My hypotheses for Hickory Run and Young Womans Creek are presented below.

4.1 Hickory Run Blockfield

Hypothesis 1: The blocks have formed by slow creep downslope from the local valley sides, as opposed to forming in-situ. If this were true, then my data would show an increase in cosmogenic nuclide concentration in a downslope transect of the blockfield.

Hypothesis 2: The blocks have been transported by creeping, not by rolling or overturning, and have not experienced any significant periods of burial or overturning. If this is the case, then my data would show a ratio of ^{26}Al:^{10}Be similar to the surface production rate of 6.75:1.

Hypothesis 3: Rounded blocks have longer exposure ages than angular blocks. If this is true then rounded blocks would contain higher concentrations of ^{10}Be than more angular blocks because they have been exposed and weathered longer.

3.1 Young Womans Creek

Hypothesis 1: Areas below knickpoints will have higher erosion rates (less ^{10}Be), and unincised areas above knickpoints will have lower erosion rates (more ^{10}Be). Erosion rates measured below knickpoints will be higher than existing data on average rates of erosion in the Susquehanna Basin (Reuter, 2005) because they are in a transient state of response to incision.

Hypothesis 2: Erosion rates correlate with the mean slope of the contributing basin above each sampling point.

4. Methods

I used LiDAR, orthoimagery, and geologic maps in conjunction with Arc Hydro© tools and a set of geomorphology tools in MATLAB (Whipple, 2007) to identify knickpoints and delineate subbasins with areas > 3 km^2 (to ensure perennial streamflow) in Young Womans Creek. I then generated zonal statistics on the slope and elevation of all subbasins, and generated a probability distribution curve of subbasin slopes. I used this curve to select samples (n=15) in a manner that represents the actual distribution of slopes in the watershed, selecting sites that fell both above and below knickpoints. (fig. 2). These sample sites will be accessed in the field by hiking and driving, confirmed using high precision GPS, and stream sediments will be collected and sieved in the field to isolate the sand fraction.

I will sample Hickory Run (n=30) in a series of transects (fig. 3) that will allow me to test whether ^{10}Be concentrations vary down the field and across the field. At three areas in the center transect I will sample one large, one medium, and one small boulder in order to determine the influence of boulder size on ^{10}Be concentration (circles in fig. 3). Rock samples will be a minimum of 100 g each and will be collected by hammer and chisel. Coordinates of the transects will be extracted in GIS using high resolution aerial imagery, and these sites will be located in the field using high precision differential GPS. Fieldwork at Garner Run will consist of making observations, deliberating on sampling strategy, and collecting samples (n=15) of talus rock debris and soil.

After fieldwork is completed, I will catalogue and re-evaluate samples for cosmogenic nuclide dating suitability. Approximately 20 g of purified quartz is needed per sample in order to yield measurable concentrations of ^{10}Be and ^{26}Al. This quartz will be extracted from the sand fraction in Young Womans Creek stream sediments, a mix of clasts from rock and sand fraction of alluvium and soil at Garner Run, and rock chips from Hickory Run.

All samples will be analyzed for ^{10}Be /^{9}Be ratios using AMS at Lawrence Livermore National Laboratory in California. Due to budget constraints, only a subset of samples from Hickory Run and Garner run will be analyzed for $^{26}Al/^{27}Al$, most likely at PRIME lab in Indiana.

Quartz isolation will be performed at the University of Vermont using standard methods (Kohl and Nizhiizumi, 1992). First, the samples will be crushed and ground and the magnetic fraction will be removed. Next, samples will be etched in strong HCl (to remove grain-coating oxides from grains, carbonate material, and meteoric ^{10}Be) and HF and HNO_3 (to dissolve all other minerals but quartz). Samples will then be placed in a furnace to burn off any organic material that may have survived etching, and if any mafic minerals remain a density separation will be performed. A final cleansing etch will be performed using HF and HNO_3. When all quartz has been isolated from the samples, a purity test will be performed using ICP. If any impurities such as Ca, Na, K, Fe, or Ti appear then the sample will subjected to an additional week of weak acid etching. Extraction of ^{10}Be and ^{26}Al will be done using UVM Cosmogenic Nuclide Laboratory standard methods.

5. Timeline

Time Period	**Tasks to Complete**
May 2015	-May 8-15th sample collection in Pennsylvania
June-August 2015	-Sample preparation -Quartz purification -Start writing methods section, initial background
Fall 2015	-Extractions for *in situ* ^{10}Be and ^{26}Al
Winter 2015	-Start writing introduction, continue background and methods -Measure ^{10}Be at Lawrence Livermore National Laboratory and ^{26}Al at PRIME -Present progress report
Spring 2016	-Data analysis -Begin writing discussion
Summer 2016	-Finish writing
Fall 2016	-Defend thesis

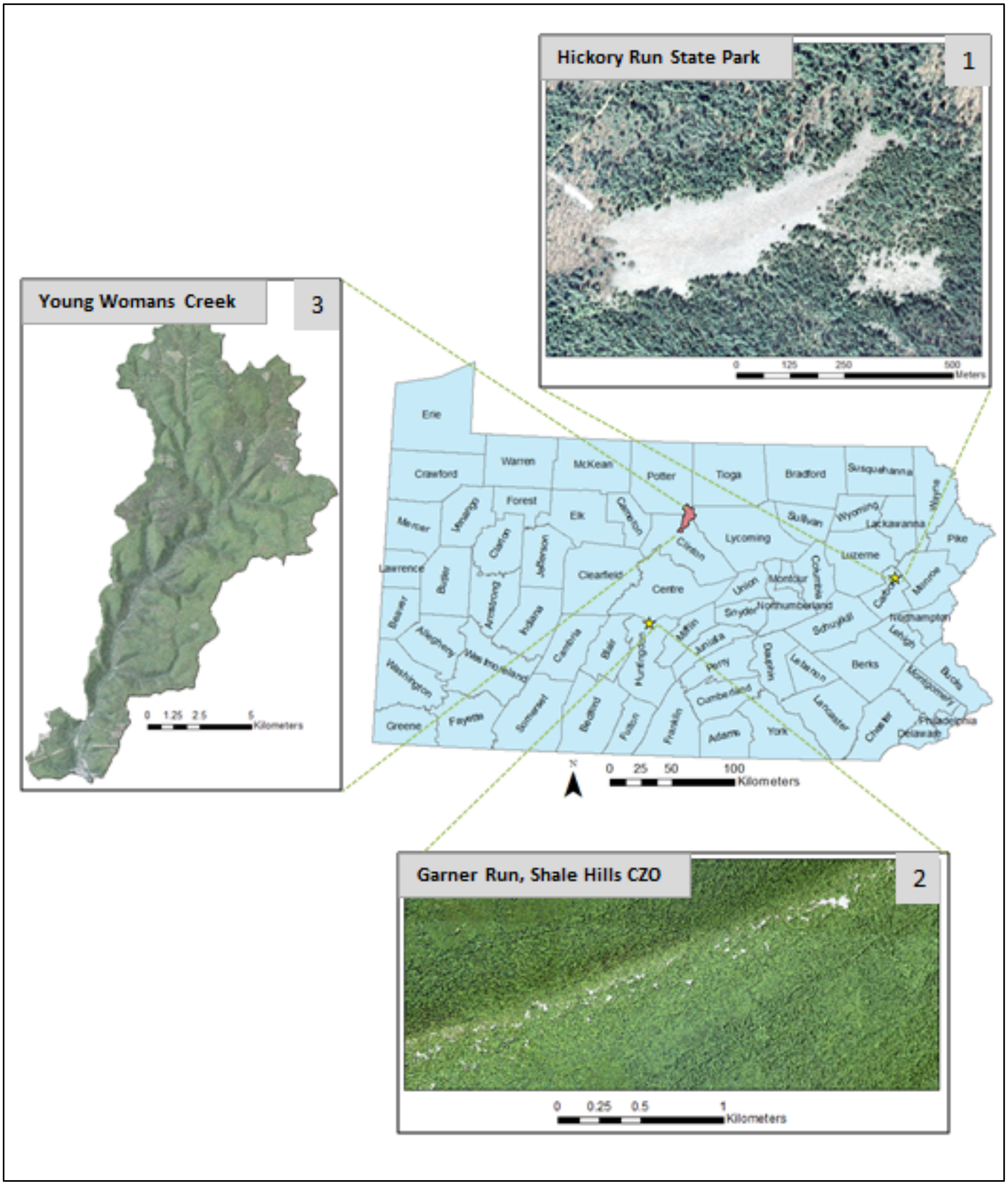

Figure 1. Locations of study sites: (1) Hickory Run State Park, (2) Garner Run, and (3) Young Womans Creek.

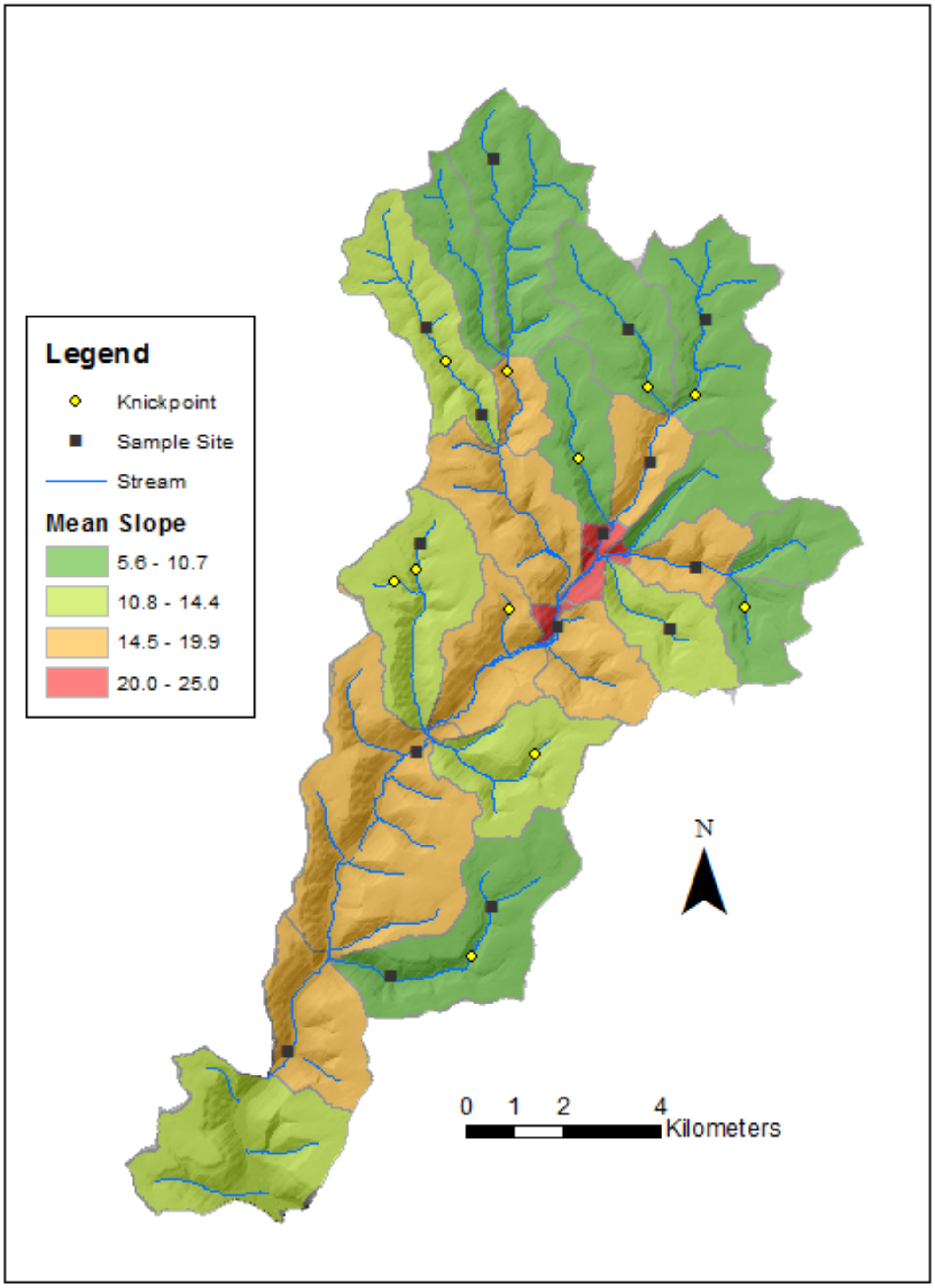

Figure 2. Sampling strategy for Young Womans Creek watershed (n=15). Subbasin polygons are displayed by mean slope, sample sites are black boxes, and knickpoints are in yellow.

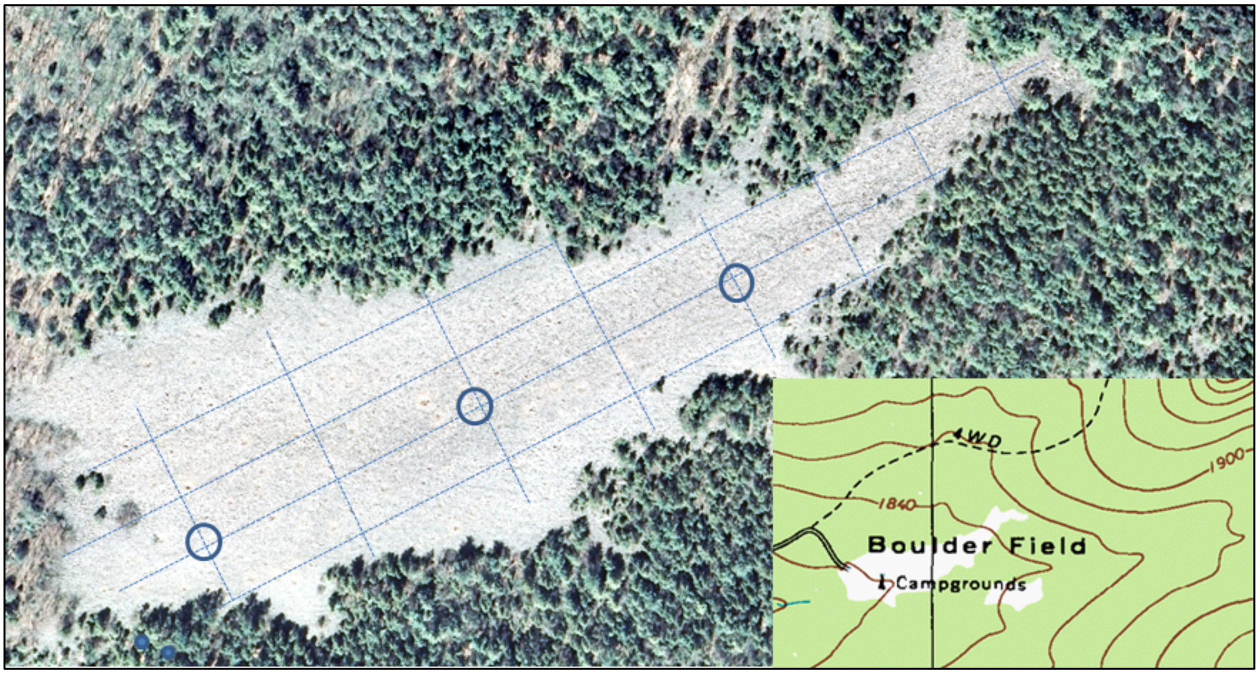

Figure 3. Sampling strategy for Hickory Run State Park. Samples will be taken at each intersection between long and short transects, and three samples for size analysis will be taken in each of the blue circles.

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