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BIOMECHANICAL EFFECTS OF TREES AND SOIL THICKNESS IN THE CUMBERLAND PLATEAU

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BIOMECHANICAL EFFECTS OF TREES AND SOIL THICKNESS IN THE
CUMBERLAND PLATEAU

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements of the degree of Doctor of Philosophy in the
College of Arts and Sciences
at the University of Kentucky

By
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Lexington, Kentucky

Director: Dr. Jonathan Phillips, Professor of Geography

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ABSTRACT OF DISSERTATION

BIOMECHANICAL EFFECTS OF TREES AND SOIL THICKNESS IN THE CUMBERLAND PLATEAU

Previous research in the Ouachita Mountains, Arkansas suggests that, on relatively thin soils overlying bedrock, individual trees locally thicken the regolith by root penetration into bedrock. However, that work was conducted mainly in areas of strongly dipping and contorted rock, where joints and bedding planes susceptible to root penetration are more common and accessible. This project extended this concept to the Cumberland Plateau, Kentucky, with flat, level-bedded sedimentary rocks. Spatial variability of soil thickness was quantified at three nested spatial scales, and statistical relationships with other potential influences of thickness were examined. In addition, soil depth beneath trees was compared to that of non-tree sites by measuring depth to bedrock of stumps and immediately adjacent sites.

While soil thickness beneath stumps was greater in the Ouachita Mountains compared to the Kentucky sites, there were no statistically significant differences in the difference between stump and adjacent sites between the two regions. In both regions, however, soils beneath stumps are significantly deeper than adjacent soils. This suggests the local deepening effects of trees occur in flat-bedded as well as steeply dipping lithologies. Regression results at the Cumberland Plateau sites showed no statistically significant relationship between soil depth and geomorphic or stand-level ecological variables, consistent with a major role for individual tree effects. Nested analysis of variance between 10 ha stands, 1.0 ha plots, and 0.1 ha subplots indicates that about 67 percent of total depth variance occurs at, or below, the subplot level of organization. This highly localized variability is consistent with, and most plausibly explained by, individual tree effects.

The effects of biomechanical weathering by trees are not limited to areas with strongly dipping and contorted bedrock. Variability of soil depth in the Cumberland Plateau is likely influenced by positive feedbacks from tree root growth, that these interactions occur over multiple generations of growth, and that the effects of trees are the dominant control of local soil thickness. Since lateral lithological variation was minimal, this study

also provides evidence that the positive feedback from biomechanical weathering by trees leads to divergent development of soil thickness.

KEYWORDS: Biogeomorphology, Soil Depth Variability, Nonequilibrium,
Biomechanical Weathering by Trees, Tree Rooting

Michael Lee Shouse Jr.

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BIOMECHANICAL EFFECTS OF TREES AND SOIL THICKNESS IN THE
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To Kelly, Dot, and Kentucky straight bourbon whiskey, my companions through many
late nights of pondering and conjuring

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CHAPTER 1

INTRODUCTION

This dissertation is positioned at the intersection of geomorphology, biogeography, and pedology, where the ultimate goal is a better understanding of the patterns, processes, and reciprocal interactions that exist in and between the biosphere, pedosphere, and lithosphere. Central to these themes are the spatiotemporal and scale dimensions of soil variability, complex systems, bioturbation, and biophysical pattern-process dynamics. The biomechanical impacts of trees as a contributor to soil processes, mainly soil deepening, are highlighted in this research. Trees growing on soils formed from weathered bedrock play a significant role in local deepening and mixing of soil by facilitating weathering in joints occupied by roots, infilling of depressions created by stump rotting, and the mining of bedrock through tree uprooting. The purpose of this research is to evaluate the spatial variability of soil depth to determine the impact of biomechanical weathering by trees on development of soil and regolith thickness. This work lies primarily in the subfield of biogeomorphology. The term biogeomorphology, used to describe the feedback system between geomorphic and ecological systems, has recently gained heightened research interest (Murray et al. 2008), but has roots that trace back to Charles Darwin and Nathaniel Shaler. This introductory chapter will highlight the history of biogeomorphology to provide context for the remainder of the dissertation. To further position this work into the field of biogeomorphology, and to focus the remainder of the dissertation, pivotal research related to the biomechanical impacts of trees on soil properties.

BIOGEOMORPHOLOGY AS A DISCIPLINE

Biogeomorphology is the study of the interaction between organisms and the development of landforms. Insights from Dietrich and Perron's (2006) search for a topographic signature of life may help to determine the extent to which organisms impact geomorphic change. They approached this question from three directions. First, they considered how bioprocesses influence weathering, erosion, and sediment transport and how this could influence landscape- scale geomorphology. Second, they considered how

bioprocesses impact climate and tectonics, which are important components in landscape evolution. Third, they examined landscapes on the surface of Mars and Venus to compare them to surfaces found on Earth. Unfortunately, they were unable to identify any landforms on Earth that could not exist without life, with the exception of coral reefs, which they disqualify. In other words, landforms that exist in the absence of life on Mars are also found on Earth. They suggested that a unique topographic signature of life could be possible at a narrower spatial scale. The biomechanical weathering by trees could be the key to finding this topographic signature of life. Granted, if regolith thickness variation is not expressed in surface topography, then it could not be a topographic signature. However, if erosional processes have removed the regolith to directly expose the bedrock, then the effects of trees could possibly be observed via microtopographic variation in areas of uniform lithology. This dissertation research will help to determine if biomechanical weathering by trees is an active process in areas with said uniformity.

Phillips (2009) reviewed estimates of global rates of kinetic energy of uplift and denudation and compared those to the global rates of kinetic energy of net primary production. He found that the energy associated with net primary production was so much greater than the combination of uplift and denudation that if just 0.1 percent of net primary production were used for geomorphic work then it would far exceed the energy inputs of uplift and denudation. A case study that estimated the net primary production, rate of denudation, and rate of uplift in the University of Kentucky's Robinson Forest showed that in this area biological energy is several orders of magnitude higher than uplift or denudation rates even if only 0.001 percent of net primary production is used for geomorphic work. Phillips (2009) suggested that in some cases organisms could be the primary agents of landscape evolution. However, Phillips (2009) also stated that all geomorphological and ecological processes -- and thus their relative importance in landscape evolution -- vary both geographically and temporally. Second, energy associated with other abiotic processes driven by solar energy are greater, on average, than net primary production, though the contribution of these processes to geomorphic work is poorly known (Phillips 2009).

An argument can be made that suggests that geomorphic change is primarily driven by biologic processes in some environments. However, research on the amount of net primary production that is geomorphologically relevant is needed. Further, biological agents of geomorphic change are not so important that the same topography would not exist in their absence, at least at the landscape scale (see Dietrich and Perron 2006). Based on information from these two studies it is clear that organisms provide a significant amount of energy to geomorphic processes and that a mechanistic understanding of their role in landscape evolution is needed. This dissertation research will aid in this mechanical understanding by analyzing the effects of trees on soil thickness.

The awareness that life influences, and is influenced by, geomorphic principles is not a new phenomenon. Charles Darwin was one of the first researchers to consider organisms as agents of geomorphic change. In 1881 Darwin published a book titled “The Formation of Vegetable Mould, Through the Action of Worms, With Observations on Their Habits”. In this book, Darwin outlined the process by which worms ingest soil at depth and deposit it on the surface as fecal castings (Darwin 1881, Johnson 2002). Darwin’s research specifically examines the role of worms in the rock weathering, denudation of the land, preservation of buried artifacts, and improvement of soil growing conditions. Another early example of biogeomorphology research is Nathaniel Shaler’s book “The Origin and Nature of Soils,” one chapter of which specifically discussed the effects of animals and plants on soils. Shaler divided these effects into three classes; (1) the influence of organisms on rocks underlying mineral soils, (2) the modification of soil through animal and plant interactions, and (3) the contribution of organic remains to soils (Shaler 1892). Shaler made specific mention of Darwin’s worm research and he identified ants as agents of geomorphic change. Shaler also contributed to early research on tree uprooting by diagramming the hypothetical uprooting process and discussing its role in bioturbation. In 1899, Henry Chandler Cowles published a book titled “The Ecological Relations of the Vegetation on the Sand Dunes of Lake Michigan”. Cowles (1899) identified the stabilizing properties of vegetation and its role in the accumulation of sediment. He also noted that the physical properties of dunes help to determine what

types of flora could establish. His recognition of the reciprocal interactions between landforms and biota, and the coevolution of ecosystems and landscapes made him one of the earliest and most influential researchers of biogeomorphology (Stallins 2006).

In the late 20th century there was resurgence in research on the interaction of organisms with geomorphology due to the work of D.L. Johnson and his students in the 1980's (Johnson and Watson-Stegner 1987, Schaetzl et al. 1989, Johnson 1990). Johnson and Watson-Stegner (1987) included floral and faunalurbation as major components of pedogenesis, provided evidence of arboreal bedrock mining, and discussed the creation of surficial biomantles. Johnson (1990) focused exclusively on the topic of biomantle evolution. The investigation of bioturbation continued by Schaetzl et al. (1989) in their review of tree uprooting terminology, process, and environmental implications. Tree uprooting can occur during many disturbance events, including thunderstorms, ice storms, hurricanes, and tornados. An important aspect of tree uprooting is the creation of pit/mound microtopography. After an uprooting event, a pit is formed where the root ball was located. Soil and rock will slump off of the root plate and create an adjacent treethrow mound. Schaetzl et al. (1989) reviewed many types of observational research that has been conducted on pit/mound microtopography, including size of pits, size of mounds, distribution of pits and mounds, longevity of pit/mound topography, and slope of mounds. Perhaps more to the interest of pedologists, they showed that pit/mound microtopography play an important role in soil processes. They specifically discussed the effects of uprooting on soil morphology, effects of microtopography on soil characteristics, and the effects of uprooting on pedogenesis and soil classification.

Following in the tradition of Darwin and Shaler, Butler (1995) discussed the geomorphic contributions of multiple vertebrate and invertebrate animal species in the book "Zoogeomorphology: Animals as Geomorphic Agents". While much of this work centered on the well-studied concept of tunneling, other processes by which animals impact geomorphology were also covered. This included concepts related to soil engineering, slope stability, sedimentation, trampling, and digging. More importantly, this book marks an important historic moment in the field of biogeomorphology, which

encompasses zoogeomorphology. It is within this book that Butler criticized the field of geomorphology for overlooking the role of animals as geomorphic agents of erosion, transportation, and deposition. He cited 10 geomorphology textbooks written since the 1970's that did not include any mention of animals as agents of geomorphic change.

Another pivotal work in the current understanding of biogeomorphology is the concept of ecosystem engineering presented in Jones et al. (1994). Ecosystem engineers are organisms that modulate the availability of resources to other species by changing the physical environment. This concept provided a direct link between bioprocesses and geomorphic change (Corenblit et al. 2011). Jones et al. (1994) classified ecosystem engineers as either autogenic engineers or allogenic engineers. Autogenic engineers alter the environment through their physical structures (corals, mussels, etc.) while allogenic engineers change the environment through mechanical or chemical means (beavers, ants, trees, etc.). One of the key components of this manuscript is the list of examples of organisms that act as ecosystem engineers. This list demonstrated that ecosystem engineers could occur in any system with biologic activity. Other important topics discussed included bioturbation, keystone species, and human impacts. Jones (2012) directly linked the concepts of ecosystems engineers and geomorphology, nearly 20 years after this initial work.

In addition to the identification and analysis of biogeomorphic agents, researchers in the 21st century have placed an importance on defining key concepts in biogeomorphology. Naylor et al. (2002) divided the biological impacts on geomorphological systems into three dominant groups of processes; bioconstruction, bioprotection, and bioerosion. Bioerosion includes biologic impacts related to weathering or removal of material. Bioconstruction includes biologic impacts related to physical upbuilding. Bioprotection includes biologic impacts that hinder other earth surface processes. Stallins (2006) publication on unifying themes for complex systems in biogeomorphology revisited the concept of reciprocal interactions. In the tradition of Cowles (1899), this research focused on the bidirectional feedback that exists in biogeomorphic systems. Stallins (2006) introduced four overlapping themes that link geomorphology and ecology:

multiple causality, ecosystem engineering, ecological topology, and ecological memory. Multiple causality includes the feedback loops between biota and landforms. Ecosystem engineering includes the construction of landforms by biota. Ecological topology includes issues dealing with scale between biota and geomorphology. Ecological memory encompasses how a subset of abiotic and biotic components are selected and reproduced by recursive constraints on each other. These themes, according to Stallins (2006), enable the field of biogeomorphology to grow beyond a discipline focused on identifying and listing biotic impacts to geomorphology.

Corenblit et al. (2011) provided a comprehensive review of the feedbacks between biota and geomorphology. They outlined a conceptual evolution of the discipline of geomorphology using foundations of ecological concepts as historical markers. The concepts included were keystone species (Paine 1966), ecosystem engineers (Jones et al. 1994), facilitation (Odum 1969), extended phenotype (Dawkins 1982), eco-evolutionary dynamics (Post and Palkovacs 2009), macroevolution (Erwin 2008), niche construction (Odling-Smee et al. 2003), and ecological heritage (Odling-Smee et al. 2003). Of significance to biogeomorphology, Corenblit et al. (2011) linked the ecosystem engineer concept of Jones et al. (1994) with the bioprocesses defined in Naylor et al. (2002), adding bioturbation as a distinct bioprocess, and Phillips (2009b) argued that soils are extended composite phenotypes.

BIOMECHANICAL EFFECTS OF TREES

Much of the recent work in biogeomorphology has focused on the geomorphological impacts of biota on salt marshes (e.g., Zhang et al. 2004; Kim et al. 2012) and sand dunes (e.g., Baas 2002; Stallins and Parker 2003; Maun 2008; Smith et al 2008; Nordstrom et al. 2009). Forest ecosystems, which are temporally less dynamic than salt marshes and sand dunes, have received less attention. Individual trees have been shown to have profound impacts on the properties and nature of surface features in forest ecosystems (e.g., Wilson et al. 1997; Boettcher and Kalisz 1990; Schaetzl et al. 1989, 1990; Phillips and Marion 2004). Yet, the biomechanical impacts of trees as a contributor to soil processes remains poorly understood. This research will address this knowledge gap by

examining the impacts of biomechanical weathering by trees on a specific soil characteristic, soil thickness.

Regolith is generally defined as the unconsolidated material overlying undisturbed, unweathered sedimentary deposits or solid bedrock. Soil is generally defined as the uppermost, most highly altered portions of the regolith, excluding saprolite or the lowermost portions of the weathering profile. For this research, soil is defined as the portion of the regolith above the Cr soil horizon. The Cr horizon consists of soft, weathered bedrock and saprolite that could be dug with a spade. The point in the weathering profile where soil meets the Cr horizon is deemed the paralithic contact in this research and is thought to represent a root-limiting layer. For many locations in this research soil has direct lithic contact with the R horizon and no Cr horizon is present. In this situation soil thickness and regolith thickness are equal. So for this research, soil thickness is defined as the depth to lithic or paralithic contact. To simplify terminology, soil will be used exclusively to represent both soil and regolith. This is consistent with other geomorphologists, especially in context of hillslope or landscape evolution (Phillips et al. 2005b). For details on the methods used to measure soil thickness see Chapters 3 and 5.

Soil thickness in this research is primarily based on Johnson's soil thickness model:

$$T = D + U + R \quad (\text{Equation 1.1})$$

where the thickness (T) of a mineral soil is viewed as a dynamic interplay of deepening (D), upbuilding (U), and removals (R) (Johnson 1985, Schaetzl and Anderson 2005). Soils get thicker when $D + U > R$, $D > U - R$ and soils get thinner when $D + U < R$ (Schaetzl and Anderson, 2005). Deepening refers to the downward migration of the lower soil boundary primarily through weathering and leaching processes (Johnson 1985; Schaetzl and Anderson 2005). Upbuilding refers to the surficial additions of mineral and organic material ((Johnson 1985; Schaetzl and Anderson 2005). Removals refer to losses of materials primarily through erosion and mass wasting (Johnson 1985; Schaetzl and

Anderson 2005). The focus of this dissertation research is on deepening processes specifically related to biomechanical weathering by trees. Phillips et al. (2005b) expanded Johnson's soil thickness model to be more observationally oriented and as a result, specifically included bioturbation and bioconstruction processes. Their model for soil thickness is

$$T = (W + B) + (A + O + V) - (E + L + C_{\text{surf}} + C_{\text{sub}}) \quad (\text{Equation 1.2})$$

where W is weathering at the weathering front, B is deepening due to bioturbation, A is surface accretion, O is organic matter additions, V is volume expansion (e.g., due to tree root growth), E is surface removal due to erosion and mass wasting, L is subsurface removals due to leaching, and C is subsurface or surface consumption by fire, uptake, and such, as it applies to organic matter (Phillips et al. 2005). Mechanically, trees contribute to the local pedologic processes via uprooting, infilling of stump holes, displacement of rocks and rock fragments, and root growth. In this case, and hereafter, mechanical contributions refer to contributions via the physical growth of trees with the acknowledgment that these contributions are not void of chemical processes and/or influences. As this study focuses on tree root penetration of rock, and soil/regolith thickness, and does not directly address the bio- and hydrochemical weathering processes at the root-rock interface, for purposes of this proposal these impacts are lumped into the biomechanical category. These processes don't all directly contribute to mechanical soil deepening, but they are active participants in soil formation, which is explained by the model of self-reinforcing pedologic influences of trees (SRPIT).

Former tree locations have been identified as prime locations for new tree establishment. Van Lear et al. (2000) suggested that decomposing loblolly pine roots are nutrient-rich microsites and that they are ideal locations for new tree establishment. Phillips and Marion (2004) proposed a model of self-reinforcing pedologic influences of trees to explain the locally variable forest soil found in the Ouachita Mountains as a function of repeated occupancy of trees over time. The SRPIT conceptual model proposes that there are self-reinforcing mechanisms that provide a favorable advantage to trees occupying

the location of former trees. The primary mechanisms presented in this model include the displacement of rocks and rock fragments away from the site through tree growth and uprooting and the input of nutrients through stump rot and infilling processes. Phillips (2008) expanded this model to include the effects of repeated occupancy on local soil thickness. One interpretation of this model, and the one used in this research, is that where soil is thin, pockets of deeper, relatively rock free, nutrient-rich soil provide an advantage for trees, so while trees have a random likeliness of reaching a seedling stage, trees growing in deeper, rock free, nutrient-rich soils are more likely to reach canopy height. Likewise, trees that reach canopy height likely have more extensive root systems and are more likely to penetrate bedrock joints and further weather the bedrock surface. This creates a positive feedback where $D > U - R$ for a specific tree location. This repeated occupancy represents a self-reinforcing feedback between biota and surface processes and implies that the locations of trees capable of biomechanical weathering are non-random. This also implies nonequilibrium soil thickness, which will be explained in the next chapter.

The advantage of locally thicker soil likely presents itself differently depending on the site productivity. In xeric conditions, trees try to gain a competitive advantage in water availability. Former tree locations in dry environments could locally improve moisture availability in two ways. First, these locations have systematically deeper soils that allow for the storage of more water due to there being more soil volume. Tromp-van Meerveld and McDonnell (2006) suggested that locally deeper soils lead to faster depletion of soil moisture in nearby shallow areas, which make former tree locations even more important in dry, upland areas. Second, stump holes fill with organic matter and detached soil from the walls (Phillips and Marion 2006). This increase in organic matter could lead to more water holding capacity. In mesic environments, soil resources are not as limited, so competition is for available light. Tree species try to position themselves to take advantage of recently opened pathways to sunlight. Former tree locations in mesic environments could provide pathways to more nutrients and better root development, enabling trees to outgrow adjacent trees when light becomes available. Hydric soil environments are limited by O_2 , which is needed for respiration. As with stump holes

found in xeric environments, stump holes in wet environments are also likely to fill with organic matter and detached soil from the walls (Phillips and Marion 2006), which aerates the soil. Poor aeration of the soil can slow the decay of organic materials and limit nutrient availability to plants (Brady and Weil 1996). It is possible that the increased aeration in former tree locations from stump hole filling and collapse could provide a better source of readily available nutrients, thus creating a competitive advantage.

Of the limited research that has been conducted on the biomechanical effects of trees, most has focused on tree uprooting (e.g., Johnson et al. 1987; Schaetzl et al. 1989; Johnson 1990, Gabet and Mudd, 2010; Šamonil et al. 2010). Tree uprooting is a major form of surface disturbance in forest communities. Tree uprooting can occur during many disturbance events, including thunderstorms, ice storms, hurricanes, and tornadoes. An important aspect of tree uprooting is the creation of pit/mound microtopography. Tree uprooting refers to the toppling of a tree that remains attached to large roots near the bole, which results in the upward twisting of the root mass with soil (Osterkamp et al. 2006). When a tree >13 cm in diameter at breast height (DBH) is uprooted, a portion of the soil that anchored the roots is transported to the surface, both vertically and horizontally, leaving a pit and over time a mound (Gabet et al. 2003, Gallaway et al. 2009). Schaetzl et al. (1990) explained the creation of pit/mound microtopography as two separate processes. During the uprooting of trees, a pit is formed where the root ball was located. As the tree lies, soil and rock will slump off of the root plate and create an adjacent treethrow mound, which is an upbuilding process. These visible pit-and-mound formations provide evidence of the impact trees have on soil processes. If the tree is anchored in bedrock it is possible for fragments of parent material to be transported vertically and horizontally as well, as part of the root wad. This is an important indicator of biomechanical weathering, via root/bedrock interaction, that can be observed in the field.

Schaetzl et al. (1990) reviewed observational research on pit/mound microtopography, including size of pits, size of mounds, distribution of pits and mounds, longevity of

pit/mound topography, and slope of mounds. Perhaps more to the interest of pedologists, they showed that pit/mound microtopography plays an important role in soil processes. They specifically discussed the effects of uprooting on soil morphology, effects of microtopography on soil characteristics, and the effects of uprooting on pedogenesis and soil classification. Ulanova (2000) reviewed the soil impacts of tree uprooting, where she placed a large emphasis on spatial and temporal scale, with regards to biologic and geomorphic processes. She claimed that uprooting results in sharp changes in the soil profile, which include a high amount of organic content during the first 50-200 years. She claimed that in a shallow pit the background soil combination and processes are completed in 100-200 years and in larger pits it can take more than 200-300 years.

One of the latest reviews on the role of tree uprooting, by Šamonil et al. (2010) advanced the discussion of many of the same topics discussed in Schaetzl et al. (1990) and Ulanova (2000), and provided updated information. This material included tackling scale issues in uprooting research, which entailed dating the age of pits and mounds and explaining their properties. Like Schaetzl et al. (1990), Šamonil et al. (2010) discussed the temperature fluctuations of pits and mounds, but also included details about humidity. According to Schaetzl et al. (1990) mounds are typically warmer and drier than pits, with the exception that pits can be warmer during snow cover. Newer research presented in Šamonil et al. (2010) now reports that the temperature of mounds can be several degrees higher and the humidity may be several tens of percent different than pits; which has impacts on soil classification and formation. Šamonil et al. (2010) also discussed the impacts of tree uprooting on soil formation across different scales. They, like Schaetzl (1990), stated that enhanced leaching is present in the pit, possibly due to the presence of decomposed wood.

The infilling of depressions caused by stump rot and uprooting represents one method by which tree growth aids in the development and thickening of regolith at a specific location. Depressions fill with organic material, rock, and or soil through gravitational forces (Phillips et al. 2005b). Depending on the rate of material breakdown this can either (momentarily) bury soils, or deepen them. Similar to the formation of mounds, this

is representative of a type of local upbuilding, or bioconstruction. As mentioned previously, the breakdown of this material can provide nutrients to the soil, increase the water storage capacity of the soil, and/or aerate the soil, thus creating a competitive environment for canopy tree establishment and growth. While not a focus of this research, these depressions may also aid in the biochemical weathering of bedrock by providing a pathway. Organic matter from decomposing trees has been shown to influence soil organic properties, chemistry, and weathering (Schaetzl and Follmer 1990, Van Lear et al. 2000, Phillips and Marion 2004).

While tree uprooting and depression infilling have significant impacts to soil characteristics, it is the interaction of roots with bedrock that directly facilitates the biomechanical deepening of soil. Lutz (1960) reviewed some of the earliest examples of research on root penetration, where tree roots grew several meters into sandstone and granite. Phillips and Marion (2004, 2005) suggested that trees growing on soils formed from weathered bedrock may play a significant role in local deepening and mixing of soil by facilitating weathering in joints occupied by roots and the infilling of depressions created by stump rotting. They showed that soil underlying individual tree locations were systematically deeper or thicker than at adjacent locations in the shallow forested soils of the Ouachita Mountains (Phillips and Marion 2004, Phillips 2008). Their findings suggested that individual trees may “engineer” sites to produce relatively thicker soil when thickness is less than the preferred or optimum rooting depth. Gabet and Mudd (2010) considered this microtopographical variation due to root fracture when simulating the production of soil from bare rock. Through computer simulation based on empirical data they demonstrated that root fracture, a term used to describe the occupation of roots in bedrock fractures, leads to a rough and uneven bedrock surface. It is unlikely that the biomechanical weathering required to explain this rough and uneven surface occurred during one generation of tree growth.

Gabet et al. (2003) reviewed root interactions with bedrock fractures and found that roots penetrate fractures in bedrock as small as 100 μm and expand over time, generating sufficient pressure to fracture soft bedrock. They report that radial pressure can reach .92

MPa and axial pressure can reach up to 1.45 MPa. It was also shown that roots are able to penetrate bedrock by inducing mineral dissolution. A positive feedback loop was hypothesized between the two processes; where chemical weathering causes the bedrock to be more susceptible to mechanical breakup and mechanical breakup leads to more surface area for chemical weathering. Matthes-Sears and Larson (1995) also provided key information about rooting into bedrock. They excavated eastern white cedar trees from a limestone cliff and analyzed the rooting characteristics. Their results showed that eastern white cedar could grow directly into rock without soil (32.3% of their samples). They also reported that 79.0% of their samples penetrated bedrock an average of 9 cm, with a maximum of 30 cm. The trees they observed were between 6 – 27 years old. Phillips et al. (2008) have also documented the relationship between roots and bedrock joints and fractures. Their study was conducted on recently exposed bedrock benches in the Ouachita Mountains, where trees had begun to colonize. They found that trees consistently penetrated bedrock through joints and bedding planes.

It is well known that tree uprooting is a mechanism by which rocks or rock fragments are brought to the surface (Lutz 1960, Ulanova 2000, Phillips et al. 2005a, Osterkamp et al. 2006). Of significance to the SRPIT model, rock fragments are removed from the tree location during this process. Phillips and Marion (2005) considered a low soil rock volume as an advantage to tree growth so the local displacement of rocks represents a positive feedback. Rocks and rock fragments are also displaced through general root growth (Phillips et al. 2005a). Further, locations currently occupied by trees are not impacted by the downward movement of rocks and rock fragments. An examination of the volume of rocks or rock fragments in tree throw root wads should indicate interaction between roots and bedrock, a key component to soil deepening. Phillips et al. (2005a) suggested three methods in which rocks and rock fragments may be introduced in regolith; (1) they could be present in their original stratigraphic position through inheritance from the parent material, (2) transported from upslope by mass wasting, erosion, or human agency, and, most importantly for deepening (3) they can be produced *in situ* by upward transport from the weathering front. For an examination of the volume of rocks or rock fragments in a tree throw root wad to conclusively indicate

biomechanical weathering by trees it would have to be determined that the rocks or rock fragments were produced *in situ*. The first step in determining this would be to identify the underlying bedrock and see if the rocks or rock fragments match the parent material. For example, if sandstone rock fragments were found in a tree throw at the bottom of a slope and the underlying bedrock is shale, then the likely explanation would be that the sandstone was transported to that location from an upslope location. However, if shale fragments were found in the tree throw then this provides some evidence of root/bedrock interaction. Orientation of the rocks or rock fragments found in the root wad is also important; if these are mined from underlying sedimentary rock they should have a consistent orientation.

It is reasonable to assume that other agents of weathering could result in variable bedrock weathering and regolith deepening, and thus variable soil thickness. In the Ouachita Mountains, one of the primary controls of local soil spatial variability is local lithological variation (Phillips et al. 2005b). It is possible that local lithological diversity could play an important role in controlling soil depth (Phillips 2010). For example, in areas where an easily erodible material, such as shale, is interbedded with an erosion resistant material, such as sandstone, it is possible for weathering to be unevenly distributed (Vanwalleghem et al. 2010). The number and size of bedrock joints and fractures in a given area could also influence soil depth spatial variability. Though this may be related to reciprocal interaction between roots and bedrock (Phillips and Marion 2005), it could also play an important role in the absence of trees. Further potential lithological controls of soil depth spatial variability could include karst processes. Uneven dissolution and structural failure can lead to a locally variable bedrock surface (La Valle 1968). Coal seams, which are sometimes present in the study area, could also aid in creating a variable bedrock landscape. In addition to coal seams dissecting other softer materials, they could also contribute to joint expansion and ground collapse through underground combustion (Stracher and Taylor 2004). If lithological variation was controlled and the bedrock still displayed a variable surface, then this would be indicative of biomechanical weathering by trees via SRPIT processes.

Phillips and Marion (2005) suggested that topography was a likely contributor to soil depth spatial variability. Even when rock type is consistent, weathering can still result in local soil spatial variability (Saco et al. 2006). This is due to topographic controls on water transport, water storage, and microclimate. One reason for this unequal weathering across homogenous rock types is related to microclimatic variations due to aspect, as shown by Hall et al. (2005). Aspect controls the amount of available sun available to a specific location, which results in differing moisture and temperature gradients. A slope with afternoon sun will be warmer than an equivalent slope with morning sun in North America (McCune et al. 2002). In Hall et al. (2005) aspect controlled the distribution of lichens, which act as biological weathering agents in many systems. In addition to biomechanical weathering, chemical weathering can be topographically controlled (Burke et al. 2007). Burke et al. (2007) found that weathering rates decreased with slope across the divergent ridge and increased with upslope contributing area in the convergent swale. They also found that weathering intensity decreased linearly with an increase in saprolite PH from 4.7 to almost 7 (Burke et al. 2007). If soil depth is not related to topography for a given area of homogenous parent material, then this is consistent with biomechanical effects of trees or some other localized effect on thickness.

Beyond trees, microbes play an important role in local weathering in soil-covered landscapes (see Viles 1995; van Scholl et al. 2008). Much of the research on forest soil microbial communities has focused on mineral weathering within soil. Many microbial communities have been shown to have spatially variable distributions (Calvaruso et al. 2007, Uroz et al. 2007, Calvaruso et al. 2010, Uroz et al. 2011). Based on this notion, it can be reasoned that microbial communities that directly impact bedrock could also have spatially variable distributions, which in turn could result in a variable bedrock surface, which is manifested as pockets of increased soil thickness. However, the effects of microbes cannot necessarily be removed from tree effects due to a strong dependence, and in some cases symbiosis, between tree roots and soil microbial communities (Andrews et al. 2008, Bonneville et al. 2011).

The purpose of this research is to understand the biomechanical effects of trees on localized soil deepening across spatial scales. This study focuses on soil/regolith thickness and its relationship with individual trees, and does not directly address the bio- and geochemical weathering processes at the root-rock interface. However, because the latter require contact with or penetration of bedrock, for the purposes of this study these impacts are lumped into the biomechanical category.

CHAPTER 2

RESEARCH QUESTIONS, STUDY AREA, AND BACKGROUND

The approach taken to better understand the role of biomechanical weathering by trees in this research was to answer the following three research questions, which collectively address issues related to pattern and scale. (1) How does spatial variability of forest soil depth differ between steeply-dipping and horizontally oriented underlying bedrock? (2) What is the relative importance of individual trees vs. other potential controls of local variability in soil depth? (3) How is the variance of soil depth partitioned across spatial scales? These research questions apply to forests with relatively thin soils overlying sedimentary bedrock. The explanation of each research question's development and its relationship to the research goals is presented below. In addition, this chapter will provide details about the study areas used, and provide relevant theoretical background needed to interpret the results and discussions.

RESEARCH QUESTIONS

Research Question 1 (RQ1): How Does Spatial Variability of Forest Soil Depth Differ Between Steeply-Dipping and Horizontally Oriented Underlying Bedrock?

Phillips and Marion (2004) observed that soil was deeper beneath stump holes than at adjacent locations in the Ouachita Mountains, Arkansas. In that area the sedimentary rocks are strongly dipping and contorted, providing more opportunity for root penetration of fractures and bedding planes than would be the case in other geologic settings.

Phillips and Marion (2005) found that biomechanical effects of trees and lithological variations were linked to spatial variability of soil depth in shallow (<1.5 m) forest soils. They considered this evidence of divergent evolution of the soil system and suggested that future work be conducted to investigate the importance of geological variation in this process. Thus the evaluation of this research question will test the hypothesis of systematically deeper soils beneath tree stumps in a different geologic setting, the Cumberland Plateau, where bedrock is composed of flat-bedded sedimentary rocks, which presumably offer less opportunity for roots to penetrate bedrock. If soil is

systematically deeper beneath trees in the absence of such extreme lithological variation then it will suggest that primarily the biomechanical effects of trees control this divergent condition; otherwise a major role for lithological and structural variability of parent material is indicated. In this case, and for the remainder of the dissertation, lithological variation is used interchangeably with structural variation. Due to structural variability the bedrock type at the soil interface differs more frequently at the tree influence scale in the Ouachita Mountains compared to the Cumberland Plateau even where bedrock type is the same. The expected outcome was that soil thickness would be less at the Cumberland Plateau sites than at the Ouachita Mountains sites due to this structural variation.

Compressional stress in Ouachita Mountains leads to extensive fracturing and jointing, and may expose bedding planes to root penetration from above. Flat-bedded rock of the Cumberland Plateau is jointed, but has not experienced strong tectonic stress, and dips do not expose bedding planes to root invasion from above. More details on each study area are presented in the next section of this chapter.

Research Question 2 (RQ2): How effective are relief and organic factors from the standard soil factors model at predicting soil depth in the Cumberland Plateau?

The standard soil factors model, which is credited to Jenny (1941) and sometimes referred to as the *clorpt* model, conceptualizes soil (S) as,

$$S = f(cl, o, r, p, t, \dots) \quad (\text{Equation 2.1})$$

where soil types or soil properties are a function (f) of climate (cl), organisms (o), relief (r), parent material (p), and time (t). For this research question climate, parent material, and time were held (mostly) constant by examining soils sampled in similar geographic and geologic areas. Using linear regression, the relationships between soil depth characteristics and plot and landscape variables were explored. Specific variables included were aspect, slope gradient, slope shape, and slope position, which are topographic (relief) factors and basal area, trees per hectare, and stump-hole diameter, which are ecological factors. Aspect, the horizontal direction a slope is facing, is topographic in nature, but primarily influences soil properties via microclimatic controls

to moisture regimes and vegetative communities (see, Olivero and Hix 1998; Abnee et al. 2004; Hall et al. 2005). Slope gradient is directly proportional to the rate of erosion, an important factor in soil thickness (Minasny and McBratney 1999). Slope shape, or topographic curvature, affects flow acceleration and deceleration (Odeh et al. 1991, Minasny and McBratney 1999). Slope position impacts the amount of sediment deposition, and thus soil depth (Sariyildiz et al. 2005). Basal area and trees per hectare are derivatives of tree density, which impact soil depth via vegetative community structure and leaf litter accumulation (Sariyildiz et al. 2005, Yimer et al. 2006). The role of stump diameter has not been evaluated in terms of soil thickness, but it seems logical that larger trees have a better likelihood of bedrock interaction due to their larger root systems.

Research Question 3 (RQ3): How is the Variance of Soil Depth Partitioned across Spatial Scales?

Scale-dependence has been recognized as a central concern in ecological and geographical research, where different ecological patterns and processes are dominant at different spatial scales (Mooney and Hobbs 2000, Wilson et al. 2007, Kim et al. 2012). This implies that changes in scale, by changes in grain (i.e., size of unit plot) or extent (i.e., size of study area), can result in significant changes in biotic and abiotic relationships. Recently, biogeomorphologists have placed a particular interest on understanding how broad-scale properties can emerge from lower-level interactions between geomorphic and ecological components (Stallins 2006, Corenblit et al. 2011). The effects of single trees on local soil properties are significant (Boettcher and Kalisz 1990, Phillips and Marion 2004). Examining the spatial heterogeneity of specific single tree effects with respect to scale will help better explain the biogeomorphological role of biomechanical weathering by trees. Yet, the extent to which tree effects impact the landscape across scales is unknown. This research question will examine the variance of soil depth across scales in a forest system where soil depth variability may be due to biomechanical weathering by trees. If the impacts of biomechanical weathering by trees are dominant, the local scale should explain a significant amount of variation. If the

broader, landscape scale explains a significant amount of variation, then the topographic controls of soil depth will be considered dominant.

STUDY AREAS

The sampling of biological and physical characteristics needed to answer the each research questions took place in the Ouachita Mountains and the Cumberland Plateau physiographic regions. Within the Ouachita Mountains, sampling took place in the eastern Ouachita National Forest. Within the Cumberland Plateau, sampling was conducted in the Koomer Ridge section of Daniel Boone National Forest and the Indian Trails section of Berea College Forest.

Ouachita Mountains

The Ouachita Mountains are an east-west trending folded mountain range in west central Arkansas and southeastern Oklahoma with elevations ranging from 230 m to 839 m. This research took place within the Ouachita National Forest (ONF) (34°29'45" north, 94°07'30" west) (Figure 2.1). The Ouachita Mountains have a humid subtropical climate and a mean annual precipitation of about 1200 mm yr⁻¹ (Phillips and Marion 2005). Average daily summer and winter temperature ranges are 20-30 °C and 4-10 °C, respectively. Forest cover is dominated by shortleaf pine (*Pinus echinata*) and various oak species (*Quercus sp.*).

Geology in the Ouachita National Forest consists primarily of extensively faulted and strongly dipping and contorted Paleozoic sedimentary bedrock (Stone and Bush 1984) that are primarily composed of sandstone and shale (Jordan et al. 1991). Chert, quartzite, and novaculite are also found in lesser amounts. The sample locations were within the Stanley Shale, Jackfork Sandstone, and Atoka Formation lithologic units. Intermixing and alternating strata of sandstone and shale are commonly found, in steeply dipping strata ranging from about 30° to near-vertical bedrock orientations. Phillips et al. (2005b) observed that exposed shales were deeply weathered and highly erodible, whereas sandstones were noticeably less weathered and more durable. They also noted that many of the shales were soft enough, particularly when weathered, to permit root penetration

(Phillips and Marion 2004; Phillips et al. 2008). While shale ranges from hard to soft depending on the formation, weathered shale is typically soft and has low shear strength (Bryson et al. 2012).

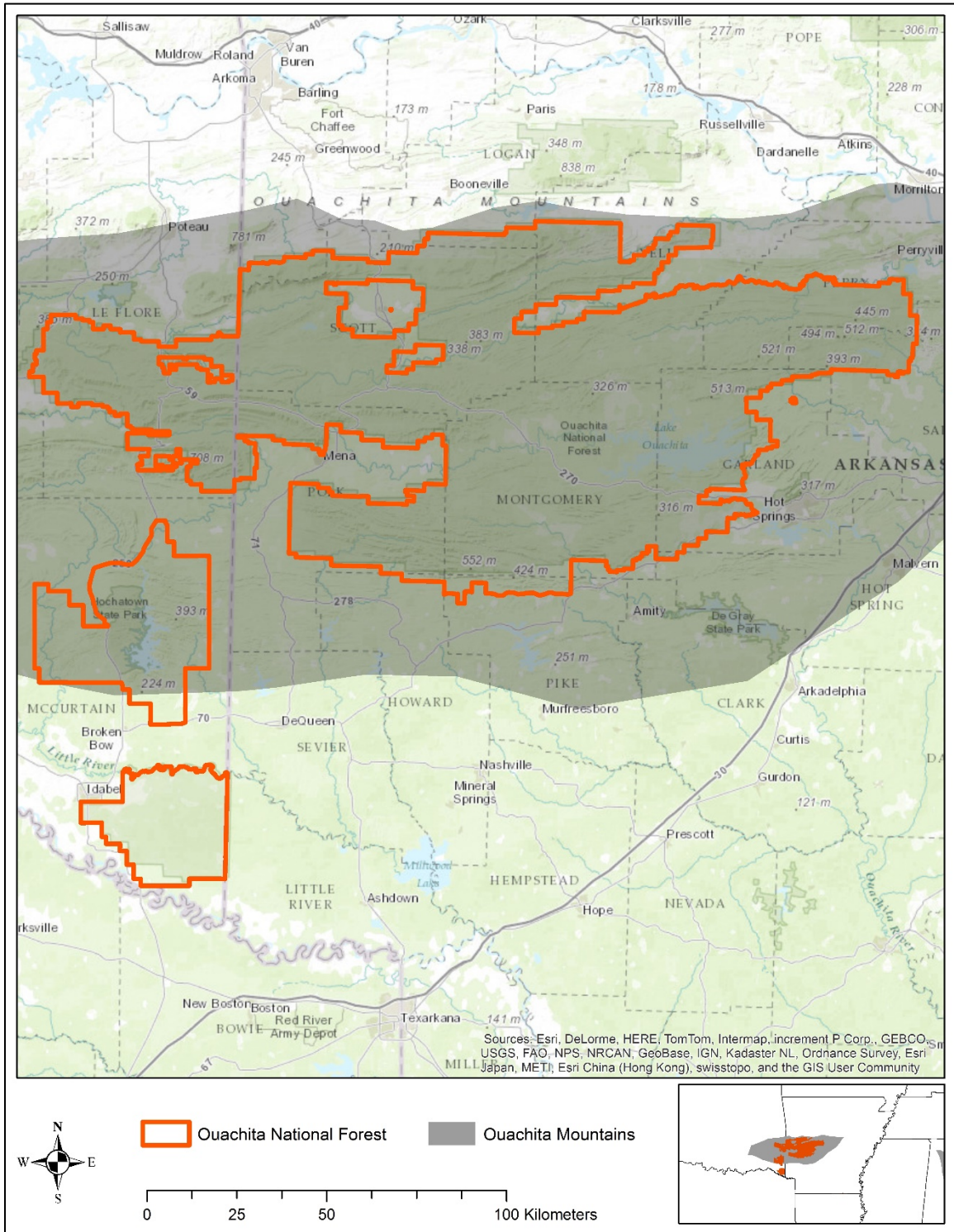


Figure 2.1: Ouachita Mountains and Ouachita National Forest

Soils in the study area are derived from weathered rock and colluvial deposits (alluvial and valley bottom sites were not sampled). Extensive mapping of depth to bedrock in the area indicates that average soil depth is less than typical tree rooting depth, which results in arboreal bedrock mining and root penetration of bedrock joints (Phillips and Marion 2004). Phillips et al. (2005b, 2008) provided a thorough explanation of the soils in this region. They are typically described as Hapludults (Phillips et al. 2008) and often have a high content of rock fragments. Phillips et al. (2005c) showed that sandstone fragments were common in all layers, even in cases where sandstone was not the parent material. Their work suggested that sandstone fragments were transported downslope from upper slope outcrops and entered the subsurface via treethrow pits and stump holes. The weathering of these fragments often resulted in sandy soil layers, even in areas with high clay content (Phillips et al. 2005b, 2008).

Cumberland Plateau

Study sites in Kentucky were located in the Cumberland Plateau physiographic region. This region is sometimes referred to as the eastern Kentucky coalfields due its abundant bituminous coal deposits. The Cumberland Plateau is in the southern section of the Appalachian Plateau province and is characterized by deeply incised drainages, narrow ridges, and steep slopes. The Cumberland Plateau has a humid subtropical climate and a mean annual precipitation of about 1200 mm yr⁻¹. According to Phillips (2010), who queried the USDA Official Soil Series Descriptions database, most soils in the Kentucky regions of the Cumberland Plateau are less than 2 m thick. Within the Cumberland Plateau, the Indian Trails section of Berea College Forest (BCF) and the Koomer Ridge section of the Daniel Boone National Forest (DBNF) were sampled. These areas were chosen due to their accessibility and their representativeness of forested areas of the western Cumberland Plateau in Kentucky that have been minimally disturbed by human activity such as mining and agriculture, though both have been logged before the early 20th century.

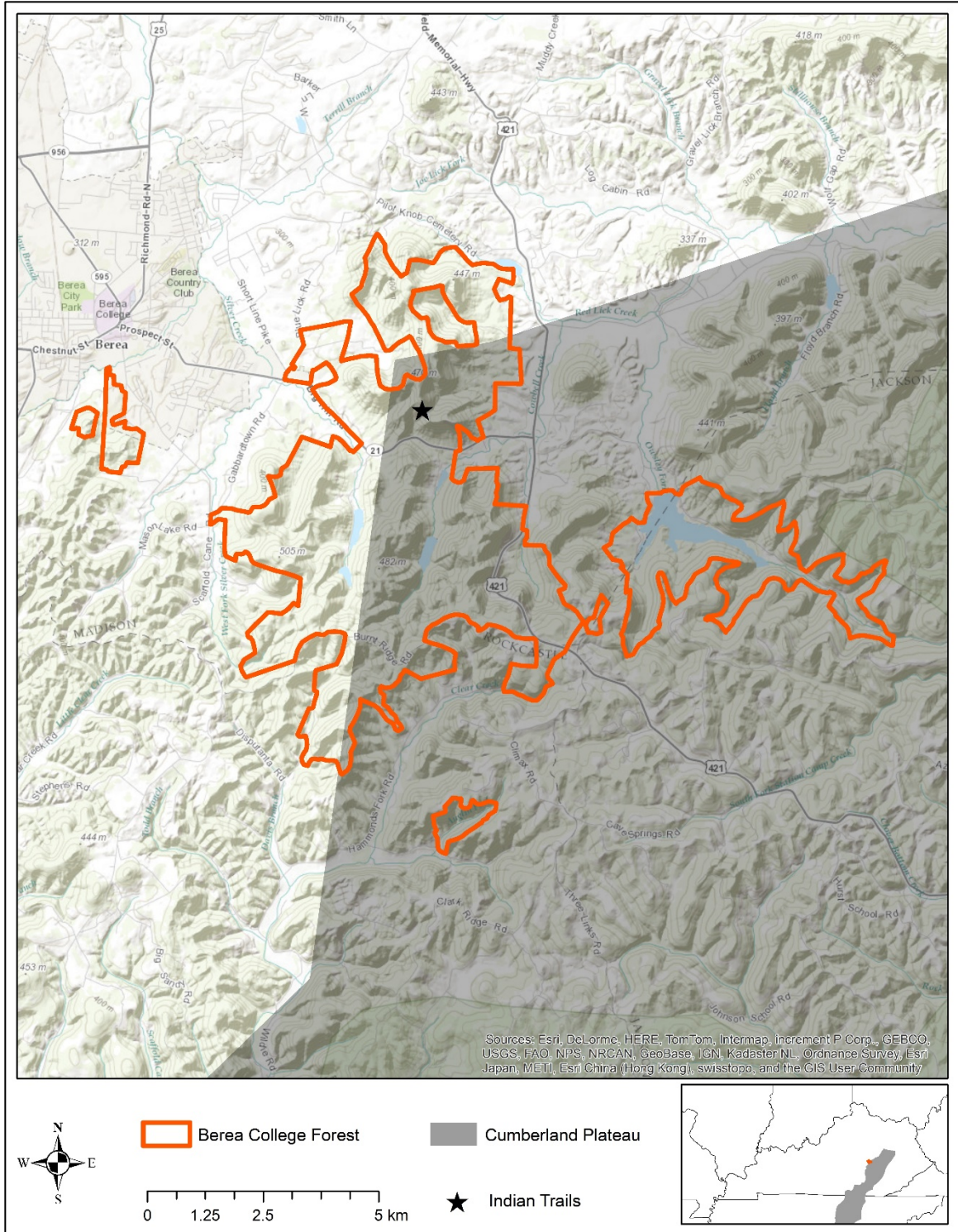


Figure 2.2: Bera College Forest

Bera College Forest (BCF) (37°29'21" north, 84°09'27" west) is a 3380 ha mixed mesophytic forest that is dominated by hickory (*Carya* sp.), oak (*Quercus* sp.), and pine

(*Pinus* sp.) overstory species (Figure 2.2). Berea College Forest elevation ranges from 250-500 m and is located at the intersection of three USGS physiographic regions: Bluegrass, Highland Rim, and Cumberland Plateau, though all sample sites were from the latter. The geology of BCF, as reported in Thompson (2008), includes Pennsylvanian conglomerate and sandstone, Mississippian limestone, dolomitic limestone, Devonian shale, and other types of shale, siltstone, and sandstone (Gualtieri 1968; Weir 1971; Thomson 2008). Specific sample sites for this study were limited to areas in, or along the boundary of, the Cumberland Plateau where sandstone and shale are dominant and horizontally bedded. The specific formations in these areas included the Slade formation, Borden Formation, Livingston Conglomerate Member, and the Grundy Formation. Although karst terrain was avoided, there was some limestone outcropping on the valley sides of Berea College Forest as typical of the Pottsville escarpment. Areas with sinkholes were specifically avoided. Based on the USDA web soil survey (websoilsurvey.nrcs.usda.gov) the majority of Berea College Forest samples were Hapludalfs from the Rarden series or Dystrudepts from the Weikert series. These are moderately to well-drained silt loams derived from shale and sandstone. Along the ridgetops and upper slope locations, Hapludalfs from the Caneyville series and Argiudolls from the Woolper series are present. These series have associations with limestone. Of these two series, the Caneyville series is most associated with limestone and extra caution was taken in these areas in an attempt to avoid karst influences.

Daniel Boone National Forest is an 8,500 km² mixed mesophytic forest. Koomer Ridge (37°47'20" north, 83°36'54" west) is located in the cliff section of the Northern Cumberland Plateau ecoregion where the overstory is dominated by red maple (*Acer rubrum*), oak (*Quercus* sp.), and pine (*Pinus* sp.) species (Washburn and Arthur 2003). In the Koomer Ridge area the underlying bedrock is horizontally oriented and composed primarily of sandstone, shale, limestone, and siltstone (Hinrichs 1978). Specifically, geology in this study site includes the Corbin sandstone member of the Lee Formation of the Breathitt Group and the Pikeville formation of the Breathitt Group. The Corbin Member of the Lee formation dates back to the Middle Pennsylvanian and is composed of relatively friable conglomerate, conglomeric, and quartz sandstone. The Pikeville

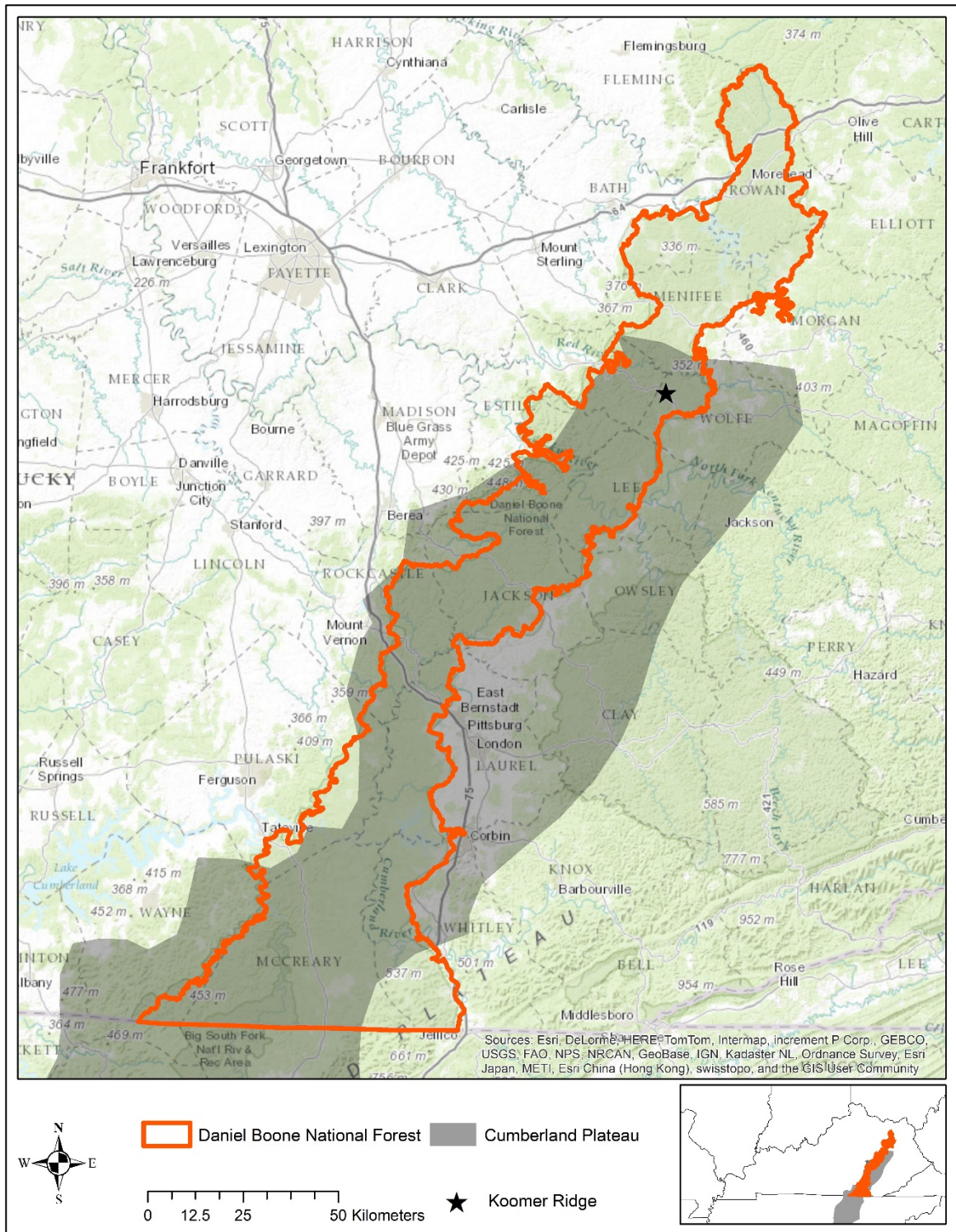


Figure 2.3. Daniel Boone National Forest

Formation includes shale, siltstone, and coal and dates back to the lower Pennsylvanian. Significant interbedding exists at the contact between these two formations (Rice 1986).

Sites were limited to areas underlain by shale and/or sandstone. Based on the USDA web soil survey soils in the sample locations for Koomer Ridge are from the Gilpin-Shelocta complex and the Alticrest-Ramsey-Rock outcrop complex. These are well drained Hapludults and Dystrudepts derived from shale and/or sandstone.

THEORETICAL BACKGROUND

This section will introduce concepts pertinent to interpreting and discussing the results of each research question. First, the concepts of equilibrium and nonequilibrium, with specific emphasis on soil thickness, will be presented. Second, a discussion on the importance of scale will be presented, along with a description of how it issues of scale will be addressed in this research.

Equilibrium Concepts and Soil Thickness

Soil thickness, and more generally landscapes and landforms, can be characterized as being in a state of equilibrium, disequilibrium, or nonequilibrium. These concepts provide systems for geomorphologists to analyze landscapes and landforms through time. Renwick (1992), who cited Howard (1982, 1988), defined equilibrium as a constant relationship between input and output or form, toward which a landform tends or fluctuates through time. With the exception of unstable equilibrium, equilibrium implies some sort of balance as well as the maintenance of that balance (Inkpen 2005). Essentially, equilibrium implies both a condition for a system and an ability of a system to maintain that condition. Dynamic equilibrium exists when an annual average input is changing through time slowly enough for the system to adjust the condition. This is sometimes referred to as quasi-equilibrium because of the tendency towards a steady-state with a trending mean (Thomas and Goudie 2000). Dynamic equilibrium has also been described as a gradual shift in response to longer-term landscape level trends (see Renwick 1992). Disequilibrium is used to describe landforms that tend towards equilibrium but have not had time to reach this condition (Inkpen 2005; Renwick 1992).

According to Phillips (1992), equilibrium implies that a given set of processes and/or environmental controls will produce, or result in a tendency toward, a particular

landscape response. Equilibrium in geomorphology is most commonly based on the concept of steady-state, which results in a balance between force and resistance. Under the equilibrium worldview, landforms and geomorphic systems move toward a steady-state, which are stable and maintain themselves through convergent evolution (Phillips, 2007). Phillips et al. (2005b) stated that under similar lithology, climate, vegetation, topography, and history, a soil system under equilibrium should have minimally variable thickness. Self-regulating adjustments, through negative feedbacks, were thought to control soil thickness and help the system return to a steady-state equilibrium (Chorley and Kennedy 1971).

The soil production function is a conceptual model for the formation of soil over time through biological, chemical, and physical rock weathering and the transport of soil through erosional processes. The model is based on a reduction of weathering rate with thickening soil (and vice-versa), which maintains an eventual steady-state. This model suggests that the rate of bedrock weathering (de/dt) can be represented as an exponential decline with soil thickness:

$$de/dt = P_0 \exp [-kh] \quad \text{(Equation 2.2)}$$

where h (m) is soil thickness, P_0 (mm/year) is the potential weathering rate of bedrock, and k (m^{-1}) is an empirical constant. Soil thickness is increased through the weathering/breakdown of parent material. According to Minasny and McBratney (1999), temperature is the most important factor in the mechanical breakdown of rock. It affects weathering indirectly through processes such as freezing-thawing and also controls chemical weathering. Soil depth is decreased by the loss of soil through erosion processes, a product of elevation. The first impact of elevation on soil production is slope gradient. Slope gradient is directly proportional to the rate of erosion (Minasny and McBratney 1999). The second impact of elevation on soil erosion is through profile curvature, which can increase or decrease the rate of sediment flux (Minasny and McBratney 1999).

The origin of the soil production function dates back to 1877, when G.K. Gilbert (1877) wrote about the dependence of soil production on soil depth, and recognized the relationships between soil production, soil depth, soil transport, and slope (Humphreys and Wilkinson 2007). Humphreys and Wilkinson (2007) believed that Gilbert was suggesting that the rate at which bedrock is converted to soil reaches a maximum under an optimal soil depth that facilitates contact between bedrock and water such that freeze-thaw and weathering are maximized. However, further development of this idea did not appear again until 1891 when Nathaniel Shaler discussed soil transport and weathering in pedogenesis (Humphreys and Wilkinson, 2007). Other geoscientists that picked up on this idea were George Merrill (1906), who considered soil depth as an important factor in weathering, and W. M. Davis (1899), who acknowledged that soil production was inversely related to soil depth and that weathering is key (Humphreys and Wilkinson 2007). Quantitative research on soil production did not occur until the 1960's when multiple scientists began measuring and modeling soil formation processes. One of the key studies that emerged from this period was Carson and Kirkby (1972), who graphically represented Gilbert's soil production function through the widely accepted "humped" function (Humphreys and Wilkinson 2007). As mentioned previously, freezing-thawing and chemical processes are important factors in soil production. When regolith cover is limited, the water essential to both processes is unavailable and soil production stalls. The rate of soil production rapidly increases as regolith depth increases until a maximum is reached. At depths beyond this point, soil production is self-limiting as thicker soil shields the underlying bedrock from weathering (Humphreys and Wilkinson 2007).

Minasny and McBratney (1999) focused on quantifying the soil production function through mechanistic modeling. Their model quantitatively represented soil thickness as a function of weathering rate and soil diffusivity (slope-dependent downslope soil movement). Weathering rate parameters were produced using an exponential decay function similar to eq. 2.2. Soil diffusivity was derived from existing soil erosion models developed by various researchers. Simulation was run on a hypothetical valley/hill

landscape more than 80,000 times, with a 500 year time-step. Simulation results indicated that over time soil thickness would reach a steady-state, where weathering and erosion are equal and soil depth is constant. Heimsath et al. (2000) examined the relationship between soil production and soil thickness on slopes associated with a retreating escarpment underlain by granite and granodiorite located in the Nunnock River basin, southeastern Australia. They calculated soil production rates by examining cosmogenic nuclide (^{10}Be and ^{26}Al) concentrations in soil minerals collected at the soil-bedrock interface. They also tested the assumption of steady-state soil thickness by comparing these results with cosmogenic nuclide analysis of nearby tors; portions of the bedrock that rise abruptly above the soil surface. In agreement with Minasny and McBratney (1999), they interpreted their results as confirming the notion of steady-state soil thickness.

This view has since been disputed through nonequilibrium concepts. Nonequilibrium contrasts with traditional equilibrium while still recognizing the presence of steady-state equilibria, the difference being that equilibrium is not necessarily more common or important than nonequilibrium. Nonequilibrium concepts arose out of nonlinear dynamical systems approaches. Within the nonequilibrium worldview multiple possible equilibrium states can exist for geomorphic systems, equilibria may be unstable or stable, geomorphic systems are overwhelmingly nonlinear, and landscape evolution may be divergent or convergent (Phillips 2007). Nonequilibrium systems are inherently dominated by frequent disturbances and/or dynamical instability and do not develop a steady-state condition (Phillips et al. 2005b). Nonequilibrium describes landforms that do not tend toward a steady-state, even during long periods of environmental stability (Renwick 1992). This could either be the result of thresholds at high-magnitude/low-frequency levels, positive feedbacks, or deterministic chaos (Phillips 1992, Renwick 1992, Phillips 1999a, Phillips et al. 2005b, Phillips 2006).

With respect to soil thickness, steady-state implies that that over sites of consistent parent material small enough so that regional climate and the general biotic community are constant, soil thickness is “tuned” to topography. Thus, under these conditions, soil

thickness not closely related to topography indicates nonequilibrium, as found for the Cumberland Plateau in Kentucky by Boettcher and Kalisz (1990), for the Ouachita Mountains by Phillips et al. (2005b) and elsewhere by, e.g., Zinke (1962), Yair (1990), Twidale (1991), Stolt et al. (1993), Wright (1996), Migon (1997), Phillips (1997a; 2001) Tromp van-Meerwald and McDonnell (2006), Migon and Latocha (2008) and Delrue et al. (2009).

Phillips (2010) argued that deep weathering, regolith stripping, inherited regolith features, spatial patterns of depth, and nonlinear complexity in weathering-erosion feedbacks imply that steady-state soil thickness is not a normative condition for soil, regolith, or weathering profile evolution. Phillips (2010) demonstrated deep weathering using a simple ratio of soil thickness (S) to weathering profile thickness (WP) in the Cumberland Plateau. In his study weathering profile thickness was considered the length from the surface extending to an R-horizon. The thickness of the soil was considered the length from the surface to a C-horizon with relatively low rock fragment content and no unweathered bedrock material. Between soil and the R-horizon, was the non-soil regolith, which included Cr horizons, and C-horizons with high rock fragment contents, which included unweathered rock. The mean S/WP for soils derived from shales was 0.72 while the mean S/WP for soils derived from sandstone was 0.87. A value 1.0 would indicate steady-state soil thickness. This research will examine steady-state soil thickness by analyzing local patterns of soil depth in generally homogenous areas. If the pattern of soil thickness is both spatially variable and not closely related to topography, then soil depth will be considered nonequilibrium.

A threshold is defined as the critical condition at which a landform (or system) changes (Goudie 2004). According to Thomas and Goudie (2000), this concept is closely bound to the view that a landform is a system or part of a system in which there is normally a balance between morphology and processes involved. Thresholds are crossed as the result of extrinsic or intrinsic changes. That is, the change can be the result of an external variable (extrinsic) or the result of an internal variable (intrinsic), respectively (Charlton 2007; Schumm 1979). An intrinsic threshold implies that changes can take place in the

absence of an external variable (Thomas and Goudie 2000). Internal variations that develop over time “prime” the system, which in turn makes the system sensitive to abrupt changes. The example used in Thomas and Goudie (2000) is that of a surging glacier. The accumulation of snow and ice to a critical level leads to a sudden transition to a fast mode of flow. This leads to the lowering of the ice surface to a point where the flow is once again slowed. Another example is when a relatively minor rainfall triggers a landslide (Charlton 2007; Schumm 1979). An example of more relevant to pedology and soil geomorphology would be the humped function. At low soil depth, the soil production rate increases rapidly. As soil depth continues to increase, a threshold is crossed where the rate of soil production decreases as soil depth increases.

Phillips (2014) reviewed convergence and divergence theory in geomorphology. Convergence results in increasing isotropy, decreasing amplitudes of variations, and progression towards spatial uniformity. An example of convergence presented by Phillips (2014) relevant to this dissertation research was the smoothing of rough, irregular rock surfaces by weathering processes. On the other hand, divergence results in decreasing isotropy, increased amplitudes of variations, and increasing spatial variability. An example of divergence presented by Phillips (2014) is the diversification of soils and regoliths over time. The formation of soil can be convergent, where minor initial variations or effects of small disturbances are reduced or obscured, or it can be divergent, where minor initial variations and disturbance effects can be exaggerated (Phillips and Marion 2005). Phillips and Marion (2005) suggested that instability and chaos leads to divergent soil variability, whereby the impacts of biomechanical weathering by trees persist and become exaggerated over time.

Phillips et al. (2005b) stated that “Untangling the relative importance of various processes of deepening, up-building, and removals may allow the interpretation of regolith thickness variations in terms of the interacting geomorphic, pedologic, and biological processes involved”. They examined these interacting processes in the Ouachita Mountains and suggested that regolith thickness in the Ouachita Mountains is in a state of nonequilibrium. Their assumption was that if regolith thickness was in

equilibrium then settings with relatively uniform topography and geomorphology should have a predictable relationship with elevation, slope gradient, and/or slope curvature (Phillips et al. (2005b)). A similar approach is taken in this study, using sites small enough so that the underlying geologic formations, general geomorphic setting, climate, and vegetation community are constant, so that only local topographic variations and local factors such as tree effects could conceivably account for spatial variations.

Spatial Variability of Soil

Soil and soil properties vary in space and time and are influenced by different combinations of soil-forming factors acting through space and time. Soil spatial variability in this research focuses on soil depth or thickness and ignores soil characteristics such as pH, organic matter, and carbon. The latter soil characteristics are generally fast-reacting and transient, and arguably do not offer as much insight into landscape evolution and pedologic memory as geomorphic properties do. According to Lin et al. (2005) soil variability is a function of five-space-time factors including, spatial extent or area size, spatial resolution or map scale, spatial location and physiographic region, specific soil properties or processes, and time. Scale plays an important role in evaluating spatial variability and will be discussed further in the next section. Lin et al. (2005) found that soil spatial variability is a function of map scale, spatial location, and specific soil property. This research is concerned about soil variability over small areas, which suggests a potential role for the effects of individual trees. Phillips and Marion (2005) pursued this topic in the Ouachita Mountains, Arkansas and found that the diversity of soils in the Ouachita Mountains was high and that soil series varied with respect to geomorphological properties. This research is also concerned with how this localized variability is partitioned over larger scales. Lin et al. (2005) pursued this topic in the Backswamp Watershed in South Carolina and found that the majority of soil variability for A-horizon thickness, depth to calcium carbonate, and surface pH values were best explained at the local scale.

Because soil is variable over space and time, sampling at a finite number of places in space and time provides an incomplete picture. Lapses in this picture, manifested as gaps

between soil samples predictions about the future, can be remedied via modelling approaches. This was the central theme in Heuvelink and Webster (2001), which discussed this topic in detail and reviewed different modelling approaches that could be implemented in different scenarios. They mentioned two principal approaches to representing spatial variability. The first approach is traditional soil mapping and classification. Soil mapping divides soils into discrete classes based on their physical properties at a predetermined scale. Soil maps are created using information from soil surveying. Typical soil surveying is based on aerial photo interpretation and collated information on the soil as it relates to landform, geology, vegetation, and land use (Lin et al 2005; Schaetzl and Anderson 2005). From this, field observations are conducted and areas are classified based on formal knowledge and intuition (Lin et al 2005; Schaetzl and Anderson 2005). Phillips and Marion (2005) classified soils in the Ouachita Mountains and supported it as a viable evaluation technique of soil spatial variability based on three factors. They argued that soil classification is useful because it integrates the effects of many soil properties, is a rule-based approach that distinguishes similar soils from dissimilar soils, and has been frequently used with great success (Phillips and Marion 2005).

The second principal approach to representing soil spatial variability mentioned in Heuvelink and Webster (2001) envisions soil as a suite of continuous variables and seeks to describe how they vary. This is more aligned with the approach utilized in this research, focused specifically on soil thickness. Because it is a continuous variable it can be modeled using traditional statistical methods, making it a convenient object of analysis. As will be discussed in later chapters, soil thickness measured and defined in different scenarios to compare its variability between two physiographic regions, to evaluate the biomechanical effects of trees on its spatial variability, and to examine the controls of its spatial variability across scales.

Scale Concepts and Biogeomorphology

Scale issues have been recognized as a central concern to environmental and earth science disciplines. Schneider (2001) noted a sharp rise in scale considerations occurred

in the 1980's. This coincided with the rapid growth of the sub-discipline of landscape ecology (Turner 2005), which deals extensively with the issues of scale in geographic landscapes. Schneider (2001) suggested that growth in scale considerations was related to the recognition of the "problem of scale in ecology". The "problem of scale in ecology" consists of three components: (1) problems in ecology exist at large temporal and spatial scales, which include large ecosystems, (2) most variables and rates can only be measured in small study sites over short periods of time, and (3) patterns identified at small scale studies do not scale-up to large scales in a linear fashion, if at all (Schneider 2001). Ecologists have long understood that generalizations and conclusions made at one scale do not necessarily hold true at other scales (Haggett et al. 1965, Schneider 2001). This implies that as scale changes, the questions that can be asked change, as well as the answers that can be obtained.

The issue of scale is also a concern in the field of geomorphology and has been for quite some time. Schumm and Lichty (1965) suggested that geomorphic variables dependent at one time scale may not be dependent at other times scales. McMaster and Sheppard (2004) reviewed the concept of scale in geography. Related to geomorphology, they reviewed Phillips (1997b; 1999b) who argued that research on scale in earth science addresses four kinds of issues. The first issue was to identify and measure the range of scales of a particular process (Phillips 1997b; 1999b; McMaster and Sheppard 2004). The second issue was to reconcile the scales of processes with those of observation and measurement (Phillips 1997b; 1999b; McMaster and Sheppard 2004). The third issue was to address ranges of scale across which relationships are constant or where down- or up-scaling are appropriate (Phillips 1997b; 1999; McMaster and Sheppard 2004). The fourth issue of scale was related to operational problems of scale linkage, where relationships may vary across multiple scales (Phillips 1997b; 1999b; McMaster and Sheppard 2004). McMaster and Sheppard (2004) argue that key take away from this list is that there are multiple spatial and temporal scales to consider.

Prior to the development of this list, Phillips (1995) discussed the "problems of scale" in biogeomorphology and landscape evolution and addressed the scale linkage problem.

Vegetation change and landform change operate on disparate temporal scales, which create challenges for investigating their interactions. Phillips (1995) proposed four methods for handling this scale linkage problem. First, he proposed using a landscape sensitivity analysis to compare landform or ecosystem relaxation time with the recurrence interval of geomorphic or vegetative disturbances. Second, he developed the information criterion approach, which was based on the ratio of the most rapid vegetation changes and slowest geomorphic responses. Third, he proposed the abstracted earth surface systems model where the rates of geomorphic and vegetation responses were estimated. If the rates were more than an order of magnitude different, based on this approach the geomorphic and vegetation responses could be treated independently. Fourth, he suggested comparing relaxation times and durations of endogenous forcings. To address scale linkage issues in this research, hierarchy theory and methods will be adopted.

As Levin (1992) suggested, a single phenomenon can actually be observed at a range of spatial and temporal scales. Hierarchy theory conceptualizes this notion of variable scale interactions by defining isolated levels of organization that each operate at distinct time and space scales (Pachepsky et al. 2003; Phillips 2004). O'Neill et al. (1989) discussed scale within a hierarchy theory framework. Their argument is rooted in the assumption that all biological systems are hierarchically structured. Being hierarchically structured implies that at a given level of resolution, a biological system is composed of interacting components, and is itself a component of a larger system (O'Neill et al. 1989). A hierarchical framework removes some of the "problems of scale" by including multiple scales in analysis.

Delcourt and Delcourt (1988) provided an early example of a hierarchical framework in research that could be considered biogeomorphic in nature. By using paleoecological methods combined with geomorphic data, paleoethnobiological data, historic records, and shorter-term ecological data, they were able to reconstruct past landscapes and their changes through the Quaternary period (Delcourt and Delcourt 1988). This hierarchical multi-spatiotemporal scale project used data from multiple case studies, from many disciplines, to understand Quaternary environmental changes in the southern

Appalachians. They examined major biota shifts during the late Pleistocene and early Holocene periods of the Quaternary period. Through this analysis they found that quaternary time scales influenced natural landforms slowly, while human cultural evolution has transformed the landscape more profoundly, on a temporal scale of 5,000 years (Delcourt and Delcourt 1988).

de Boer (1992) reviewed hierarchies and spatial scale in geomorphology. He identified four characteristics of scale linkage in geomorphology that are still relevant today. First he found a relationship between catastrophic events and hierarchical level. Second, he stated that differences between the temporal patterns of process-oriented inputs and outputs increases with hierarchical level. Third, he identified that nonlinear processes can occur at the same hierarchical level. The fourth point he made was “differences between geomorphic systems at the same level are controlled by variables varying over distances equal to or smaller than the distance between the system, but equal to or larger than the spatial dimensions of the systems”.

In many cases the identification of the appropriate scale involves identifying which variables explain changes in the phenomena under observation. In soil science, the patterns identified in a landscape and the interpretations of those patterns are determined by the scale at which they are viewed (Hupy et al 2004). Turkington and Paradise (2005) discussed scale issues relative to sandstone weathering and identified seven contributing factors in durability studies. These were variability of external conditions, heterogeneity of internal conditions, inheritance effect, inconsistent response, episodicity of processes and response, singularity, and inherent complexity (Turkington and Paradise 2005). Phillips (2007) identified these same factors as having applications to geomorphology more generally. Identifying characteristic scales involves a deep understanding of the forcing agents and constraints of the phenomena under question. In many cases it might be beneficial to consider a hierarchical framework, which provides information about constraints placed on the phenomena from forcing agents at different scales. Figuring out the scales at which forcing agents interact with phenomena is critical for applying results from one scale to another. For this reason, a hierarchical (or nested) sample design was

used in this dissertation to evaluate Research Question 3. In addition, multi-scale covariates were used in modeling procedures to answer Research Question 2.

The hierarchical levels of scale considered in this research were termed subplot, plot, and stand. These scales generally follow the scales used by Ulanova (2000). The subplot level, which is 10 m² in this study, was meant to capture the variance of soil depth due to individual tree effects. The goal of selecting this scale boundary was to represent the influence of single trees capable of interacting with the bedrock interface in shallow soil. This was based on the concepts of single tree influence circles (Boettcher and Kalisz 1990) and soil influence area (Phillips and Marion 2006). The single tree influence concept suggests that soil properties vary predictably in relation to distance from the bole and edge of the tree crown. The soil influence area concept estimates the area of influence of a single tree on soil physical properties as a circle whose diameter is twice the tree diameter at breast height. Ulanova (2000) considered this the “fallen tree ecosystem” scale of disturbance and associated it with pit-and-mound and log creation. The plot scale, which is 1.0 ha, was meant to capture the variance in soil depth due to forcing agents associated with a small number of trees. This scale generally coincided with the forest community scale as described by Ulanova (2000). This level of organization likely captured environmental factors related to species competition, resource availability, and microtopographical variability. In this research, the plot scale variables slope shape, basal area, and trees per hectare were used in a multi-scale modeling procedure to answer Research Question 2. Temporally, this organization level operates on longer time scales than the tree influence, but shorter time scales than the stand level. The stand level, which is 10 ha, was intended to capture forcing agents that operate over longer time and space intervals. This level of organization likely captured controls of soil depth other than single tree effects. Ulanova (2000) associated a similar organization level with the phenomenon of catastrophic windthrow and secondary succession. Variables that were referenced and/or measured at this scale included the topographic variables slope gradient, slope position, aspect, and elevation. Additionally, environmental changes related to forest composition or successional changes were thought to have occurred at this organization level.

A nested sampling scheme can be used, along with analysis of variance methods, so that a limited number of study sites can be used while still representing a number of spatial scales. Essentially, a nested sampling scheme can upscale data from a lower level of a hierarchical structure to higher levels. Lin et al. (2005) demonstrated and stated that a hierarchical sampling design was a useful approach for assessing soil property variability at multiple scales. For this research, soil depth variance at a lower scale, can be used to estimate soil depth variance at the next level in the hierarchy. Therefore, a thorough sampling of depth to bedrock at the subplot level was all that was required to examine how the variance of soil depth was partitioned across spatial scales. Using well established and accepted statistical techniques this data was then used to make informed estimates of soil depth variance at the plot and stand scales. This research utilized nested ANOVA procedures, which have been an accepted statistical analysis in geography for nearly 50 years (Haggett et al. 1965; Phillips 1986; Lin et al. 2005). By using a nested ANOVA procedure the contribution of each level of sampling hierarchy to the variance of soil depth was determined. For example, if it was determined that the majority of soil depth variance is accounted for by the subplot level, then it can be reasoned that single tree processes are most important. If it was determined that the majority of soil depth variance is accounted for by the stand level, then it can be reasoned that tree effects only have a local influence on soil depth variance.

In addition to hierarchical scale procedures, the issue of upscaling can be resolved using theoretical and empirical evidence. Underwood et al. (2005) identified three challenges of up-scaling in population biology: (1) increased abiotic and biotic heterogeneity as scale increases, (2) changes to species pools as spatial scale changes, and (3) behavioral changes that can occur as spatial scale changes. They addressed each problem in a theoretical framework and provided examples of empirical analysis. While the final two challenges identified in Underwood et al. (2005) were primarily biological, the first challenge related quite well to biogeomorphic research. Melbourne and Chesson (2005) overcame this challenge by quantifying the degree of nonlinearity and spatial

heterogeneity at different scales. They demonstrated how to scale up from a local-scale to a regional-scale using an integration of scale transition theory and field data.

With any scale oriented research an understanding of “domains of scale” is important. Domains of scale exist when phenomena exhibit discontinuities in scale-dependence (Wiens 1989). Domains are separated by transitions from dominance by one set of factors to dominance by a different set of factors. In this research a hierarchical scheme was used as discussed above. As explained previously, a nested sampling strategy was designed to allow for the measurement of variance of a particle phenomenon at different scales. If domains of scale exist in the system, then the results of the nested ANOVA should reflect this. If variance is convincingly explained by one level of organization, and thus one scale, then it is likely that domains of scale exist in the system. If variance is equally distributed across levels of organization, then it is possible that scale-dependence of soil depth is continuous and generalizations will be difficult to make (Wiens 1989).

Related to the domains of scale concept is the notion of the proper choice of scale. Kim et al. (2012) explained that an arbitrary choice of scale could greatly hinder the resultant insights into biogeomorphological relationships. However, it is often difficult to choose an appropriate scale at which to analyze a particular pattern or process. In some cases, choosing different scales can lead to different results. Turner et al. (2001) used the example of oak seedling mortality. At local scales, an increase in precipitation led to increased mortality, while at regional scales the relationship between oak seedling mortality and precipitation was negative (Neilson and Wullstein 1983, Turner et al. 2001). According to Turner et al. (2001) the best approach to choosing the correct choice of scale might not be to choose one scale, but rather incorporate multiple scales in analysis. Further, multiple regression using variables from multiple scales has confirmed that there is no single appropriate scale at which researchers can expect to analyze their data (Pearson 1993, Turner et al. 2001). This dissertation research avoided issues of domains of scale and scale choice by incorporating multiple regression analysis with multi-scale variables and by incorporating a hierarchical framework.

The spatial scale constraints of biomechanical effects of trees are more difficult to speculate, though presumably they would relate to tree size as represented by trunk diameter, rooting depth, and rooting area. The hierarchical analysis of variance procedure proposed in the research has the potential to provide insight about which level of organization accounts for the most variance in soil depth. The stand level of organization is thought to represent the scale at which factors such as topography or forest structure become dominant. If results from the hierarchical analysis of variance procedure indicate that factors at this scale are dominant, this would suggest that factors that control slope position are most important and that biomechanical effects of trees is constrained within this hierarchy (that is, individual tree influences on soil depth are small compared to topographic controls). If the tree influence level of organization is found to be dominant in this hierarchy, then considerations could be made to consider additional levels or organization. In this system, single tree effects are thought to be the dominant process at the tree influence scale. As spatial scale increases, it is likely that tree effects decrease. So while tree rooting processes could contribute to soil depth variance at the plot scale, other forcing agents could play a more important role.

CHAPTER 3
SOIL DEPTH VARIABILITY: STEEPLY DIPPING VS. FLAT-BEDDED
PARENT MATERIAL

METHODOLOGY

As discussed earlier, the Ouachita Mountains and Cumberland Plateau have comparable climatic, geologic, biologic, and topographic conditions. However, they differ quite greatly in their structural characteristics. The sedimentary rocks in the Ouachita Mountains are strongly dipping and contorted and in many areas bedded near-vertical. The sedimentary rocks in the Cumberland Plateau are flat-bedded and presumably offer less opportunity for roots to penetrate bedrock, as bedding planes are not accessible to penetration from above. Figure 3.1 shows a comparison of each situation. To evaluate the role of this structural variation on the presence and extent of biomechanical weathering by trees the following methodology was employed.



Figure 3.1: An example of the contrasting bedrock orientations of the Ouachita Mountains, on the left, and the Cumberland Plateau, on the right. The yellow arrows indicate the bedding direction.

Stump Pair Sampling

Opportunistic sampling was conducted to collect depth to bedrock measurements within and adjacent to stump-holes in the Ouachita Mountains and Cumberland Plateau physiographic regions. Partially rotted tree stumps provide an opportunity to sample soil depth at former tree locations without having to damage live trees. The SRPIT conceptual model posits that the effects of trees are reciprocal due to generations of

growth (see Chapter 1). This generational impact is discussed further in Chapter 4, but it is acknowledged here that the soil characteristics beneath a stump are not necessarily due to the tree that was last growing at that location, but also possibly due to previous trees occupying that same location. For this reason, stump-holes were not excluded from sampling based on size. The criteria for identifying a stump-hole and the general methodology of their measurement closely followed the procedure used in (Phillips and Marion 2006). A stump hole was considered such only if there was evidence of an identifiable bark ring or the presence of decayed wood remnants around the edges of the depression. A soil auger was used to drill a hole until lithic or paralithic contact (hereafter bedrock) was made within the stump-hole and at an adjacent location within 1 m of the stump-hole on the same contour (Figure 3.2). To reach bedrock, the auger was used until a point of refusal (lithic contact) or when three-dimensional fragments of weathered parent material could be identified from the extracted soil (paralithic contact). The 1.0 m radius was derived from the soil influence area concept, which estimates that the area of influence of a single tree on soil physical properties is as a circle whose diameter is twice the tree diameter at breast height (Phillips and Marion 2006). The depth to bedrock was recorded for each pair (hereafter referred to as a stump-pair) using a metric folding ruler. If bedrock could not be reached, then the depth to bedrock was recorded as greater than the maximum measurement and the data was omitted from comparative analysis.

Stump-pairs were collected in the Cumberland Plateau and the Ouachita Mountains physiographic regions at locations described in Chapter 2. Opportunistic sampling in the Cumberland Plateau began in 2012 and continued through the fall of 2013. At the time of writing, 122 stump-pairs have been collected in the Cumberland Plateau with the help of many people, including undergraduate geography students at the University of Kentucky. The Ouachita Mountains samples were collected over a larger timeframe. Phillips and colleagues began conducting soil geomorphology research in the Ouachita Mountains more than ten years ago (see Phillips 2008, 2009; Phillips and Lorz 2008; Phillips and Marion 2004, 2005, 2006; Phillips et al. 2005a, 2005b, 2008). For this research, stump-pair data from Phillips (2008) was updated, which itself was updated

from Phillips and Marion (2006). At the time of writing, 118 stump-pairs have been sampled in the Ouachita Mountains.

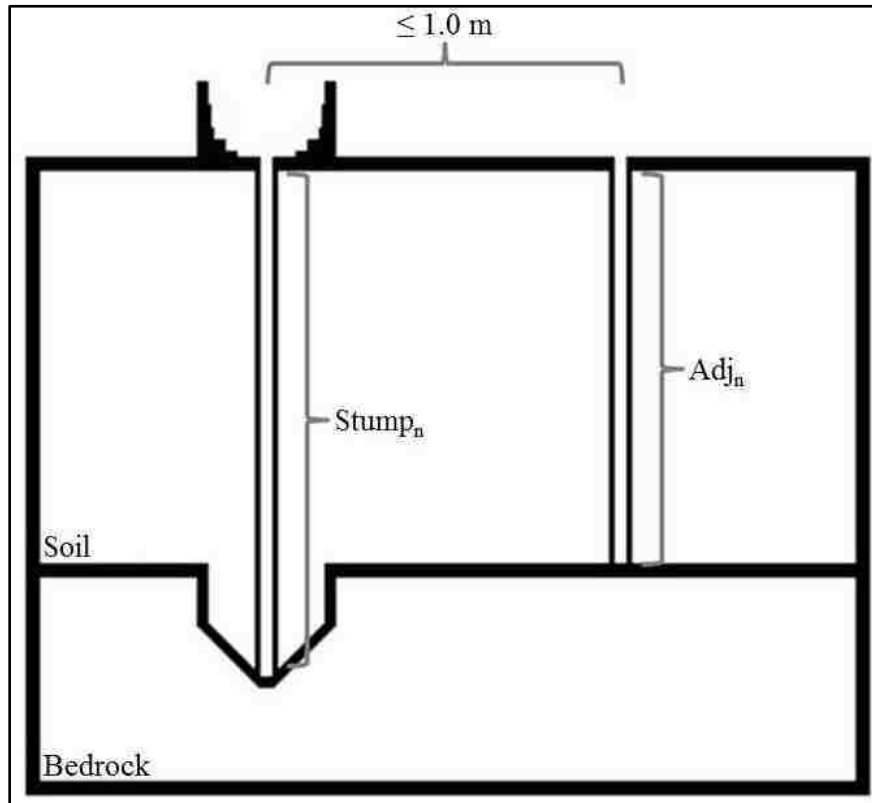


Figure 3.2: Illustration of the sampling procedure in a theoretical stump pair. The basic procedure uses a soil auger and folding ruler to measure the distance to bedrock contact beneath a stump hole, $Stump_n$, and the distance to bedrock beneath an adjacent non-stump location, Adj_n , that is located on the same contour within one meter.

Variable Creation and Analysis

The Ouachita Mountains data and the Cumberland Plateau data were treated as separate datasets for analysis. For each stump-pair the following variables were derived:

1. $Stump_n$ = soil depth beneath stumps
2. Adj_n = soil depth adjacent to stumps
3. $Diff_n = Stump_n - Adj_n$ = difference between measurements at each stump pair
4. $Ratio_n = Stump_n \div Adj_n$ = ratio of measurements at each stump pair

Where, $n = \begin{matrix} i = \text{Ouachita Mountains samples} \\ j = \text{Cumberland Plateau samples} \end{matrix}$

To analyze the data within each physiographic region the mean, standard deviation, and variance was calculated for each variable. To analyze the data between each physiographic region, and thus compare the role of structural variation, four null hypotheses were tested using unpaired t-tests to determine if the means of each corresponding variable were equal:

H_{01} : Stump_i is greater than Stump_j

H_{02} : Adj_i is greater than Adj_j

H_{03} : Diff_i is greater than Diff_j

H_{04} : Ratio_i is greater than Ratio_j

Analysis of student's t-tests were based on $\alpha \leq 0.05$ to determine statistically significant differences. Based on the background information presented on the Ouachita Mountains soil system, one-tailed t-tests were used for this analysis. F tests were conducted on the variance of each corresponding variable to determine the type of t-test to be calculated. If the variances were equal, unpaired equal variance t-tests were performed in Microsoft Excel 2010. If the variances were not equal, unpaired unequal variance t-tests were conducted.

RESULTS

The augering of stump-pairs in the Ouachita Mountains and Cumberland Plateau concluded in the fall of 2013 for the analysis presented in this dissertation. Augering was found to be sufficient in accurately measuring lithic and paralithic contact in both environments. Stumps located on trail embankments were used to ensure the methodology was sound. At these locations, augering was conducted as normal, but as a secondary check, a mattock was used to clear material so that a profile view of the stump-pair could be visually inspected. The ability to confidently and accurately measure the soil depth using this methodology remains high. Determining the bedrock type using only an auger was difficult, especially when a lithic contact was made. Due to this, much of the data was recorded without confirming bedrock type in the field. This was

especially difficult to discern in the Ouachita Mountains because of the high degree of interbedding between shale and sandstone. As a result, bedrock type was excluded as an independent parameter for Research Question 1 and Research Question 2.

Results are shown in Table 3.1. In the Ouachita Mountains, soil depth under stumps had a mean of 69.54 cm (standard deviation (σ) = 28.19), which was 24.11 cm greater than mean depth of the paired adjacent samples. Ratio_i had a mean value of 1.75 (σ = 0.99), meaning that on average the depth of a stump-hole in the Ouachita Mountains was 1.75 times as deep as the depth at the adjacent location. In the Cumberland Plateau, mean soil depth under the stumps was 60.94 cm (σ = 28.95), which was 18.51 cm greater than the adjacent samples. Ratio_j had a mean value of 1.67 (σ = 0.80).

Table 3.1: Comparison of paired-soil sample statistics for the Ouachita Mountains and the Cumberland Plateau physiographic regions.

	Ouachita Mountains	Cumberland Plateau
Number of sample pairs	118	122
Pairs with stump > adjacent	102 (86.4%)	102 (83.6%)
Stump _n		
Mean (cm)	69.54	60.94
Standard deviation	28.19	28.95
Variance	794.51	838.12
Adj _n		
Mean (cm)	45.43	42.43
Standard deviation	19.75	24.75
Variance	390.01	612.40
Diff _n		
Mean (cm)	24.11	18.52
Standard deviation	27.29	20.14
Variance	744.83	405.52
Ratio _n		
Mean (cm)	1.75	1.67
Standard deviation	0.99	0.80
Variance	0.98	0.63

F-tests were conducted to determine if the corresponding variables in each physiographic region were equal. This was then used to determine what type of t-test would be used. Results of this analysis are recorded in Table 3.2. The variances related to Stump_n were

statistically equal, so a one-tailed unpaired equal variance t-test was conducted. Results of this t-test indicate that soil depth beneath stumps in the Ouachita Mountains is deeper, on average, than in the Cumberland Plateau. Therefore, H_{01} wasn't rejected. F-tests for the other 3 variable pairs indicated that the variances were not equal so one-tailed unpaired unequal variance t-tests were required. Based on a p-value of 0.04 (see Table 3.3) H_{03} wasn't rejected either. However, H_{02} and H_{04} were rejected meaning that the adjacent depths and ratio of stump depth to adjacent depth weren't greater in the Ouachita Mountains compared to the Cumberland Plateau.

Table 3.2: F-test results for soil depth variables $Stump_n$, Adj_n , $Diff_n$, and $Ratio_n$.

	Ouachita Mountains	Cumberland Plateau	p-value
variance, $Stump_n$	794.51	838.12	0.39
variance, Adj_n	390.01	612.4	<0.01
variance, $Diff_n$	744.83	405.52	<0.01
variance, $Ratio_n$	0.98	0.63	<0.01

Table 3.3: t-test results for soil depth variables $Stump_n$, Adj_n , $Diff_n$, and $Ratio_n$.

	Ouachita Mountains	Cumberland Plateau	p-value
mean, $Stump_n$	69.54	60.94	*0.01
mean, Adj_n	45.43	42.43	**0.15
mean, $Diff_n$	24.11	18.52	**0.04
mean, $Ratio_n$	1.75	1.67	**0.23

* one-tailed unpaired equal variance t-test

** one-tailed unpaired unequal variance t-test

DISCUSSION

The primary goal of this research question was to determine if the systematically deeper soil associated with sites recently occupied by trees observed in the Ouachita Mountains, was observable in the Cumberland Plateau, where lithological variation is much less extreme. This analysis was based on the assumption that soil depth differences between stumps and adjacent sites were due to tree effects.

Surprisingly, the descriptive statistics from each physiographic region were remarkably close. So close in fact, that when evaluated, it could not be concluded that the adjacent soil depths (Adj_n), difference between stump-pair depths ($Diff_n$), or ratio of stump-pair

depths ($Ratio_n$) were statistically different between each physiographic region. It would be interesting to measure ratio of stump-pairs from additional physiographic regions to determine if this relationship is universal, or if the value of this ratio in the Ouachita Mountains and the Cumberland Plateau were coincidentally equal. The only significant difference was that depth beneath stumps in the Ouachita Mountains was greater than in the Cumberland Plateau. Based on the results of this analysis it is evident that trees effects in the Cumberland Plateau are similar to the Ouachita Mountains. So while soil beneath tree stumps in the Ouachita Mountains is deeper than the soil beneath tree stumps in the Cumberland Plateau, the effects of biomechanical weathering by trees still result in variable soil thickness. In other words, the soil deepening effects of biomechanical weathering by trees are not limited to areas with strongly dipping, contorted, near vertical, extensively faulted bedrock. This is evidence that the variability of soil depth in the Cumberland Plateau is likely influenced by positive feedbacks from tree root growth.

One possible explanation for this difference in depth beneath stumps is related to vegetation differences between the two physiographic regions. Tree uprooting literature shows species composition is an important factor in uprooting rates (Brewer and Merritt 1978; Osterkamp et al. 2006; Whitney 1986). Gallaway et al. (2009) reported that the volume of displaced soil during an uprooting event is likely influenced by tree species and age, health of tree at time of fall, soil texture, soil moisture, and rooting architecture, structure, and depth. Species-specific differences in rooting architecture and rooting depth are likely influential in the biomechanical weathering by trees. Roering et al. (2010) showed that differences in root density impacted biomechanical weathering. If there are species-specific differences in how roots interact with bedrock, then differences in species composition could result in differences in soil thickness variability.

Unfortunately, identifying trees species based on rotted stumps is not possible in the field. Even if it could be determined, it would be impossible, based on current research, to know exactly which species have occupied, and possibly interacted with bedrock, at that location in the past. This is especially true for ecosystems as biologically rich as temperate forests. Root architecture typically falls within one of the following patterns; plate-like, herringbone, tap, or heart-like patterns (Dupuy et al. 2007). Differences in

these rooting patterns could have significant impacts on how tree species interact with the bedrock surface, how well they grow in shallow soils, and how deep their roots grow. Under normal conditions, the tree species of a stump is immeasurable based on field observation alone and detailed species data was not recorded for stump-pairs or stump-pair sites. Future research should thoroughly detail the current species composition at the plot level. For this research, general observation and published research will help discern differences between the two physiographic regions.

Generally, the Ouachita Mountains have an abundance of coniferous species, particularly shortleaf pine (*Pinus echinata*), that are not dominant in the Cumberland Plateau. Coniferous species typically have a taproot style architecture, which would likely root deeper than differing architectures, all other things being equal. Many of the hardwood species in the Ouachita Mountains also exhibit taproot style architecture including blackjack oak (*Quercus marilandica*), post oak (*Quercus stellata*), and Mockernut hickory (*Carya tomentosa*), which were the most common hardwood species at many of the Ouachita Mountains stump-pair sites (Phillips and Marion 2005). This differs from the Cumberland Plateau, where rooting architecture is more diverse. Washburn and Arthur (2003) described the overstory of the Koomer Ridge section of Daniel Boone National Forest as being dominated by chestnut oak (*Quercus prinus*), white oak (*Quercus alba*), scarlet oak (*Quercus coccinea*), and black oak (*Quercus velutina*). Shortleaf Pine (*Pinus echinata*), pitch pine (*Pinus rigida*), and red maple (*Acer rubrum*) were also present in the overstory (Washburn and Arthur 2003). Parrot et al. (2012) and Dillaway et al (2007) described the canopy of Berea College Forest as primarily mixed oak. These descriptions are consistent with general observation of the Cumberland Plateau during soil sampling. Chestnut oaks (*Quercus prinus*) were commonly observed along the ridgetop and upper slope positions in the Cumberland Plateau. Chestnut oaks utilize a taproot, but also has an extensive lateral root system that extends more than five times the radius of the crown (Burns and Honkala 1990). Other examples from the Cumberland plateau include red oak (*Quercus rubra*) and beech species (*Fagus* sp.) which have a heart-like rooting pattern that exhibits strong roots near the base of the tree

and dense rooting further away from the tree (Burns and Honkala 1990, Dupuy et al. 2007).

One of the main differences between the two physiographic regions is the rock content of the soil. Based on observation, the Ouachita Mountains has higher rock content compared to the Cumberland Plateau on the surface and in the soil. Perhaps the high rock content favors a taproot architecture where SRPIT processes are present. Phillips and Marion (2004) showed that trees are preferentially established in nutrient rich, rock fragment poor locations and suggested that these types of sites are repeatedly occupied. In this area, a tree root growing vertically downward would be less likely to be impeded by rock fragments than a tree root growing laterally. If high rock content prevents the growth of lateral roots then trees that develop a taproot would be better equipped to occupy the locations of former trees and contribute to the positive feedback explained by the SRPIT model. In the Cumberland Plateau, lateral tree growth is not impeded by high rock content of the soil, which could promote more diverse root architectures. Lateral root systems provide additional stability and anchorage to a tree without as much dependence on a taproot. Stokes et al. (1996) suggested a positive relationship between root length and shear resistance of the soil, decreasing the likelihood of uprooting.

A stronger reasoning for the differences observed in soil depth beneath stumps and adjacent samples between the Ouachita Mountains and the Cumberland Plateau is the difference in bedrock orientation. The more steeply dipping interbedded sedimentary parent material common in the Ouachita Mountains likely provides easier root access to bedrock, and thus more biomechanical weathering and bedrock mining opportunities than the Cumberland Plateau. The results of this research support this claim. In the Cumberland Plateau, tree roots are plausibly taking advantage of joints and fissures in a horizontally oriented bedrock surface and due to this arrangement the tree roots are likely contacting a single bedrock type at a given depth. For example, in sandstone layered on top of shale in a horizontal orientation, then tree roots occupying a joint in the sandstone must weather the sandstone before reaching the softer shale. The results of this research suggest that this interaction still results in an uneven, nonequilibrium bedrock surface;

but not quite to the extent of the Ouachita Mountains. Tree roots in the Ouachita Mountains are likely selectively weathering softer bedrock material within an interbedded system that includes harder material due to the vertical bedrock orientation observed in the Ouachita National Forest.

Because bedrock orientation and type was consistent within the Kentucky study sites, this study also provides evidence that the positive feedback from biomechanical effects by trees leads to divergent development of soil thickness. Phillips and Marion (2004) observed that soil was deeper beneath stump holes than at adjacent locations in the Ouachita Mountains, Arkansas. In Phillips and Marion (2005) they found that biomechanical effects by trees and lithological variations were linked to spatial variability of soil depth in shallow forest soils. They considered this evidence of divergent evolution of the soil system and suggested that future work be conducted to investigate the importance of geological variation in this process. Because soil in the Cumberland Plateau is systematically deeper beneath trees in the absence of such unique lithological variation, lithological variation can be ruled out, suggested that this divergent condition is controlled primarily by the effects of individual trees. While the role of lithological variation may not be the primary control of divergent soil development in these soil environments, such variations could help explain why the depth of soil beneath tree stumps in the Ouachita Mountains is deeper than in the Cumberland Plateau, even though the adjacent depths in each region are the same, presumably because the more common and vertically-oriented rock partings of the Arkansas sites facilitate root penetration of bedrock.

CHAPTER 4

SOIL DEPTH IN THE CUMBERLAND PLATEAU

METHODOLOGY

Data Collection in the Cumberland Plateau

In the last chapter (Chapter 3) stump-pair sampling was described for the Cumberland Plateau. Of these 122 stump pairs, additional data was collected for 116 of them to answer research question 4. Aspect, slope gradient, slope shape, slope position, and stump-hole diameter were also measured for each stump-pair. Slope gradient was recorded using a clinometer to measure the gradient downslope of the stump-hole. Slope shape was categorized as linear, concave, or convex based on field observation from the stump hole position. Slope position was categorized as ridge top, upper slope, mid slope, lower slope, or valley bottom. Aspect was recorded using an orienteering compass and categorized in eight directions: N, E, S, W, NE, NW, SE, and SW. The stump-hole diameter was measured using a folding ruler where the trunk meets the ground. Additionally, basal area and trees per acre, measurements of tree density, were calculated based on point sampling procedures at each stump-pair location.

Point sampling, also known as angle-count sampling, variable-plot sampling, or prism cruising, is a method of selecting trees to inventory based on their size and distribution rather than on their frequency of occurrence. This is accomplished using a wedge prism that subtends a fixed angle of view to select (and count) trees from a single point of reference based on distance and size (Avery and Burkhart 2001). The sighting angle recommended for use in the eastern United States, and the one used in this research, was fixed at 104.18 min. At this angle all trees located within a distance of 33 times their DBH will be included in the sample (Avery and Burkhart 2001). Essentially, trees are selected based on the sighting angle used and their cross sectional areas. Each tree counted in this way represents a basal area of 10 square feet per acre. This is considered the basal area factor (BAF) for that angle (Avery and Burkhart 2001). In other settings different sighting angles are more appropriate that have different BAF values. An

estimate for the average basal area per acre was calculated using the following equation from Avery and Burkhart (2002).

$$BA = \left(\frac{n}{i}\right) * BAF \quad (\text{Equation 4.1})$$

In this equation basal area (BA) is equal to the total number of trees tallied (n) divided by the number of points (i) multiplied by BAF. To represent the conditions at each stump, the number of points (i) was set to one and the basal area per acre for each point was equal to the number of trees tallied multiplied by ten.

Point sampling was also used to calculate trees per acre (TPA), which required the measurement of diameter at breast height (DBH) for each sighted tree. Trees were then classified based on their DBH, in 2 in. increments, and a per-acre conversion factor (cf) was determined using Avery and Burkhart (2001):

$$cf = \frac{BAF}{0.005454 * DBH^2} \quad (\text{Equation 4.2})$$

The conversion factor is used in the following equation for trees per acre for any given diameter class (TPA_{class}).

$$TPA_{\text{class}} = \frac{(n) * (cf)}{i} \quad (\text{Equation 4.3})$$

Total TPA is the sum of TPA associated with each class. To represent the conditions at each stump, the total number of points was constricted to one so TPA is essentially the sum of each tallied tree multiplied by its per-acre conversion factor. Basal area and TPA were converted to metric units for analysis. Basal area was converted to m²/ha, which is abbreviated as BAHA hereafter. Trees per acre were converted to trees per hectare, which is abbreviation as TPHA hereafter.

Statistical Analysis

To determine the relative importance of current organic and relief soil state factors on soil thickness, numerous multiple linear regression models were developed. The dependent variables considered for this analysis included soil depth variables $Stump_j$, Adj_j , $Diff_j$, $Ratio_j$, $Combo_j$, and Ave_j . The variable $Combo_j$ was created by combining the $Stump_j$ measurements with the Adj_j measurements under the assumption that soil samples from the same stump-pair were independent measurements of soil depth. The variable Ave_j is the average of each stump-pair sample. Prior to the development of statistical models the dependent variables were tested for spatial dependence using Moran's I in ArcGIS 10.2. Spatial autocorrelation occurs when the values of variables sampled at neighboring locations are not independent from each other (Tobler 1970; Dormann et al. 2007). Spatial autocorrelation is almost always present in natural systems and can occur over a wide range of spatial and temporal scales (Fortin and Dale 2005). Statistically, it violates the assumption of independently and identically distributed (i.i.d.) errors, which inflates Type I errors (Legendre 1993; Dormann et al. 2007). Moran's I is a statistical test of spatial autocorrelation that results in a value ranging from -1 to 1. Negative values indicate negative spatial autocorrelation where -1 indicates perfect dispersion from randomness. Positive values indicate positive spatial autocorrelation where +1 indicates perfect correlation. A value of zero indicates a random spatial pattern and the absence of any spatial autocorrelation. The independent variables considered for analysis included the categorical variables aspect, slope position, and slope shape (see, Table 4.1), and the continuous variables slope gradient, stump-hole diameter, basal area, and tree density. Each explanatory variable was evaluated in a correlation matrix to determine independence, where $r \geq 0.7$ was considered dependent. If any variables were found to be dependent they were considered for removal.

Multiple linear regression modeling was used to analyze the unique effects between each dependent variable and all independent variables. Unique effects describe the relationship between the dependent variable and one independent variable, holding all other independent variables fixed. Multiple linear regression modeling uses least squares analysis to determine significance and direction of the relationship between the

dependent variable and each independent variable and is one of the most widely used tools in statistical analysis (Burt et al. 2009). For this research a series of multiple linear regression models were developed for each dependent variable with the end goal to produce a full model and a best fit model that was significant based on a p-value (p) \leq 0.05 for each. R^2 values, which determine the amount of variance explained, were also used to evaluate each model. All modeling was conducted in SAS 9.3.

The first step was to produce a full Generalized Linear Model (GLM) with a multiple regression structure for each dependent variable. The term full means that all independent variables were included in the model. This included the categorical variables aspect, slope position, and slope shape (see Table 4.1) and the continuous variables slope percent, elevation, stump diameter, trees per ha, and basal area (see Table

Table 4.1: List of categorical variables and a breakdown of their classes

Variables	Classes
Aspect	north (N)
	northeast (NE)
	East (E)
	southeast (SE)
	south (S)
	southwest (SW)
	west (W)
	northwest (NW)
slope position (slpos)	Valley
	lower slope
	mid slope
	upper slope
	Ridgetop
slope shape (slshp)	Concave
	Flat
	Convex

4.2). Full models indicate how well all of the chosen variables combine to explain the variance in in the data. As such, full models produce the largest R^2 values and are useful in speculating the absence of additional variables. For example, an $R^2 = 0.30$ implies that

30% of variance is accounted for by the model terms. This means that the remaining 70% of variance may be accounted for by other, possibly immeasurable, factors. The PROC GLM function was used for this step because it allows both categorical and continuous variables for linear regression. In many cases, this would be sufficient for an analysis framed like Research Question 2. This research took this a step further by limiting each model to only those variables that expressed significant relationships with the dependent variables. The PROC GLMSELECT function was used for this. This function utilizes a model selection criterion. For this step, stepwise selection with an entry and exit p-value of 0.15 was selected as a conservative model structure. The purpose of this step was to identify independent variables that expressed a significant relationship with the dependent variable using the well know stepwise selection. However, the GLMSELECT function is considered experimental by the SAS Corporation so it was not used as a standalone function. Instead, the variables identified as having a significant relationship with the dependent variable were used as model terms in a best fit GLM model using the PROC GLM function once again.

Table 4.2: List of continuous variables and their abbreviations

Continuous Variables	Abbreviations
slope percent (%)	Slope %
elevation (m)	elem
stump diameter (cm)	dia
trees per ha	TPHA
basal area (m ² /ha)	BAHA

In summary, a workflow of Full GLM → GLMSELECT → Best Fit GLM was performed for each dependent variable Stump_j, Adj_j, Diff_j, Ratio_j, Combo_j, and Ave_j using functions in SAS 9.3 that accept both categorical and continuous variables. The best fit GLM models for each dependent variable are representative of the strongest, most significant relationships found in the data. These models were used to discuss the impact of current organic and relief soil state factors on soil thickness in the Cumberland Plateau.

RESULTS

Combo_j was highly spatially auto-correlated (Moran's I = 0.44) and violated the assumption of i.i.d. errors. This made sense due to the paired nature of the data. However, Stump_j and Adj_j were spatially non-dependent. As a result, the Combo_j variable was dropped from analysis with the understanding that the results from Stump_j and Adj_j modeling were more robust and represented the same data as two separate models. Ave_j, Diff_j and Adj_j were also spatially non-dependent, so traditional modeling techniques were employed for Stump_j, Adj_j, Ave_j, Diff_j, and Ratio_j. Correlation analysis, presented in Table 4.3, indicated that all variables were independent based on the criteria of $r \leq 0.7$, although BAHA and TPHA were somewhat correlated ($r = 0.54$). These variables weren't removed from analysis but their potential for model interaction was noted.

Table 4.3: Correlation matrix for all continuous variables used for analysis.

	Slope %	dia	elem	TPHA	BAHA
Slope %	-	0.31	-0.01	-0.18	-0.28
dia	0.31	-	0.01	-0.02	-0.11
elem	-0.01	0.01	-	0.27	0.21
TPHA	-0.18	-0.02	0.27	-	0.54
BAHA	-0.28	-0.11	0.21	0.54	-

Results from Adj_j indicated that the full model accounted for a significant amount of variance based on the F-test ($p = 0.05$). While the model was significant, the R^2 value indicated that the model only accounted for 24% of total variance in Adj_j. The only significant variable in this model was elevation, which had a p-value < 0.01 (Table 4.4). The stepwise regression model for Adj_j was in agreement with the full GLM model and selected only one variable, elevation. Both models indicated a negative relationship between Adj_j and elevation. When the GLM was limited to just elevation the resulting model was highly significant ($p < 0.01$) but it only explained 6% of total variance ($R^2 = 0.06$). The full GLM model provided much better results, but did not identify any significant relationships besides elevation. To further explore Adj_j, another GLM was developed that included all variables except elevation. This resulted in a significant model ($p = 0.04$) that explained 24% of the variance of Adj_j ($r^2 = 0.24$). This model

identified two new variables as having significant relationships with the dependent variable: trees per ha and slope position (see Table 4.5). One logical explanation for this complexity is that elevation and slope position are interacting and correlated. Because slope position was recorded in the field and better reflected the intended relationship between soil depth and plants, elevation was removed from all modeling procedures in this research.

Table 4.4: Results from regression analysis using all independent variables for the dependent soil depth variable Adj_j.

Source of variation	<i>df</i>	Type III SS	Mean Square	<i>F</i>	<i>p</i>
Slope %	1	88.68	88.68	0.18	0.68
Elevation (m)	1	125.06	125.06	0.25	0.62
Stump Diameter (cm)	1	0.08	0.08	<0.01	0.99
Trees per Ha	1	1625.09	1625.09	3.21	0.08
Basal Area (m ² /ha)	1	1105.82	1105.82	2.18	0.14
Aspect	7	4501.59	643.08	1.27	0.27
Slope Position	4	2769.68	692.42	1.37	0.25
Slope Shape	2	588.61	294.31	0.58	0.56

After model selection, the only variable left in the best fit GLM for Adj_j was slope position. The results of this model are presented in Table 4.6. This final best fit model was highly significant ($p < 0.01$) and explained 13% of variation. This more than doubled the explanatory power of the model that included only elevation, justifying its removal from analysis. The intercept for this model was based on the mean Adj_j depth for the valley slope position class, which was 60.71 cm. The individual parameter estimates reveal how much change in Adj_j depth was expected at each slope position with respect to the valley slope position. For example, a soil sample taken at a “lower slope” location would be predicted to be 4.36 cm less than the average valley slope position mean. Generally, the lower slope and valley slope positions were similar and the mid slope, upper slope, and ridgetops were similar. Based on this model, the deepest adjacent

Table 4.5: Results from regression analysis using all independent variables except elevation for the dependent soil depth variable Adj_j.

Source of variation	<i>df</i>	Type III SS	Mean Square	<i>F</i>	<i>p</i>
Slope %	1	115.13	115.13	0.23	0.63
Stump Diameter (cm)	1	0.02	0.02	<0.01	0.99
Trees per Ha	1	2024.80	2024.80	4.03	0.05
Basal Area (m ² /ha)	1	1163.38	1163.38	2.32	0.13
Aspect	7	4388.77	626.97	1.25	0.28
Slope Position	4	6073.33	1518.33	3.02	0.02
Slope Shape	2	521.07	260.53	0.52	0.60

soil depths would be expected at valley slope positions and the shallowest would be expected at mid slope positions.

Table 4.6: The final best fit regression model for the soil depth variable Adj_j. This model included only categorical variables and is equivalent to an ANOVA model.

Parameter	Estimate	SE	<i>F</i>	<i>p</i>
Intercept	60.71	8.53	7.12	<0.01
slpos mid slope	-26.50	9.39	-2.82	0.01
slpos ridgetop	-24.13	9.44	-2.56	0.01
slpos upper slope	-20.65	9.44	-2.19	0.03
slpos lower slope	-4.36	10.44	-0.42	0.68
slpos valley	0.00	-	-	-

The full GLM model for Stump_j accounted for a significant amount of variance based on the F-test ($p = 0.01$). While the model was significant, the R^2 value indicated that the model only accounted for 27% of total variation. The terms aspect and slope position were the only variables that shared a significant relationship with Stump_j, which had p-values of 0.04 and 0.01, respectively (Table 4.7). The stepwise regression model for Stump_j identified significant relationships with aspect and slope position. A final best-fit

Table 4.7: Results from regression analysis using all independent variables for the dependent soil depth variable $Stump_j$ are presented in this table.

Source of variation	<i>df</i>	Type III SS	Mean Square	<i>F</i>	<i>p</i>
Slope %	1	4.20	4.20	0.01	0.94
Stump Diameter (cm)	1	321.47	321.47	0.40	0.53
Trees per Ha	1	729.95	729.95	0.91	0.34
Basal Area (m ² /ha)	1	339.08	339.08	0.42	0.52
Aspect*	7	13696.46	1956.64	2.45	0.02
Slope Position*	4	13213.65	3303.41	4.13	<0.01
Slope Shape*	2	2228.13	1114.07	1.39	0.25

GLM model was created for $Stump_j$ using these two variables (aspect and slope position) only. This produced a highly significant model ($p < 0.01$) that explained 24% ($R^2 = 0.24$) of total variation in the data (Table 4.8). Specific relationships of the best fit model are presented in Table 4.9. With respect to the valley slope position, the lower slope position had a positive relationship with $Stump_j$ while the mid slope, upper slope, and ridgetop slope positions had a negative relationship. Soil thickness was expected to decline for all aspect classes with respect to the SE aspect class. Based on the parameter estimates, aspect had a greater influence over soil thickness at stump locations than slope position.

Table 4.8: The best fit regression model for the soil depth variable $Stump_j$. This model included only categorical variables and is equivalent to an ANOVA model.

Source of variation	<i>df</i>	Type III SS	Mean Square	<i>F</i>	<i>p</i>
Aspect	7	12344.00	1763.43	2.24	0.04
Slope Position	4	12058.19	3014.55	3.83	0.01

Modeling of $Diff_j$ and $Ratio_j$ did not produce any significant results. $Diff_j$ had a p-value of 0.18 and an R^2 of 0.20. $Ratio_j$ had a p-value of 0.07 and an R^2 of 0.23. Model selection did not increase the significance of either model.

Results from the Ave_j full GLM model were significant based on a p-value of 0.01. This model explained 27% of variance in average soil depth and revealed significant relationships with slope position and slope shape. Results from this model are presented in Table 4.10. The stepwise regression model was in agreement with the full GLM

model. The best fit GLM model, presented in Table 4.11, was highly significant and explained 23% of variance in the dependent variable. However, aspect had a p-value of 0.09 and was not significant based on the criteria of $p \leq 0.05$. This was the only example where the conservative entry and exit points for model selection included a questionable result. As a result, a final best fit GLM was developed using only slope position. This model, presented in table 4.11, was significant and explained 14% of variance in the average soil depth at each stump-pair location. The valley slopes position was again selected as the control class. The mean depth of Ave_j was 67.43 cm and all other parameter estimates were with respect to this. The parameter estimate for the lower slope position indicated that an expected change between it and the valley slope position would be only 2.32 cm. The other classes were all negatively associated with the mid slope position being the most influential.

Table 4.9: Detailed view of the best fit model for Stump_j, which includes parameter estimates for each categorical variable class.

Parameter	Estimate	SE	<i>F</i>	<i>p</i>
Intercept	99.21	12.91	7.69	<0.01
aspect W	-30.38	11.11	-2.73	0.01
aspect NE	-37.43	11.61	-3.22	<0.01
aspect S	-34.63	12.48	-2.77	0.01
aspect SW	-38.64	12.06	-3.20	<0.01
aspect E	-29.87	12.50	-2.39	0.02
aspect N	-21.90	12.91	-1.70	0.09
aspect NW	-43.62	14.39	-3.03	<0.01
aspect SE	0.00	-	-	-
slpos mid slope	-18.17	12.34	-1.47	0.14
slpos ridgetop	-12.27	12.00	-1.02	0.31
slpos upper slope	-11.63	12.15	-0.96	0.34
slpos lower slope	19.28	14.56	1.32	0.19
slpos valley	0.00	-	-	-

Table 4.10: Results from regression analysis using all independent variables for the dependent soil depth variable Ave_j .

Source of variation	<i>df</i>	Type III SS	Mean Square	<i>F</i>	<i>p</i>
Slope %	1	40.83	40.83	0.07	0.79
Stump Diameter (cm)	1	81.79	81.79	0.15	0.70
Trees per Ha	1	1296.55	1296.55	2.32	0.13
Basal Area (m ² /ha)	1	689.65	689.65	1.24	0.27
Aspect*	7	7991.74	1141.68	2.05	0.06
Slope Position*	4	8765.27	2191.32	3.93	0.01
Slope Shape*	2	965.32	482.66	0.87	0.42

For Adj_j and Ave_j only one factor, slope position, was significant. Because of this, the resulting best fit models were equivalent to one-way Analysis of Variance (ANOVA) models. Analysis of Variance is a common statistical method used to analyze differences between group means. More detail on the ANOVA model will be presented in Chapter 5. Based on an ANOVA perspective, the models for Adj_j and Ave_j indicated that the means of Adj_j and Ave_j were significantly different between each slope position class. The best-fit model for $Stump_j$ included slope position and aspect. The result of this model was equivalent to a two-way ANOVA, where the main effects of two factors were tested. The result of this model indicated that the mean soil depth beneath stumps at each slope position class was different and that the mean soil depth beneath stumps at each aspect class was different.

Table 4.11: The best fit regression model for the soil depth variable Ave_j . This model included only categorical variables and is equivalent to an ANOVA model.

Source of variation	<i>df</i>	Type III SS	Mean Square	<i>F</i>	<i>p</i>
Aspect	7	7155.62	1022.23	1.85	0.09
Slope Position	4	8708.43	2177.11	3.95	0.01

Table 4.12: Detailed view of the best fit model for Ave_j that includes parameter estimates for each categorical variable class.

Parameter	Estimate	SE	<i>T</i>	<i>p</i>
Intercept	67.43	9.11	7.40	<0.01
slpos mid slope	-26.23	10.03	-2.61	0.01
slpos ridgetop	-20.54	10.09	-2.04	0.04
slpos upper slope	-18.35	10.09	-1.82	0.07
slpos lower slope	2.32	11.16	0.21	0.84
slpos valley	0.00	-	-	-

Because slope shape has been identified by many researchers to be a key control of soil thickness (see Minasny and McBratney 1999), more analysis was conducted to evaluate it as a predictor of soil depth. This was accomplished by calculating descriptive statistics for each slope shape class for each dependent variable and by conducting one-way ANOVA for each dependent variable and slope shape. The descriptive statistics are presented in Table 4.13.

Table 4.13: Shows the mean and standard deviation for soil depth variables based on slope shape classification.

Slope segment	n	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
		<i>Stump</i>		<i>Adj</i>		<i>Diff</i>		<i>Ratio</i>		<i>Ave</i>	
Convex	*50	57.2	32.0	41.2	24.3	16.1	21.0	1.6	0.8	49.2	26.4
Straight	44	62.5	31.0	43.9	23.8	18.6	20.7	1.5	0.6	53.2	25.6
Concave	22	56.2	27.4	33.1	21.5	23.1	14.5	2.0	1.1	44.7	23.5

*for Ratio n was 49

The concave slope shape class had the lowest mean for Stump_j, Adj_j, and Ave_j and the highest mean for Diff_j and Ratio_j. However, results from one-way ANOVA, which are presented in Table 4.14., indicate that the mean soil depths of each slope shape class are not statistically different. As one final measure the slope shape class was reclassified as Concave and Other, and the process was conducted again. Results revealed the same non-significance for every depth variable except Ratio, which had a p-value of 0.026. So for the Ratio variable, there was a significant difference between ratio values on concave slope shapes and ratio values on other slope shape.

Table 4.14: The ANOVA results for each soil depth variable based on the categorical variable slope shape.

Depth variable	F-value	p-value
Stump	0.45	0.64
Adj	1.55	0.22
Diff	0.96	0.39
Ratio	2.54	0.08
Ave	0.84	0.44

DISCUSSION

Recall, from Chapter 2, that the standard soil state factors climate, parent material, and time were all controlled for at the broad scale in the sampling of soil thickness in the Cumberland Plateau (recognizing that local topographic variations may be associated with variations in, e.g., microclimate). This was based on the premise that all soils sampled for this research question were of the same age, subject to the same climate, and derived from the same parent materials. It would be expected then, that if soil thickness in this area were in equilibrium, than it would be closely related to the topographic variables included in this analysis. Most ANOVA procedures are only interested in determining if a relationship exists and are not necessarily interested in the strength of the relationship, or the amount of variance explained. As such, R^2 values are not typically calculated in ANOVA procedures. In this case, the lack of significant relationships with slope gradient and slope shape, and poor R^2 values of models that included aspect and/or slope position is of utmost importance, because it indicates nonequilibrium soil thickness.

The amount of variance explained is also important because it allows for the inference of other possible sources of variance not accounted for by the model parameters, such as biomechanical weathering. Based on the low R^2 values of the best fit models, which were essentially ANOVA models, it is clear that the relief factors included in this analysis do not tell the entire story of soil depth in the Cumberland Plateau. As mentioned previously, slope curvature has been shown to be an important factor in soil development. Slope shape, which was used as a proxy for slope, did not help to explain soil depth whatsoever. Phillips et al. (2005b) did not find a significant statistical relationship

between soil thickness and slope curvature in the Ouachita Mountains either. They concluded that the variable soil thickness observed was most likely due to the biomechanical effects of trees and lithological variation. As sampling in the Cumberland Plateau was limited to horizontally bedded lithology of specific parent materials, this is consistent with biomechanical effects of trees as a potential source of unexplained variation. So while, relief factors were identified as important indicators of soil thickness, there is some evidence that soil deepening by trees could play an important role in controlling soil thickness in the Cumberland Plateau.

None of the current ecological factors included in this research were shown to have significant interaction with the soil depth variables. The likely explanation for this missing relationship is temporal in nature. Of the standard soil state factors, it can be argued that the organic factors are the most temporally dynamic. Tree density is snapshot measurement of the current forest condition and does not reflect changes in tree density or forest composition through time; both of which have drastically changed since the last glacial maximum. Williams (2002) evaluated tree densities since the last glacial maximum (21ka) based on fossil and pollen records. Between 21 ka and 11 ka tree density increased in the eastern United States, with a rapid increase occurring between 14 ka and 11 ka (Williams 2002). Tree density continued to increase during the late Holocene (Williams 2002). Wilkins et al. (1991) also evaluated pollen records during this time period for changes in species composition. They estimated that Kentucky was dominated by a closed canopy spruce forest between 21 ka and 17 ka, which shifted to an open canopy spruce-jack pine forest in 17 ka and continued to 11 ka. Between 11 ka and 7 ka drastic changes occurred that led to the decline of spruce and pine and the incline of oak and other deciduous species. Between 7 ka to 3 ka forest composition changed once again to the oak-hickory forest associated with Kentucky to the present day. It is possible that at some point since the last glacial maximum, tree density could have explained the current variability in soil thickness. What is known is that current tree density does not have a significant relationship with soil thickness.

The lack of relationship with stump diameter, which ranged from 9.0 to 93.0 cm, indicates that soil depth beneath trees and differences relative to nearby depths are not related to the size of the most recent tree to occupy the patch. This is consistent with the SRPIT model. If trees occupy the same locations over time, then the effects of biomechanical weathering by trees are not necessarily related to the last tree that occupied the site. As the soil beneath trees deepens over time, it is likely that the size of trees capable of impacting the site will also have to increase. Based on this research it is not possible to know whether or not the last occupant (i.e. tree stump) had any impact on regolith thickness during its life. Essentially, this research question did not capture the direct biomechanical effects of trees, because these effects could be active or dormant depending on the size of the tree, depth of the soil, and possibly the architecture of the roots.

Chapter 3 suggested that individual trees could be having an impact of soil thickness in the Cumberland Plateau. This was supported by evidence showing that more than 80% of soil depths beneath stumps were deeper than their adjacent partners and that the Cumberland Plateau is comparable to the Ouachita Mountains, where biomechanical impacts have been shown to contribute to soil thickness. Interestingly, the soil depth variables used to validate the biomechanical effects of trees on soil depth variability, $Diff_j$ and $Ratio_j$, had no relationship with any of the biological or relief factors tested. One interpretation of this is that biomechanical weathering by trees is independent of these factors. Overall, the modeling efforts in this chapter indicate that topography has some weak relationship to soil depth, but there are other agents at work. Based on results of this study, topographic effects manifest at the scale of slope position differences. The biomechanical effects of trees are thought to locally influence nonequilibrium soil thickness. An analysis of these scale relationships is logically the next step in understanding soil thickness variability in the Cumberland Plateau.

CHAPTER 5

SOIL DEPTH VARIABILITY AND SCALE

METHODOLOGY

The analysis of research question 1 (see Chapter 3) provided evidence that the biomechanical effects by trees were expressed locally in the Cumberland Plateau. The analysis of research question 2 (see Chapter 4) identified relationships between soil thickness and landscape level topographic variables in the Cumberland Plateau. The purpose of this research question, research question 3, was to further investigate the relationship between scale and soil thickness variability in a forested area where tree effects were present.

Study Design

This study used a three factor hierarchy to examine variance in soil depth across one forested hill-slope in Berea College Forest. This specific hill-slope was located in the Cumberland Plateau and possessed the horizontally bedded shale and sandstone lithology desired, and is accessible via hiking trails. Details regarding Berea College Forest can be found in Chapter 3. The highest level of the hierarchy was deemed the stand level. One 10 ha stand was established at the top, middle, and bottom of the hill-slope. Within each stand two 1.0 ha plots were selected. This represented the plot level in the hierarchical structure. Within each plot, two subplots, measuring 0.1 ha were established. This hierarchy is displayed in Figure 5.1. The locations of each subplot (Figure 5.2) were generally chosen due to their location on the hill-slope, with two caveats. First, subplots had to remain on Berea College Forest Property. Second, subplots needed to be free of potential disturbances by the trail system. The general location of each subplot was selected based on a topographic map and field reconnaissance. To minimize bias, the specific location of each subplot center was randomly selected once the general location was chosen. The orientation of the grid was laid out perpendicular to the base of the slope. The aspect relative to the downslope direction was recorded. Measurements of depth to bedrock at the subplot scale were aggregated to estimate soil depth variance at

higher levels of the hierarchy. Soil depth was sampled at 25 locations within each subplot, as described in the next section.

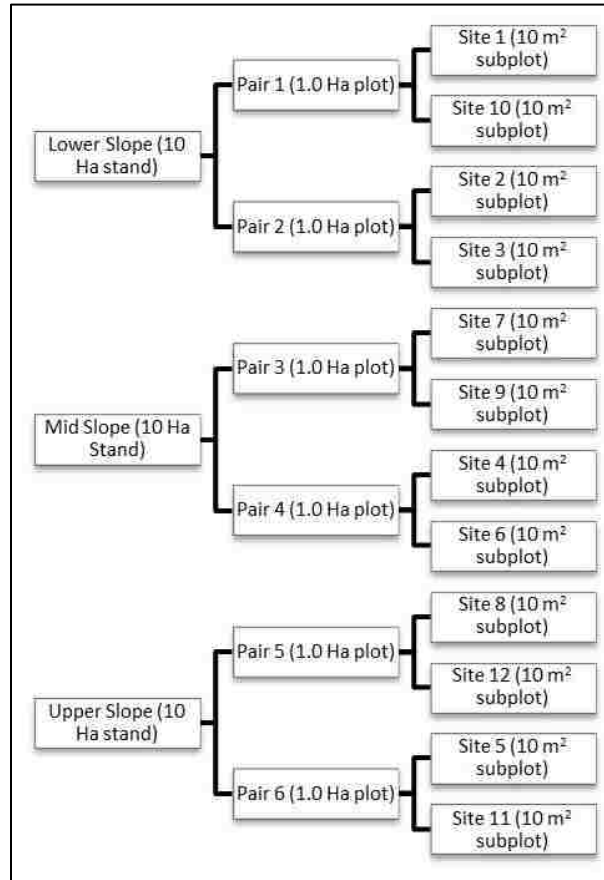


Figure 5.1: A diagram of the three factor hierarchy used to investigate the impacts of scale on soil depth variability.

A nested sampling scheme was used so that a limited number of study sites could be sampled while still allowing for an investigation of multiple spatial scales using nested Analysis of Variance (ANOVA). ANOVA is a common statistical method used to analyze differences between group means. It allows for significance testing using the F-distribution. The assumptions of ANOVA are: (1) each population has a normal distribution, (2) the variances of all the population are equal, and (3) the samples from each population are independent and random. The ANOVA procedure is robust, so modest departures from these assumptions will still result in accurate significance testing (Burt et al. 2009). Nested ANOVA is a special case of ANOVA that allows for the variance of the lowest level of a hierarchy to be used to estimate the variance of all other

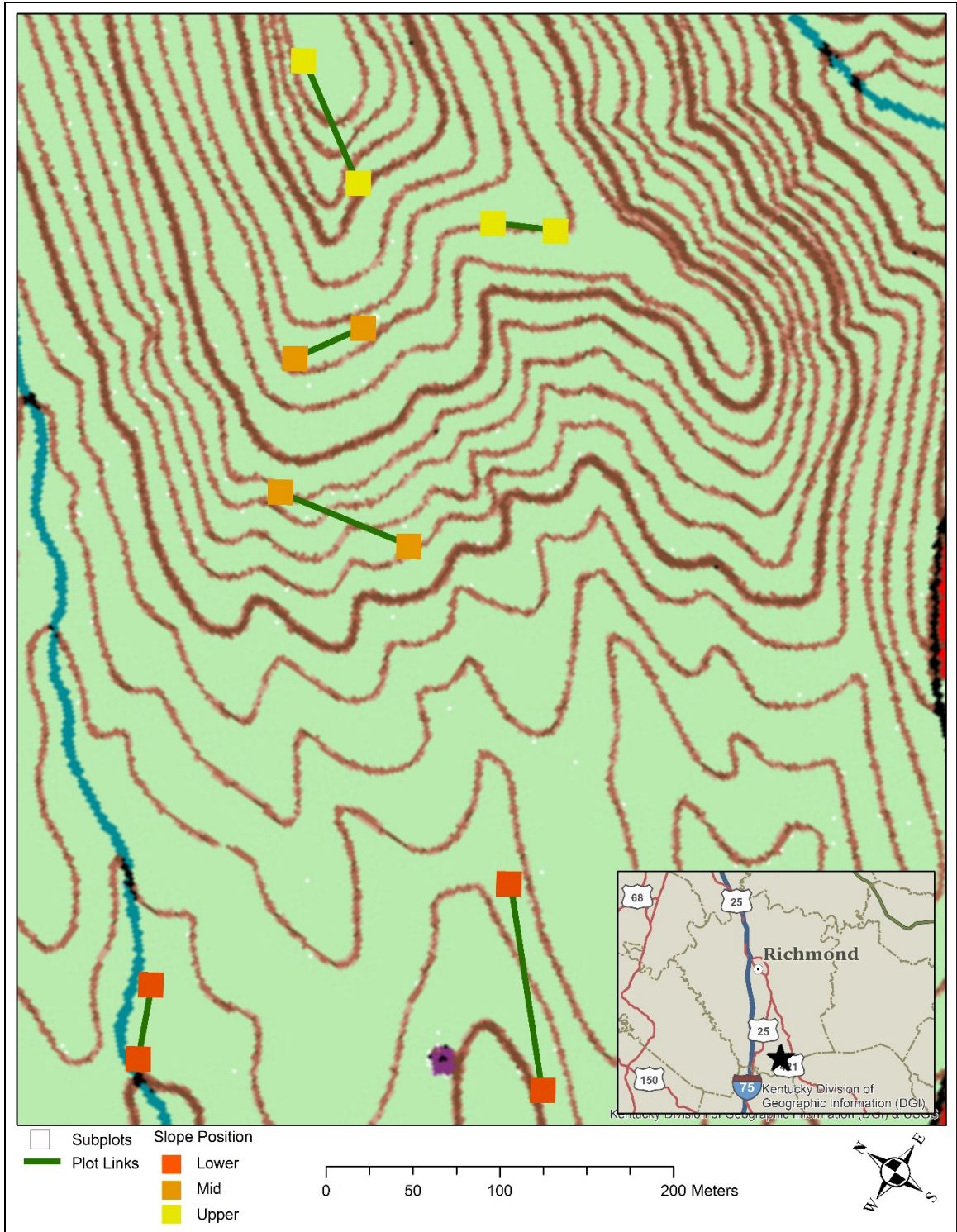


Figure 5.2: This figure depicts the hierarchical structure used in this research. Each subplot is represented by a square. The green lines link subplots that are within the same plot. The color of the squares are representative of the slope position.

levels. Nested ANOVA procedures have been an accepted statistical analysis method in geography dating back at least to 1965 (Haggert 1965; Phillips 1985).

In nested ANOVA there is a hypothesis being tested at each level. In this research the null hypotheses are,

H_{01} : The variance between stands is different

H_{02} : The variance between plots, within the stands is different

H_{03} : The variance between sites, within plots is different

The nested ANOVA procedure also allows the contribution of each level of sampling hierarchy to the total variance to be determined. This means that the percent of variance attributable to each hierarchical level will be determined, and as a result the role biomechanical weathering by trees has on soil depth spatial variability across multiples scales will be inferred. For example, if it is determined that the majority of soil depth variance is accounted for by the subplot scale, then it can be reasoned that single tree processes are most important. Alternatively, if it is determined that the majority of soil depth variance is accounted for by the stand level, then it can be reasoned that the topographic processes are most important. Results of this analysis are referred to as nested effects.

Analysis of Variance testing was conducted in SAS 9.3.

Sampling Depth to Bedrock

Due to the nested design, soil depths were measured within each subplot. To keep with the design of the stump-pair sampling presented in previous chapters, each 10 x 10 m subplot was divided into 2 x 2 m cells, so that 2 points measured 1.0 m apart could be located in a different grid. Essentially, each 2 x 2 m grid represented a possible soil influence area. The soil influence area concept estimates that the area of influence of a single tree on soil physical properties is as a circle whose diameter is twice the tree diameter at breast height (Phillips and Marion 2006). In the study area the typical tree

diameter at breast height is < 1.0 m. Soil depth was measured in each 2 x 2 m cell for a total of 25 soil depth samples per subplot. The soil type at each location was determined based on the USDA Web Soil Survey (websoilsurvey.nrcs.usda.gov) for Madison County. The underlying geology at each subplot was determined based on the 1:24,000 Kentucky Geologic map accessed via the Kentucky Geologic Survey map services (kgs.uky.edu) in ArcGIS 10.1. An attempt was made to measure depth to bedrock using a Malå GeoScience RAMAC/GPR ground penetrating radar (GPR) system with a 500 MHz shielded antenna following the procedure used in Roering et al. (2010). However, field trials in a pilot study indicated that GPR would not work for the intended application because of high clay contents in the soil, and difficulties in maintaining direct ground contact and in maneuvering around obstacles in the forest. Personal communication with archaeologists and engineers using GPR in the region suggests that these difficulties are common.

A piece of rebar (steel bar) and a hammer is one tried and true method of measuring depth to bedrock. This is a straight forward technique of physically hammering a piece of rebar into the ground until refusal. Once the rebar is as deep as possible a measurement is recorded of how much of the rebar remains above the ground. This measurement is then subtracted from the total length of the rebar to get the depth to bedrock measurement. There are a few drawbacks to this technique, however. The rebar can be quite difficult to remove from the ground once it is deeply inserted. This can be overcome by attaching something to the end of the rebar to provide a point of contact to hammer in the upward direction. A piece of metal welded to the rebar to form a “T” shape accomplishes this, as does a set of vise grip pliers. Another drawback is that this process can be very tiring by itself and even more so when compounded with a difficult hike. One of the positives of employing this method is that the rebar is effective at moving subsurface rock fragments out of the way. In this way, it is better than a soil auger, especially in rocky soils. This method is also less invasive, particularly on the surface, than a soil auger, which leaves a much larger hole or a GPR unit, which requires the removal of surface debris and ground litter to maintain a contact.

Based on this hammer and rebar method, a new technique for quickly and accurately measuring soil depth in shallow soils was developed for this research. Instead of using a hammer to drive the rebar into soil, a cordless hammer drill was used. A traditional drill turns a drill bit at a fast rate and uses the shape of the drill bit, which usually includes a sharp point, and the force of the user to drill into materials. A hammer drill adds an action along the axis of the drill bit that delivers thousands of low force blows per minute to the bit to help it to penetrate into hard materials. The primary use of a hammer drill is to crack and penetrate hard materials, such as concrete or brick, using a masonry bit that has a wedge shaped tip. A jack hammer is sometimes considered a type of hammer drill. Experimentation using flat tipped rebar as the bit revealed that a cordless hammer drill would not penetrate shale or sandstone bedrock in Berea College Forest—an advantage, as the measurements require a method that will penetrate regolith but not underlying bedrock.

Specifically, a DeWalt hammer drill (Model Number DCD985M2) with DeWalt 20V MAX VR Premium Lithium Ion batteries (4.0 Ah) was used. This drill has a 13mm keyless chuck that tightly fits onto a 120 cm diameter piece of rebar. Keyless means that it is easy to remove the drill from the rebar, a useful feature in the event that wasp nests or other hazards are accidentally impaled. This drill has a 3-speed all metal transmission which allows for the precise control in the number of revolutions per minute (0 to 575, 0 to 1350, and 0 to 2000, for first, second, and third gear, respectively) and the number of blows per minute (0 to 9,775, 0 to 22,950, and 0 to 34,000, for first, second, and third gear, respectively). The drill itself weighs 2.35 kg, which is a little more than a hammer but weighs significantly less than the GPR equipment. Besides its low weight, one key benefit of using a hammer drill was that it was easy to remove from the ground using the reverse gear. The spinning action of the drill made the hole wider than the rebar itself (due to a very small bending force) so in many cases the drill and rebar could be pulled directly out of the ground if needed.

As a proof of concept, exposed shale and sandstone bedrock along the trail system in Berea College Forest was used to test that the rebar would not penetrate into bedrock

once contact was made and to ensure that it would make it all the way to contact before refusal. In some locations, the trails are cut into the side of the hill, revealing the contact between bedrock and regolith. The hammer drill method worked perfectly in these demonstration areas. Video was recorded of this as evidence that the drill does not penetrate shale, the softer of the two strata. As it turned out, first gear was sufficient to penetrate the soil without problems and was used in all sampling to reserve battery life. A soil auger was also used at approximately 10% of subplot hammer drill samples to confirm that the hammer drill method gets comparable results. The most any sample differed was 3.0 cm, and the majority of comparisons yielded identical results. The hammer drill did have problems going through thick tree roots, as is the case with any drilling, probing, or excavation method. If tree root contact was suspected, additional samples were taken a few cm away to ensure an accurate depth measurement was taken. Thanks to the grid system employed, soil depth next to living trees could still be taken, just not in the same physical space. Again, this would be no different if alternative methods were employed. Tree stumps were not excluded from being sampled but were not preferentially selected either.

RESULTS

Details describing the four upper slope subplots are presented in Figure 5.3. Slope shape was not consistent between subplots in the upper slope position, where each qualitative possibility was represented at least once. According to the USDA Web Soil Survey (websoilsurvey.nrcs.usda.gov) three different soil types were represented by these four subplots. Basal area per hectare ranged from 21 to 34 m²/ha with an average of 26 m²/ha. Aspect was generally in the southwest direction. The mean slope gradient and mean elevation of subplots in the upper slope position was 17.2 and 368 m, respectively. The mean soil depth for subplots in this landscape position was 33.1 cm with a standard deviation of 14.6 cm. Figure 5.3 also displays 3D charts of the actual soil depth measurements for each subplot. Note that the color scheme is representative of soil depth categories and do not describe the soil profile. Based on the 1:24,000 Kentucky Geologic Map (kgs.uky.edu) subplot 05 and 11 (the right pair in Figure 5.3) were underlain by limestone and shale from the Slade Formation. The other two subplots were underlain by

shale from the Borden Formation. Subplot 05 was located near a limestone outcrop but shale fragments were found near the bedrock surface while auguring. No visible karst formations were present. Each site in this stand had sandstone fragments on the surface which suggested transport from further upslope

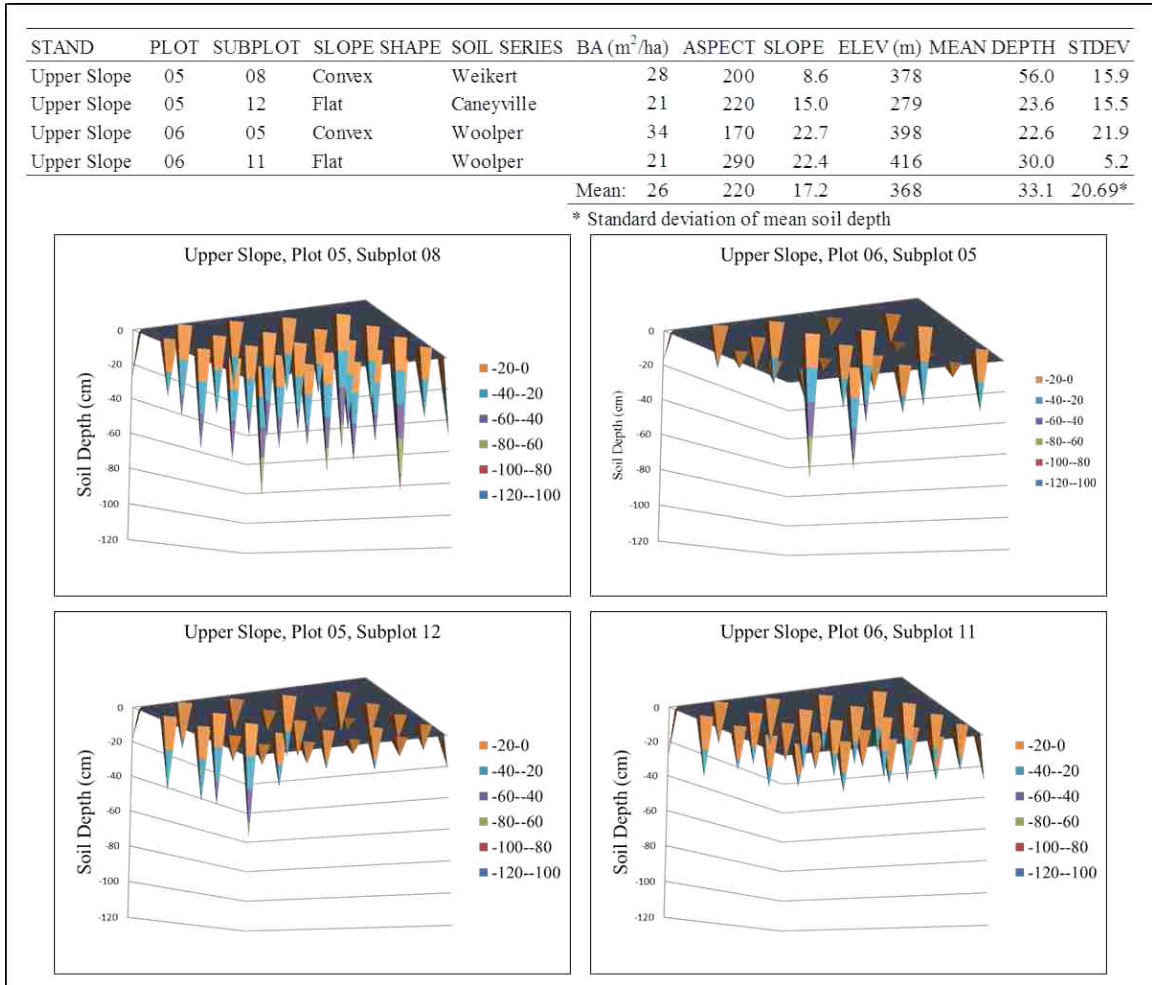


Figure 5.3: 3D soil depth charts for each subplot in the upper slope position. Additionally, subplot characteristics are presented. Note that the color scheme is representative of soil depth categories and do not describe the soil profile.

Descriptive statistics and 3D charts for the mid slope position are presented in Figure 5.4. All possible qualitative slope shapes were represented by the four subplots within this stand. Three of the subplots were from the Weikert series and one subplot was from the Caneyville series based on the USDA web soil survey (websoilsurvey.nrcs.usda.gov). Basal area had a mean of 26 m²/ha. Aspect ranged from 215° to 270° and elevation

ranged from 341 m to 382 m. The mean slope gradient for subplots in the mid slope position was 17.8 percent. Mean soil depth ranged from 25.5 to 39.3 cm and had an overall average of 33.1 cm ($\sigma = 15.8$) for all soil samples. Based on the 1:24,000 Kentucky Geologic Map (kgs.uky.edu) soils in this stand were underlain by shale from the Borden Formation. Shale and small amounts of sandstone were found on the surface of each subplot. Subplot 07 was located near a shale outcrop and there were significant amounts of weathered shale fragments on the surface.

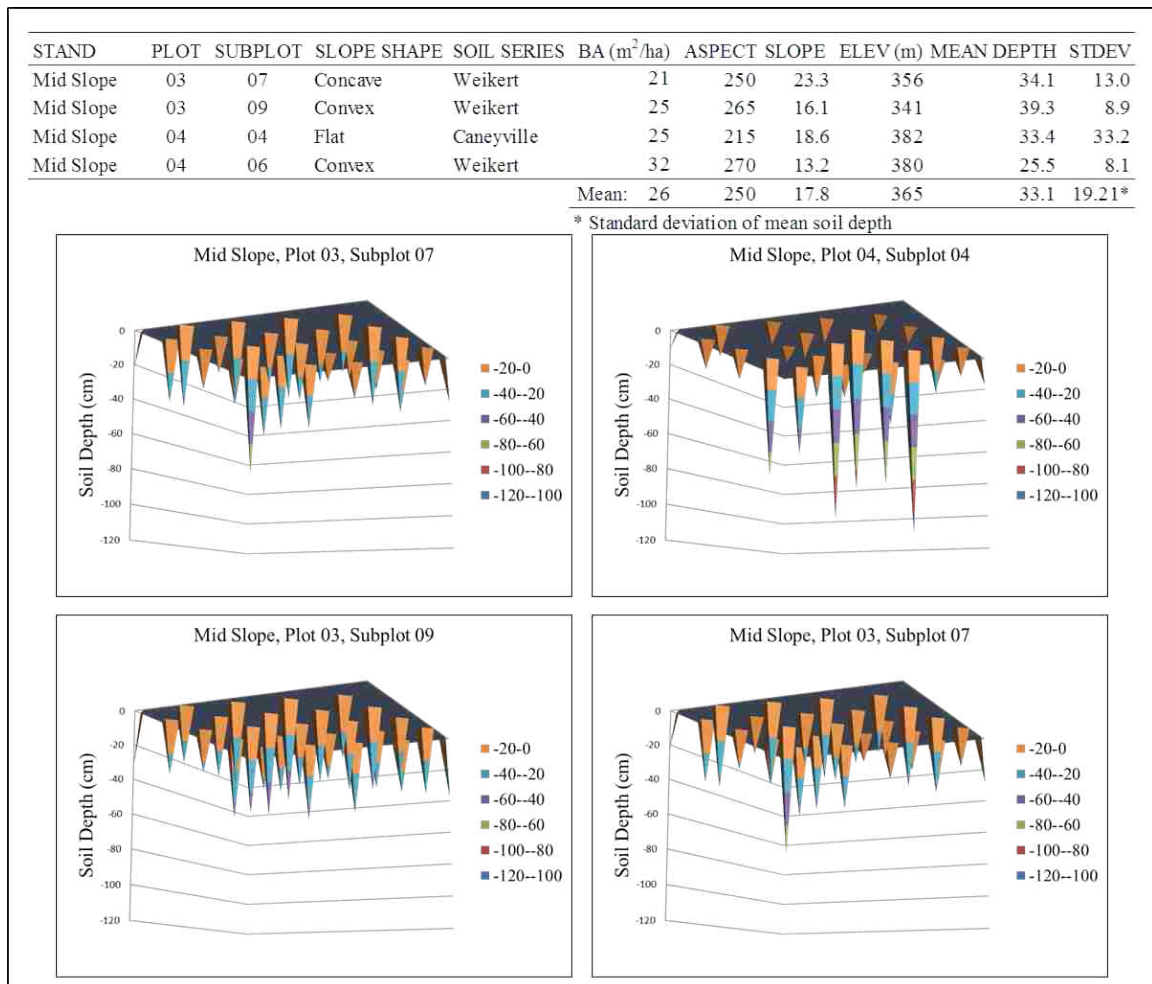


Figure 5.4: 3D soil depth charts for each subplot in the mid slope position. Additionally, subplot characteristics are presented. Note that the color scheme is representative of soil depth categories and do not describe the soil profile.

Figure 5.5 shows the 3D charts for soil depth and soil characteristics in the lower slope stand position. Every subplot within this stand had a flat slope curvature and soil from

the Rarden series. Basal area ranged from 18 to 30 m²/ha and slope gradient ranged from 3.5 percent to 12.5 percent. Aspect ranged from 190° to 310°. Mean elevation was 308 m. Mean soil depth for this stand position was 59.2 cm ($\sigma = 18.04$). Subplots in plot 01 were located near a deeply incised channel so fluvial activity could have contributed to the soil thickness in this area. Based on the 1:24,000 Kentucky Geologic Map (kgs.uky.edu) subplots in this slope position were underlain by shale from the Borden Formation.

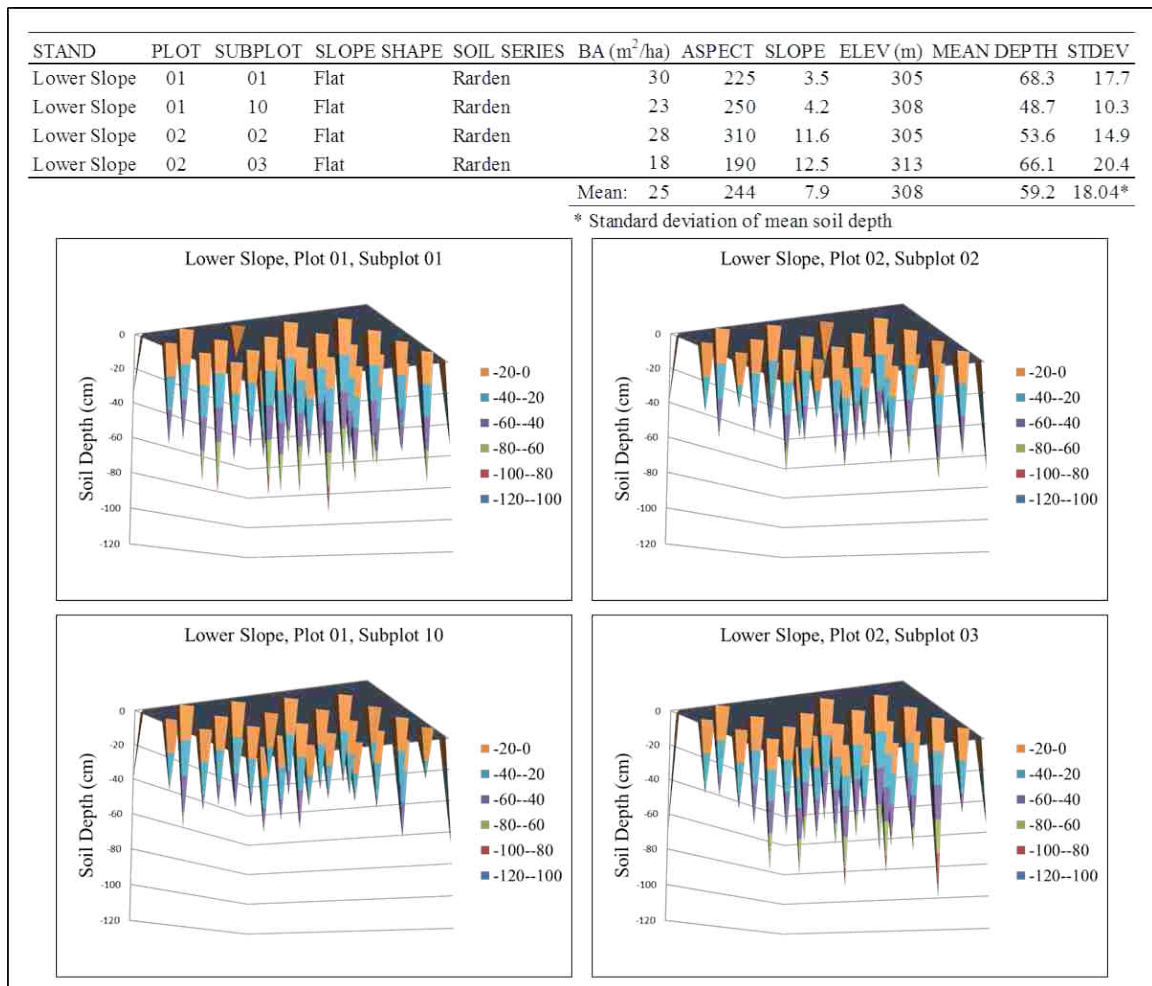


Figure 5.5: 3D soil depth charts for each subplot in the upper slope position. Additionally, subplot characteristics are presented. Note that the color scheme is representative of soil depth categories and do not describe the soil profile.

The mean soil depth for all subplots was 41.79 cm ($\sigma = 22.89$). Each slope position had similar aspects and basal areas. Soil series and elevation were distinguishable between

each slope position. Mean soil depth between the upper slope position and mid slope position was nearly identical but the standard deviations suggest that upper slope position might be more variable. Mean soil depth at the lower slope position was much greater and mean slope was much less than the other two slope positions. The mid slope position had the highest mean slope gradient.

Results of the nested ANOVA are presented in Table 5.1. Hypothesis testing was based on the reported P-values listed in this table. The variance between stands, and thus slope position, was significant based on a p-value of 0.04. Therefore, H_{01} was accepted and slope position is an important factor in determining the variance of soil depth. The variance between plots was found not to be significant based on a p-value of 0.67 and as a result H_{02} was rejected. The results indicate significant variation between the subplots based on a p-value approaching zero. Based on this result, H_{03} was accepted and site local scale mechanisms are important. In summary, the main effects of the nested ANOVA model indicate significant variance between slope positions and significant variance between sites.

Table 5.1: Results from three factor nested ANOVA for soil depth along a hillslope in Berea College Forest, KY.

Variance Source	DF	Sum of Squares	F-Value	P-value	Error Term	Mean Square	Variance Component	Percent of Total
Total	299	156692	-	-	-	524.06	630.79	100.00
Slope Position	2	45484	11.48	0.04	Plot	22742.00	207.61	32.91
Plot	3	5941	0.55	0.67	Subplot	1980.32	-32.68	0.00
Subplot	6	21685	12.45	0.00	Error	3614.13	132.96	21.08
Error	288	83583	-	-	-	290.22	290.22	46.01

Variance is apportioned to $3+1 = 4$ scales, where the +1 (“error”) represents the localized variation within the sites themselves, akin to nugget variance in geostatistical analysis (Miesch (1975) showed that nested ANOVA can be used to estimate a geostatistical variogram). The variance component is provided as a percent of variation associated with each spatial scale in the column named “percent of total” in Table 5.1. The stand level accounted for nearly 33% of total variation in the data. The plot level accounted for

none of total variation in the data. The subplot level accounted for 21% of total variation in the data. The error, or within subplot effects, accounted for 46% of total variance. In total, the local scale conditions accounted for two thirds of the variation (21% between subplots + 46% within subplots) of total soil depth in the area sampled.

DISCUSSION

Broader scale impacts acting at the stand level were shown to be important factors in the variance of soil depth. This hierarchical level was thought to represent the level of organization where topographic changes could play a significant role in limiting the biomechanical impacts of tree growth. With the exception of two upper slope position subplots that were located on mapped limestone (but near the geologic contact), all other subplots were underlain by horizontally oriented shale so lithological variations were not acting on the slope position level of organization. Based on the descriptive statistics reported in Figures 5.3, 5.4, and 5.5 the upper slope and mid slope subplots were more similar than the lower slope subplots in terms of mean slope gradient and mean soil depth. At the upper slope and mid slope positions, where soil thickness is shallower, there is more variability in soil thickness. The upper slope position had the highest standard deviation for mean soil depth, followed by the mid slope position. This is made even more meaningful by the fact that the lower slope position had much deeper soil on average. The deeper soils at the lower slope position could be a function of colluvial processes. Colluvial material derived from ridgetops and upper slopes accumulates on lower slope positions, and soil and regolith, in the aggregate, is typically deeper. Perhaps the deeper soils in the lower slope position limits variability because of reduced weathering rates at the bedrock surface as theorized by soil production parameters discussed in Chapter 2 and described in Minasny and McBratney (1999). Humphreys and Wilkinson (2007) suggested that the rate at which bedrock is converted to soil reaches a maximum under an optimal soil depth that facilitates contact between bedrock and water such that freezing-thawing and weathering are maximized. Perhaps the upper slope and mid slope positions are more susceptible to these processes because they are not heavily impacted by colluvial processes.

The plot level complicated the issue through both its main and nested effects. This could be due to study design or because plot level mechanisms do not contribute much influence to soil depth properties. To determine if this was due to study design, a second nested ANOVA model was conducted with only two factors: stand and subplot. Results (Table 5.2) show the same general relationships with respect to both the main effects and nested effects. Therefore, the inclusion of the plot level in the three factor nested ANOVA model did not limit the results interoperability. Based on this, it can be concluded that plot level dynamics did not significantly contribute to soil depth variability in this system. As a result, the variance between plots, within the stands was not shown to be different and was the reasoning for rejecting H_{02} .

Table 5.2: Two factor nested ANOVA results

Variance Source	DF	Sum of Squares	F-Value	p-value	Error Term	Mean Square	Variance Component	Percent of Total
Total	299	156692	-	-	-	524.06	598.11	100
Slope Position	2	45484	7.41	0.012	Subplot	22742	196.73	32.89
Subplot	9	27626	10.58	0	Error	3069.53	111.17	18.59
Error	288	83583	-	-	-	290.22	290.22	48.52

More than two-thirds of the total variation was due to mechanisms at the local scale, irrespective of slope position or plot location. This is consistent with the idea that effects of individual trees are the dominant control of local soil depth in relatively thin forested soils overlying bedrock. Slope shape was considered a between-subplot factor for this research, but results from Chapter 4 and from Phillips and Marion (2006) suggest that the influence of slope shape is insignificant as a control of soil depth. Chapter 4 also showed that basal area was not a significant contributor to soil thickness. This also seems to be the case in this analysis, since basal area was similar in each slope position. The influence of pit-mound processes likely act at the within-subplot scale as well (Šamonil et al. 2010), but pit-mound formations were not present in any subplots sampled. Neither lithological variation nor topography seemed to be variable at the subplot or lower scale. The most plausible explanation, and the one supported by field observation, is that biomechanical effects of trees control local variability of soil depth. The majority of variance was explained by within subplot effects. Since the grid design used in this

research was representative of the soil influence area concept it can be reasoned that single tree influences are operating at this level. This supports the notion that the location of self-reinforcing feedbacks between biota and subsurface processes are not random.

From a scale perspective, it seems that first-order control is associated with the stand level, representing topographic position and lithological variations. Overlaid on this, however, the primary controls over variations in soil depth and thickness operate at a local scale. Given the characteristics of the study site, and other findings reported here regarding soil depth variations between stump and adjacent sites, tree effects on soil deepening are certainly a contributing factor and most likely the dominant factor. It is possible that other localized biological effects such as faunalurbation contribute to this variability. Microtopography can also contribute to local variation in soil thickness in some settings, but the lack of a relationship between topographic variables and thickness at the study site argues against this in the present study. Independently of bedrock type, slope, or any number of broad scale influences, local scale processes are actively altering soil thickness. Chapter 3 and 4 showed convincing evidence that the trees preferentially select pockets of deeper soil and strengthened the argument for the self-reinforcing pedologic influences of trees. Based on this information it can be reasoned that the high variability of soil depth found within and between subplots is representative of divergent soil evolution.

CHAPTER 6

CONCLUSION

Phillips and colleagues have been publishing on the topic of biomechanical effects of trees for over a decade. They have released a myriad of research located in the Ouachita Mountains and have linked the interaction between trees and bedrock to concepts of nonlinear dynamics, nonequilibrium soil thickness, divergent soil evolution, and pedological memory. However, the geology of the Ouachita Mountains is atypical and can be characterized by its variable structural resistance associated with fractures and bedding planes associated with strongly dipping and tilted Paleozoic sedimentary parent material. Limited similar work (e.g. Roering et al. 2010) has also been conducted in areas of high lithological and structural complexity. Thus it has been difficult to separate tree effects—which, after all, are largely associated with root interaction with bedrock—from geological variability. Thus some testing of the model of self-reinforcing pedologic influence of trees in a region less geologically complex than the Ouachita Mountains was needed.

The purpose of this research was to gain further insight into this phenomenon by separating the biomechanical effects of trees from extreme lithological variation with the hope to further highlight the role of local, point centered pedological influences of trees in forests with relatively thin soils overlaying sedimentary bedrock material and to encourage future research into this biogeomorphological topic. This project extended these concepts to the Cumberland Plateau region of Kentucky, where flat, level-bedded sedimentary rocks are the norm. The approach taken to better understand the role of biomechanical weathering by trees in this research was to answer three research questions, which collectively address issues related to pattern and scale. (1) How does spatial variability of forest soil depth differ between vertically and horizontally oriented underlying bedrock? (2) What is the relative importance of individual trees vs. other potential controls of local variability in soil depth? (3) How is the variance of soil depth partitioned across spatial scales? As a result of this research the following statements can now be made:

- A cordless hammer drill is a fast and reliable method of sampling soil depth in thin soils underlain by sedimentary bedrock.
- Soil thickness on forested sideslopes in the Cumberland Plateau is highly variable. This variability is at least partially controlled by tree locations, as soil is systematically thicker beneath stumps than at adjacent locations. Soil thickness in the sampled areas could be classified as nonequilibrium due to the lack of any significant relationship with topographic variables. The model of self-reinforcing pedologic influences of trees is a reasonable explanation for the observed variability.
- The biomechanical weathering by trees in the Cumberland Plateau is comparable to that of the Ouachita Mountains, with the primary difference being that soils are deeper beneath stumps in the latter. While bedrock orientation may limit biomechanical processes in the Cumberland Plateau, it does not prevent their effects from being expressed through divergent soil evolution. Results also suggest that in the Ouachita Mountains tree effects are more important than local lithological variation as an influence on soil thickness.
- In both the Ouachita Mountains and the Cumberland Plateau, two areas impacted by biomechanical effects of trees, neither slope gradient nor slope shape were significant factors in determining soil thickness. In the landscape-scale topographic variation—slope position--does have significant influence over soil thickness in the Cumberland Plateau.
- Slope position explained a significant amount of variation in soil depth in the Cumberland Plateau and is a first-order control. However, local scale effects linked explained twice as much variance.
- This highly localized variability is consistent with, and most plausibly explained by, individual tree effects.

The take home message of this dissertation is that the effects of biomechanical weathering by trees are not limited to areas with strongly dipping and contorted bedrock. However, they are most likely limited to areas where soil depth is less than the optimal rooting depth for trees. This research has provided evidence that the variability of soil depth in the Cumberland Plateau is likely influenced by positive feedbacks from tree root growth, that these interactions occur over multiple generations of growth, and that the effects of trees are the dominant control of local soil thickness. This study also provides evidence that the positive feedback from biomechanical weathering by trees leads to divergent development of soil thickness. Presumably, this divergent development will perpetuate until pockets of deeper, relatively rock free, nutrient-rich soil no longer provides a competitive advantage for trees in a given area. However, the uneven bedrock surface would likely persist for much longer periods of time.

Naylor et al (2002) suggested six approaches that would benefit future biogeomorphic research, which are echoed, at least indirectly, in more recent commentaries (c.f. Marston, 2010; Corenblit et al., 2011; Fei et al., 2014). The first approach was to identify key theoretical and practical research questions (Naylor et al. 2002). The research presented in this dissertation was designed around three research questions that included both theoretical and practical components. The second approach was to modify existing, or develop new, methodologies to investigate biogeomorphic relationships (Naylor et al. 2002). This dissertation research borrowed the stump-pair sampling method and developed the hammer drill method for sampling soil thickness. The third, fourth, and fifth approaches were to place the research into the context of existing knowledge, develop sound sample designs and to improve the quality of existing data (Naylor et al. 2002). These approaches were utilized in this research by building directly on previous work in the Ouachita Mountains, expanding it to a new region using a hierarchical study design, and by more than doubling the existing data on the topic. The sixth approach was to develop theoretical, conceptual, and process models which illustrate the role of organisms in geomorphological processes (Naylor et al. 2002). This research provided new empirical support for the SRPIT model, and demonstrated that the controls over process-response relationships and spatial variability can vary with spatial scale even

within a relatively small range of resolutions. This suggests that future work on reciprocal interactions between vegetation, soils, and landforms in forests—and in biogeomorphology more generally—should pay explicit attention to scale linkage issues. Overall, beyond the well known geographical and historical contingency in the Earth and environmental sciences, this work highlights the issue of scale contingency.

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PUBLICATIONS

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