AN INVENTORY AND MAPPING OF CLIFFS WITHIN THE SOUTH CUMBERLAND PLATEAU REGION OF TENNESSEE

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ABSTRACT

The high concentration of cliffs that permeate Tennessee's South Cumberland Plateau (SCP) significantly influences the development, economy, and ecology of the region, yet little effort has been made to quantify these geophysical features. This study examined the use of LiDAR-derived digital elevation models (DEMs) to (1) create an exhaustive dataset of cliffs throughout a 2-county study area within the SCP region, and (2) better understand the implications of this quantification on conservation and rock climbing within the region. An impressive 428 km of total cliff line was modeled. Cliffs were GPS-verified to an average error of ±13.9 m and a length RMSE = 91 m. The study determined that 36% of cliffs in the study area lie on public lands, and 7% of cliffs are currently accessible for rock climbing. Results from this study clarify and reinforce the ecological and recreational significance of cliffs within the SCP region.

DEDICATION

To the numerous scientists, conservationists, trusts, non-profits, and land managers that help steward the wild places of the Cumberland Plateau: thank you so much for the time, effort, and energy you have given to study and stand-up for this beautiful corner of the world.

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To the rest of my family, friends, and peers, for continually reminding me that there's little in life more valuable than the people around you.

And to the cliffs – to the sandstone walls that stretch throughout the plateau, to the granite domes of Western North Carolina, and to the snow-covered peaks across the West – for teaching me to risk well, to take action, and to be present.

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LIST OF ABBREVIATIONS

3DEP, 3D Elevation Program

DEM, Digital Elevation Model

ESRI, Environmental Systems Research Institute

GIS, Geographic Information Systems

GPS, Global Positioning System

LiDAR, Light Detection and Ranging

PAD, Protected Areas Database

RMSE, Root Mean Square Error

SCP, South Cumberland Plateau

TNGIC, Tennessee Geographic Information Council

TWRA, Tennessee Wildlife Resources Agency

UAS, Unmanned Aerial System

US EPA, United States Environmental Protection Agency

USGS, United States Geological Survey

UTC, The University of Tennessee at Chattanooga

WMA, Wildlife Management Area

CHAPTER I

INTRODUCTION

As in many parts of the world that contain significant geographic relief, the cliff faces and bluffs that permeate the South Cumberland Plateau (SCP) are integral to the natural history, settlement, and development of the region. The steep cliffs, rugged gorges, waterfalls, caves, rockhouses, arches, and other geologic features are a large part of what define the SCP region (Byerly, 2013). The high concentration of these geophysical features has allowed for the development of world class outdoor recreation in the region. Activities such as rock climbing, whitewater paddling, hiking, and caving draw large numbers of recreation enthusiasts from around the world and result in a significant economic impact to the region (Bailey et al., 2016). From an environmental conservation perspective, the geophysical features and climate of the SCP create and support many unique and endemic species and ecosystems that contribute to the region's high levels of biodiversity (Stein, 2000). Some of these "micro" cliff ecosystems support cliff-obligate species found nowhere else in the world (Larson et al., 2000a).

Despite the economic and environmental significance of cliffs within the SCP region, these geophysical features have received (compared with other ecological systems) minimal study. Additionally, the effects of climate change and increased anthropogenic pressures on these cliff-based ecosystems and the ecology of the surrounding landscape is also unknown. A thorough inventory or map that accurately identifies and quantifies cliffs would help provide a baseline assessment for responses of these systems to such pressures, but no such map or dataset currently exists within the SCP region. This thesis project aimed to remedy this problem by examining the use of Tennessee's LiDAR-derived digital elevation model (DEM) dataset to assess how accurately the presence of cliffs within a landscape can be identified. The study's hypothesis was: the DEM dataset can be used to accurately determine cliffs and calculate basic statistics to better understand the region's cliffs.

Specific objectives of this project were:

1. Produce a high-resolution, exhaustive dataset of cliffs within the Tennessee counties in which the SCP occurs.
2. Analyze the dataset and explore an application of the derived cliff maps to improve understanding of how these cliffs impact the SCP region by:
    a. Examining the conservation status of cliff ecosystems by comparing their distribution on protected public lands versus private lands.
    b. Demonstrating potential usefulness through a case study focused on regional rock climbing by quantifying and comparing existing legal climbing areas with a predictive climbing area model based on protected lands and preferred geologic type.

CHAPTER II

LITERATURE REVIEW

Study Area

Stretching from New York to Alabama, the Appalachian Plateaus province is the westernmost portion of the Appalachian Highlands division, bordered on the east by the Ridge and Valley province and to the West by the Highland Rim section of the Interior Plains province (Omernik, 1987). The U.S. Environmental Protection Agency's (EPA) breakdown of physiographic provinces (based on studies completed by Hack (1966) and Omernik (1987)) defines the SCP as the southern- and western-most section of the Appalachian Plateau province. This study focused on the portion of the SCP that occurs within the boundaries of Tennessee (Figure 1).

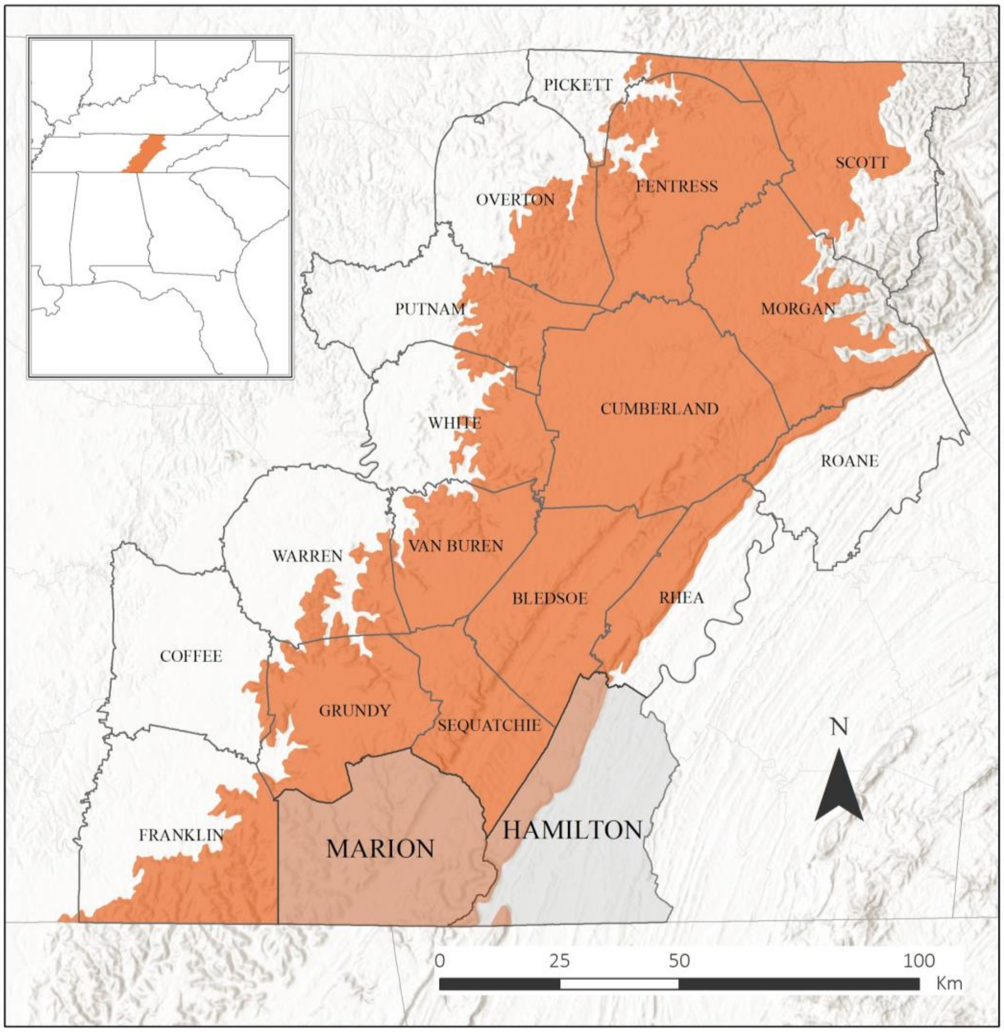

Figure 2.1

A map showing the South Cumberland Plateau Region (orange) and the Tennessee counties that contain it; the study area for this site (Hamilton County and Marion County) are shown in light grey (US EPA, 2010)

The majority of the SCP is an elevated tableland ranging in width from 50 to 120 km. Average elevations in the northern Tennessee portion of the plateau are approximately 500 m above mean sea level; plateau elevations in the southern portion are slightly higher at 600 m (US EPA, 2010). With the exception of the Sequatchie Valley, the SCP is relatively undeformed within the state of Tennessee (Byerly, 2013). The eastern border of the SCP is a well-defined escarpment, in some places rising over 300 m over the neighboring Ridge and Valley province (Omernik, 1987). Its western border is a less obvious drop in elevation and change of underlying geology to the Highland Rim plateau (Omernik, 1987). In total, the SCP comprises an area of approximately 7700 km^2 within the state of Tennessee (US EPA, 2010), an area slightly larger than the state of Delaware (US Census Bureau, 2010a).

Geologic Background

In a process that can be traced back nearly 1 billion years, organic and inorganic sediments in the ancient seas and river deltas that once existed across much of the southeastern United States were laid down, compressed, and eventually uplifted through tectonic forces (Byerly, 2013). This uplift, combined with the erosive power of the region's abundant precipitation, create the dramatic relief that makes up the present-day SCP (Miller, 1974). As is typical of other karst geologic regions, the SCP is constructed of various layers of limestone, dolomite, shale, and other sedimentary rocks (Figure 2.2); this stratification is ultimately capped by layers of sandstone that tend to be more erosion-resistant than the aforementioned rock types (Byerly, 2013). In the process of differential weathering, the softer and more soluble rock layers are eroded from beneath the resistant sandstone cap, creating solution caves, sinkholes, arches and pinnacles, and steep cliff bands that stretch throughout the region (Gore and Witherspoon, 2013).

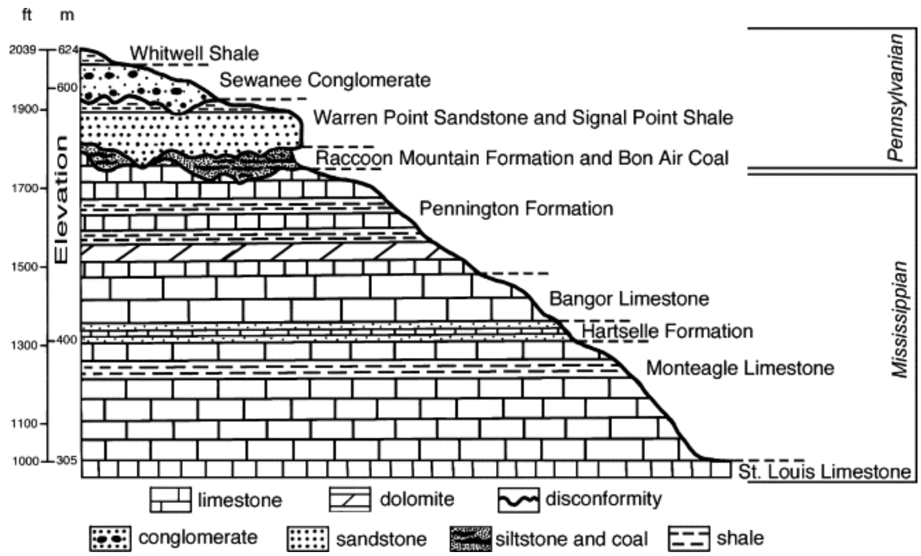

Figure 2.2

A diagram of the geologic stratigraphy typical of the SCP region; Mississippian Age rock types are generally softer/more soluble than the overlying Pennsylvanian Age rock types (differential weathering leads to undercutting of the Pennsylvanian Age rock types, resulting in the many cliffs and other unique rock formations typical to the SCP; Shaver et al., 2006)

Is *That* a Cliff?

The characteristics that define a cliff are considerably subjective and vary based on geographic region, rock type, slope, and a multitude of other variables (Larson et al., 2000a). Terms such as ‘cliff’, ‘precipice’, ‘rock outcrop’, ‘escarpment’, ‘bluff’, etc. are often used interchangeably and are subject to colloquial use. These terms can differ and sometimes even contradict each other based on the historical or regional context (Larson et al., 2000a). For example, Alum Bluff in Northern Florida is a steep, riverside slope of unconsolidated sand, clay, and shells with a rise in elevation of no more than several dozen meters (USGS, 2015). This is an entirely different geophysical feature than a place such as Big Bluff in Northern Arkansas, which is a vertical and overhanging sandstone cliff that is several hundred meters high (USGS, 2014).

This study made use of the term 'cliff', defined according to the research of Larson et al. (2000a) which requires three elements: a level or sloping base, a vertically oriented cliff "face" of mostly exposed rock (also including near-vertical and/or overhanging rock faces), and a defined, level or sloping landmass, platform, or plateau top. In the context of the SCP, personal observation indicates cliff slopes must be quite steep to maintain the exposed-rock requirement of the Larson et al. (2000a) definition. This study used 70° off horizontal as its threshold value, assuming slopes less than 70° are likely to support enough soil/vegetation to not meet the definition of a cliff.

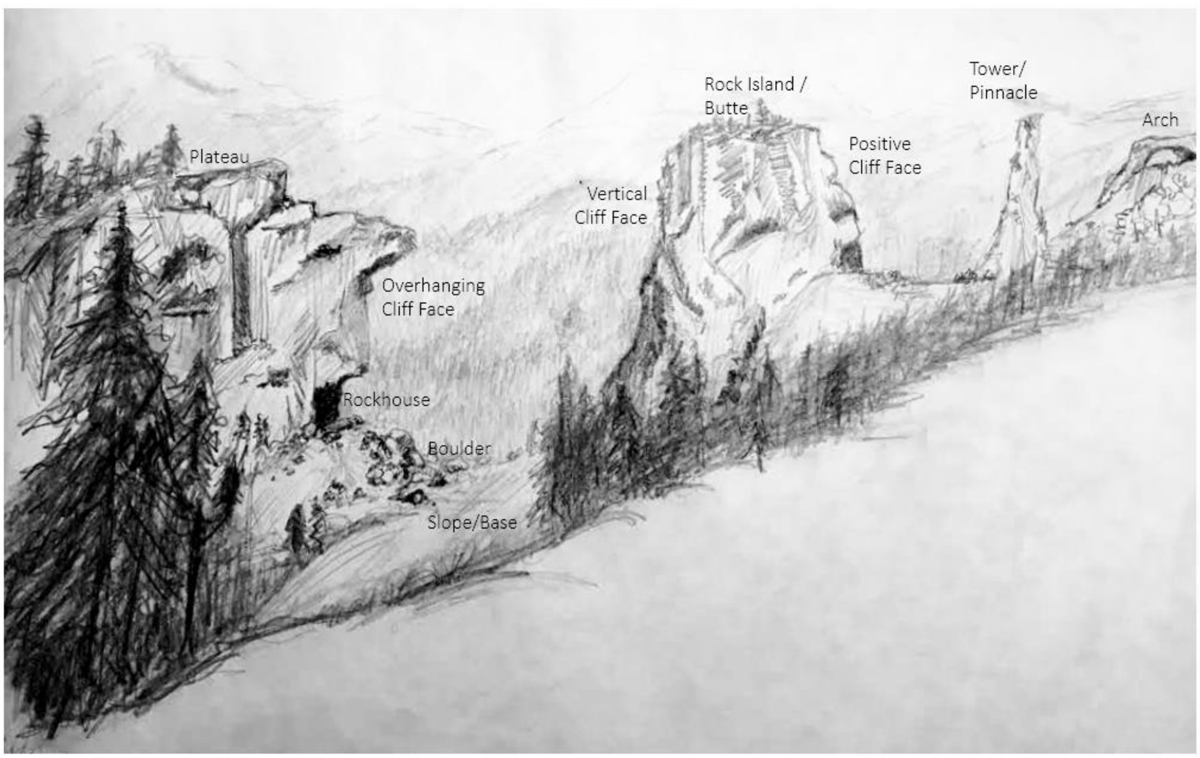

Figure 2.3

An illustration by Denise Jones showing terminology associated with cliffs and related geophysical features of the SCP region

Identification Through Remote Sensing

Given the overall size of the SCP region, the ruggedness of the terrain, and the extensiveness to which cliffs permeate its landscape, local/ground-based surveying of the landscape would be extremely difficult, time consuming, and thus prohibitively expensive. Remote sensing and geographic information systems (GIS) can be used instead, allowing for regional scale study at a fraction of the time and cost. Photogrammetry is one of the oldest methods of remote sensing and has been used successfully to study cliffs (Elevald et al., 2000; Redweik et al., 2009). However, this technology is best suited towards site specific research and/or other areas relatively free of vegetation. Because photogrammetry captures the reflected electromagnetic radiation of the study area, it is typically limited to studying subjects that are in direct view of the sensor (Jenson, 2007). This is a challenge in the SCP region, because most of the cliffs are vertical or overhanging in nature (Byerly, 2013) and thus difficult to perceive in nadir. The SCP region also contains some of the most extensive, contiguous tracts of temperate broadleaf forest on the continent (Evans et al., 2002). Personal observation will reveal that many of the cliffs in the SCP do not break the canopy of these forests, which further limits the use of photogrammetry for identification.

Fortunately, improvements in remote sensing technologies such as LiDAR (Light Detection and Ranging) are producing increasingly accurate, high resolution datasets at the landscape level (James et al., 2012). This active remote sensing method of surveying involves transmitting laser pulses and capturing the backscatter at a sensor; the various wavelengths and return times for each pulse can be used to create three-dimensional data, or point clouds of the surveyed landscape (Wandinger, 2005). These laser pulses, which are emitted at rates >100,000 s-1, are capable of penetrating vegetation and reaching the ground. These "ground hits" can be filtered from the point cloud and interpolated to create high resolution DEMs (Wandinger, 2005). LiDAR surveys are typically conducted from an aircraft flying over the survey area (Wandinger, 2005), but depending on the application, they can also be spaceborne, terrestrially based, or more recently, flown from unmanned aerial systems (UAS).

Tennessee, in conjunction with the US Geological Survey (USGS) 3D Elevation Program (3DEP) (USGS, 2017), finalized plans in 2011 to conduct LiDAR surveys for the entire state (TN.Gov, 2017a). These ongoing surveys, which were initiated during the winter months of 2015/16, are scheduled to be completed in 2018 (TN.Gov, 2017a). This will provide Tennessee with greatly enhanced elevation data at a much finer resolution and smaller degree of error than previous datasets (TN.Gov, 2017a; USGS, 2017). This elevation data, which meets or exceeds the USGS's quality level 3, is accurate enough to produce 2' contour topographic maps (USGS, 2017). In addition to helping Tennessee better predict and prevent flood occurrences (the impetus behind the LiDAR surveys), the DEM's produced from these surveys should allow for significant increases to the recognition and mapping of geophysical features (Hopkinson et al., 2009).

A review of literature was conducted, examining the use of LiDAR to identify geophysical features revealed studies related mostly to geomorphology and a better understanding of when and where cliff erosion, rockfall, landslides, etc. will occur (James et al., 2012; Schulz, 2007). The focus of these studies analyzed erosion associated with either nearby water bodies (Adams and Chandler, 2002) or roadcuts (Lan et al., 2010; Schulz, 2007).

Terrestrial-based LiDAR was used for a number of these studies because it offers the advantage of a better angle of analysis onto the faces of cliffs. This results in improved resolution, accuracy, and reducing error (Brodu and Lague, 2012; Rosser et al., 2005). Despite the improved applicability of terrestrial LiDAR for examining cliffs, this method of analysis appears to be better suited for site-based analysis (e.g. better understanding the dynamics of one or several cliffs) rather than simply the identification of many cliffs within a larger landscape.

DEMs, on the other hand, offer the advantage of geophysical analysis across much greater areas. Graff and Usery (1993) and Miliaresis and Argialas (1999) examined the feasibility of differentiating physiographic regions using the Global (GTOPO30) DEM dataset and the USGS 7.5 Minute DEM dataset (respectively). Though the coarse spatial resolutions (925m and 30m, respectively) limits these studies to analyzing large physiographic regions, the studies demonstrate the successful use of a slope-based model methodology for differentiating various landforms. More recently, the increasing availability of ultra-high resolution DEMs, such as those produced through LiDAR surveys, are allowing for improved identification of smaller and more specific geophysical features. Whereas Miliaresis and Argialas (1999) differentiated large, physiographic regions (mountains vs. non-mountains), studies such as those conducted by Asselen and Seijmonsbergen (2006) and Castañeda and Gracia (2017) successfully identified specific geophysical features (e.g. terraces, slopes, cliffs, channels, etc) within those broader regions. Another exciting application of LiDAR that demonstrates its versatility is in the identification of archaeological sites beneath vegetation (Chase et al., 2012; Devereux et al., 2005). Using LiDAR-based DEMs created from ground hits, various models (e.g. hillshade) may be applied to the DEMs; these techniques are not only allowing for the discovery of new sites hidden beneath vegetation, but they are also allowing researchers the opportunity to study past civilizations at a landscape and regional scale (Chase et al., 2012; Devereux et al., 2005).

These studies demonstrate the potential applications of LiDAR and the associated ultra-high resolution DEMs created through this technology. Based on the available literature, this study hypothesized that LiDAR-based DEMs, in conjunction with a capable GIS model, would be successful in identifying the cliffs that are of the size and distribution of those typical to the SCP region. However, there is to my knowledge no mention in the current body of literature that explores the feasibility of using high-resolution DEMs to identify cliffs (specifically) at a regional level.

Significance

Cliffs are an integral part of the identity and landscape in the SCP region. Through activities such as rock climbing, rappelling, hang gliding, hiking, and sightseeing, these geophysical features support local economies through their aesthetic and recreational opportunities (Bailey et al., 2016; OIA, 2017), Chattanooga, a city of 175,000 people (U.S. Census Bureau, 2010b), is located directly adjacent to the SCP and has received national media attention for its outdoor recreation and scenery (Handwerk, 2017; Outdoor Magazine, 2011, 2015). Research by Bailey et al. (2016) on the economic impact of rock climbing in the Chattanooga area, estimated that climbing attracted 16,000 non-resident participants to the area and generated nearly $7 million in revenue during a single climbing season. SCP cliffs also create ideal conditions for hang gliding, supporting multiple hang gliding schools across the region (Outside Online, 2011). The region’s many waterfalls, unique rock formations, and scenic viewsheds created by these cliffs also attract and support a thriving hiking and sightseeing scene, further boosting the area's economy (OIA, 2017).

Cliffs of the SCP also have enormous value within the context of biodiversity (Shaw and Wofford, 2003; Walker et al., 2009). Given the current biodiversity crisis (Pimm et al., 1995; Stein, 2000), identifying and conserving areas of ecological significance and geodiversity is of increasing importance (Anderson and Ferree, 2010; Aycrigg et al., 2013; Lawler et al., 2015). The SCP region's wide range of geodiversity and lack of ice age glaciation yield a wide array of flora and fauna (TWRA, 2015), and the SCP cliffs, among other geophysical features, are a large contributor to this diversity (Larson et al., 2000a). The variability of heights and aspects of the cliffs within the SCP, when coupled with the region's temperate climate and abundant rainfall, create a multitude of complex microclimates that support a number of species and populations of species that are cliff-obligate, small ranged, and/or endemic to the region (Baskin and Baskin, 1988; Burnett et al., 2008). In addition to height and aspect, these cliffs also contain overhanging, sheltered recesses (colloquially referred to as rockhouses) that create moderated climatic conditions able to support endemic populations of plants; some of these are tropical species which are the only known locations outside of the tropics (Farrar, 1998; Walck et al., 1996). Studies conducted by Larson et al. (1999, 2000b) point to the existence of ancient trees and old growth forests on many of cliffs around the world. This is likely due to the fact that cliff ecosystems have largely avoided the extensive anthropogenic landscape conversion that has occurred in most other ecosystems (Hannah et al., 1995; Sanderson et al., 2002). Larson et al. (2000a) supports this with their suggestion that cliffs may rank as some of the least anthropogenically disturbed ecosystems on the planet. Lastly, the relief change inherent with cliffs will likely bolster the surrounding ecosystem's resilience to rapid changes in climate in the decades ahead (Anderson and Ferree, 2010; Anderson et al., 2014).

Unfortunately, many cliff ecosystems, including those of the SCP, are beginning to experience significant anthropogenic impacts. Development of home sites, roads, and recreational trails and overlooks have been shown to have significant adverse effects on the ecology of these areas (Larson et al., 1990; McMillan et al., 2002, 2003). A number of studies have examined the effects of hiking and rock climbing on the organisms residing on and around cliffs, the majority of which conclude that these activities can be significantly disruptive to the success of cliff resident organisms (Adams and Zaniewski, 2012; Baur, 2016; Clark and Hessl, 2015; Larson, 1990). This is particularly concerning in the SCP, given the number of small ranged and/or endemic species that reside in these specific habitats (Boyer and Carter, 2006: Walck et al., 1996).

The significance of cliffs to the economy and environment of the SCP, the opportunities for ecological study they afford, and the challenges these ecosystems are likely to face in the future all warrant an increased recognition of cliff ecosystems and the associated implications and impact of cliffs on the SCP region. In order to accomplish this, it will be most helpful to have a clear understanding of the quantity and types of cliffs present within the SCP, and it is the intent of this thesis to contribute towards this objective.

CHAPTER III

METHODOLOGY

Developing a Cliff Dataset

ESRI's ArcGIS Desktop 10.5 and ArcGIS Pro 2.1 software were used to facilitate the processing and modeling of the state of Tennessee's LiDAR-derived DEM dataset. The Tennessee Geographic Information Council (TNGIC) hosts the State's LiDAR data, and all DEMs for the project were accessed and downloaded (by county) directly from the TNGIC website (http://www.tngic.org). Each county DEM is comprised of tens of hundreds of scenes; these scenes were mosaicked to create a single DEM for each county (Appendix A). Slope maps were then created for each county DEM using ESRI's slope tool. This tool creates a slope value for each pixel (measured in degrees with 0 being horizontal and 90 being vertical), using the average maximum slope technique of the 3x3 grid surrounding each pixel (Burrough and McDonell, 1998). Once a slope map had been generated for each county, the data was reclassified from continuous to discrete values of 0 and 1 (0 being those areas with slopes $<70°$ and 1 being cliff areas with slopes $\geq 70°$).

Because the purpose of this dataset is a regional-scale inventory of cliffs, these geophysical features are better understood and conveyed as lines rather than nadir areas. To accomplish this, the cliff (raster) areas were converted to cliff lines using the Vectorization toolset in ESRI's ArcScan Extension (Figure 3.1). The vectorization settings used to create these cliff lines (Appendix A) are nearly identical to the more typical scenario for which this toolset was designed: creating a centerline within a road or river area when digitizing a raster map. As a map's coverage area increases, a point is reached where it becomes more appropriate to convey a river/road as a polyline rather than polygon. The same concept applies to this cliff dataset, and thus conversion of the cliff raster area to polyline was chosen over a raster to polygon conversion.

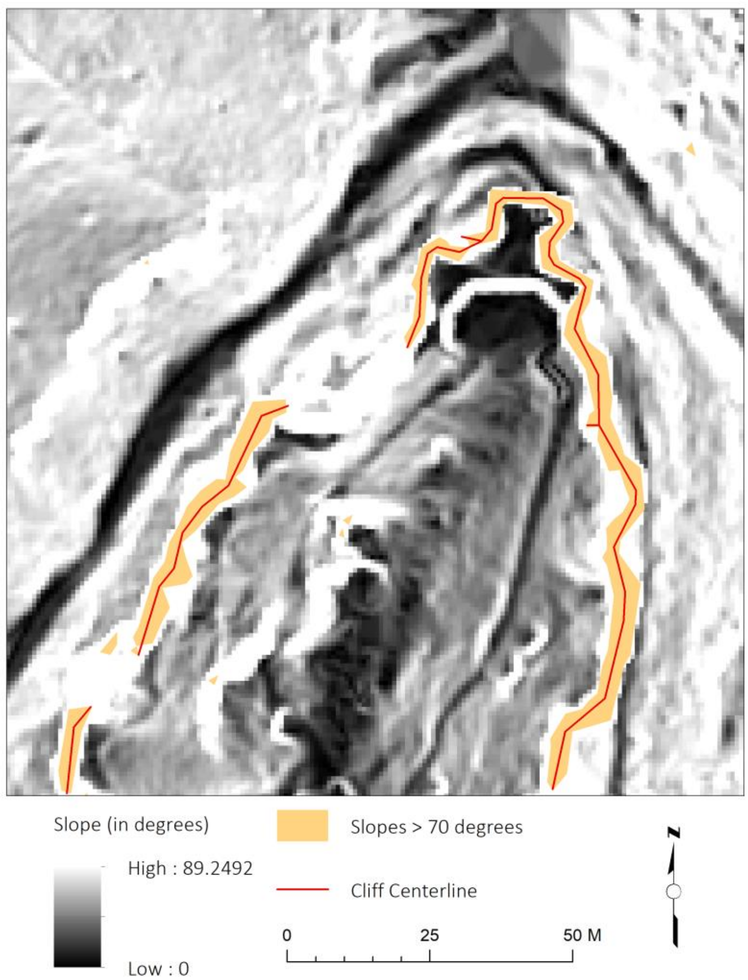

Figure 3.1

A figure of Point Park, Lookout Mountain, TN and a visual of the methodology used to create the cliff dataset; a slope model was created (showing black areas representing flat areas, lighter areas representing steeper terrain) and overlaying this are cliff areas (slopes ≥ 70°) shown in tan, and the cliff dataset (shown in red), which are the centerlines of the cliff areas

Once the cliff line dataset was created, additional layers such as the mosaicked DEMs for each county, the Tennessee geologic map (Milici et al., 1978), the Protected Areas Database (PAD) (USGS, 2016), and Tennessee State Parks and Wildlife Management Areas (WMA) (TN.gov, 2017b) were used to create subsets of the original cliff dataset. Various geoprocessing tools and/or query expressions (e.g. select-by-attribute, select-by-location, clipping, etc.) were used to generate a more in-depth analysis of the cliff line dataset. Climbing areas were selected manually, referencing the most current climbing guidebooks (Averbeck and Gentry, 2013; Robinson, 2014).

Verification of the Dataset

In order to verify and analyze the dataset, a quantitative definition of a cliff needed to first be established to delineate a true cliff (as defined earlier) from simply a steep-sided slope, boulder, etc. Based on the research of Larson et al. (2000) and observed characteristics of geophysical features within the SCP, features < 8m in height and < 10m in length are not considered cliffs for the purpose of this study.

To verify the accuracy of the cliff dataset, ground truthing field surveys were conducted using a Garmin eTrex 30x Global Positioning System (GPS). GPS points were collected at various cliff locations throughout the study area. All GPS points were collected along the base of cliffs at distance of 1 - 10 m away from the cliff base (overhanging cliffs and/or dense vegetation would at certain times reduce satellite reception, necessitating GPS points be taken further away from the base of cliffs to minimize GPS receiver error). In each location, GPS points were taken only after accuracy had stabilized to within ±10 m. Root mean square error (RMSE) and an overall weighted average was used to assess location accuracy.

While GPS verification points evaluate the accuracy of cliffs' geospatial location, points by themselves are not adequate for verifying other measured characteristics such as cliff length. In order to verify these calculations, GPS tracks (or routes) were recorded at various cliff locations. Tracks were started and completed in conjunction with specific cliff segments, with attention given to ensure the path of the GPS receiver mimicked the geometry of the associated cliff segment. These tracks were created by setting the Garmin unit to automatically record a GPS point every 5 seconds for the duration of each cliff segment; these points were then converted to vertices and a polyline drawn to connect them together. The length of this polyline was then evaluated against the calculated value for the corresponding segment of cliff line and RMSE used to determine overall accuracy.

CHAPTER IV

RESULTS

The total cliff length calculated for the Hamilton/Marion study area is 428 km (Table 4.1, Figure 4.1, Figure 4.2). Marion County accounted for the majority (67%) of that total-- an interesting outcome given that Marion County is actually 11% smaller in overall area than Hamilton County. This concentration of cliff line in Marion County can be easily observed in the cliff output map of the study area (Figure 4.1).

Table 4.1

Cliff Lengths Within the Study Area

County	Total Cliff Length (km)
Hamilton	141
Marion	287
Total Study Area	428

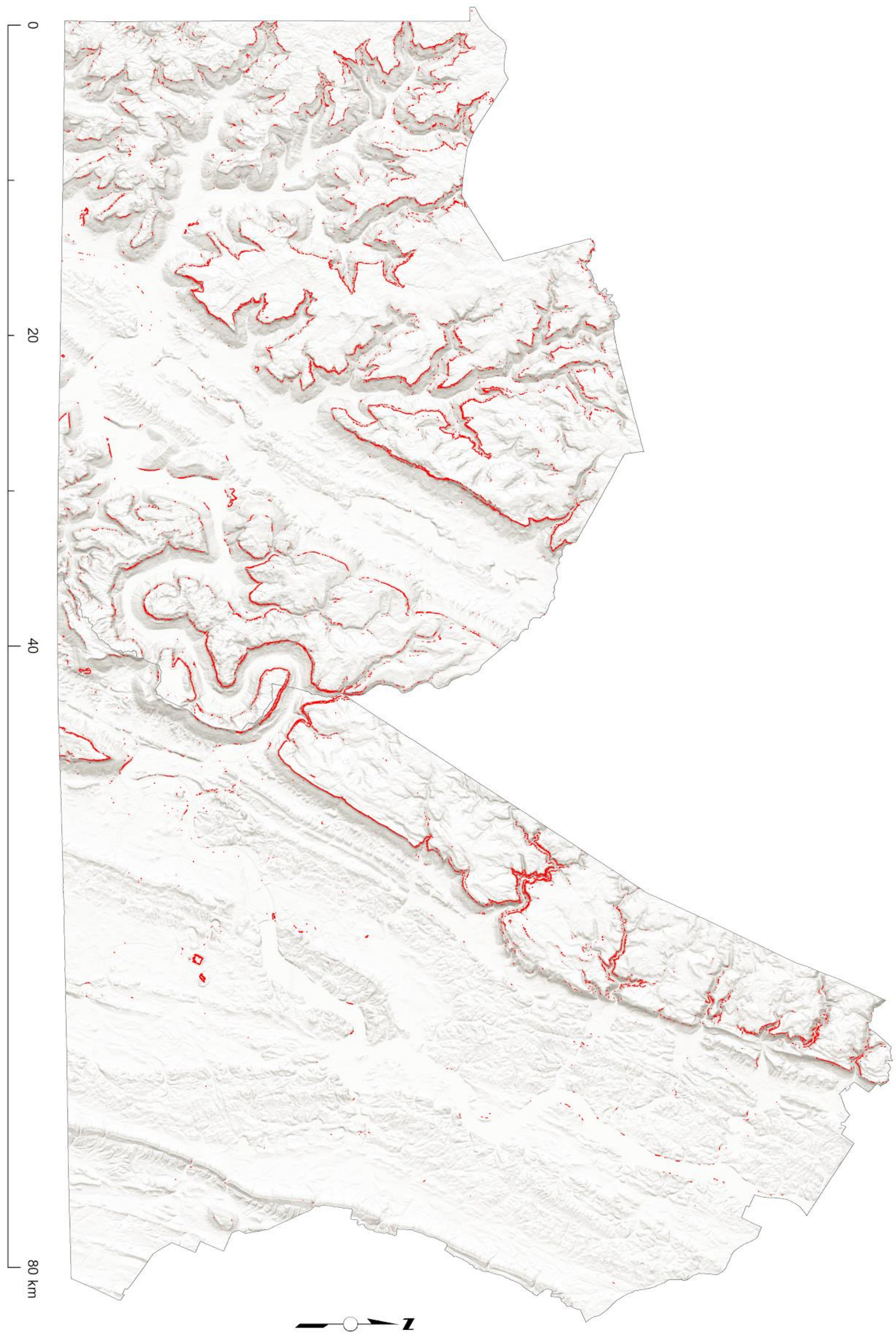

Figure 4.1

A map showing cliff lines (in red) within the Hamilton/Marion County study area

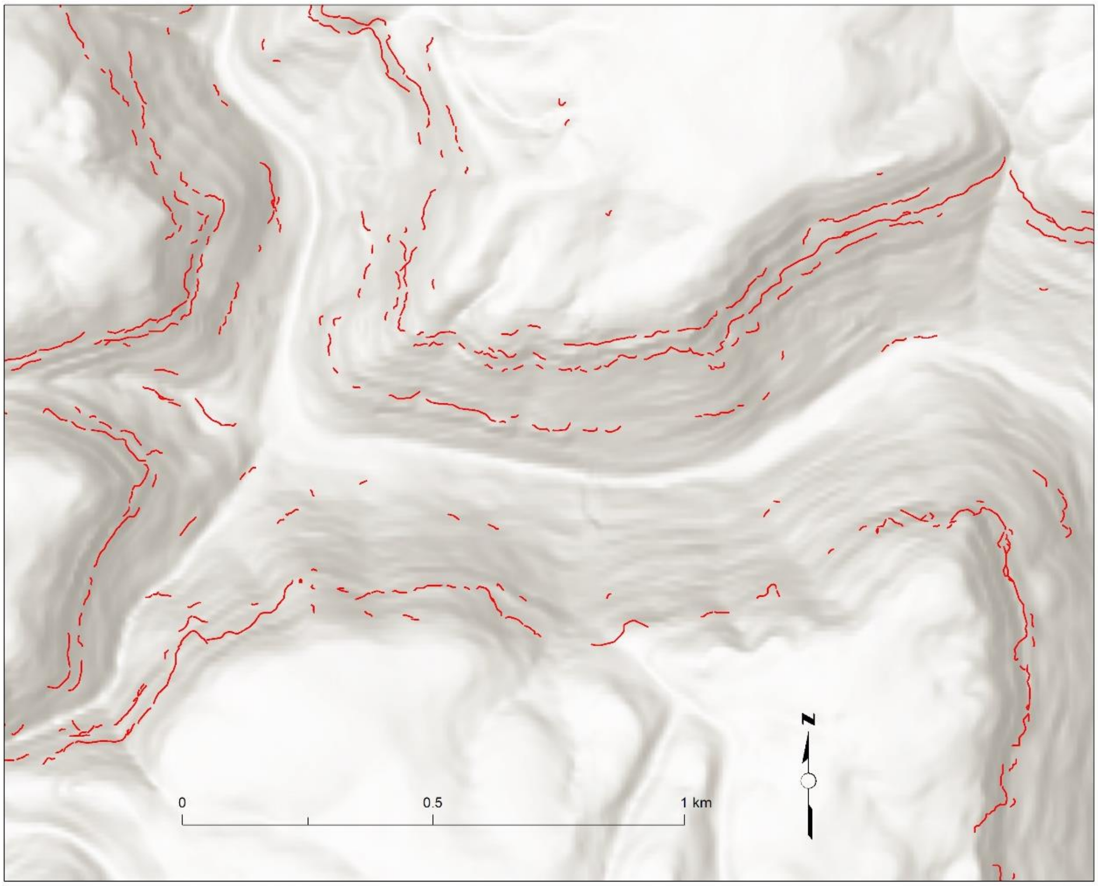

Figure 4.2

A close-up example of the modeled cliff dataset in the North Chickamauga Creek Gorge portion of Hamilton County (cliff lines shown in red)

A total of 71 validation points were collected via GPS across the study area for assessing the location of the cliff dataset (Figure 4.3; Appendix A). Buffer rings were created at 5-meter intervals around these points to obtain a weighted average error of 14 m (Figure 4.4). Of the 71 total GPS points recorded, 66 (or 93%) fell within 20 m of the modeled cliff centerline (Appendix A)

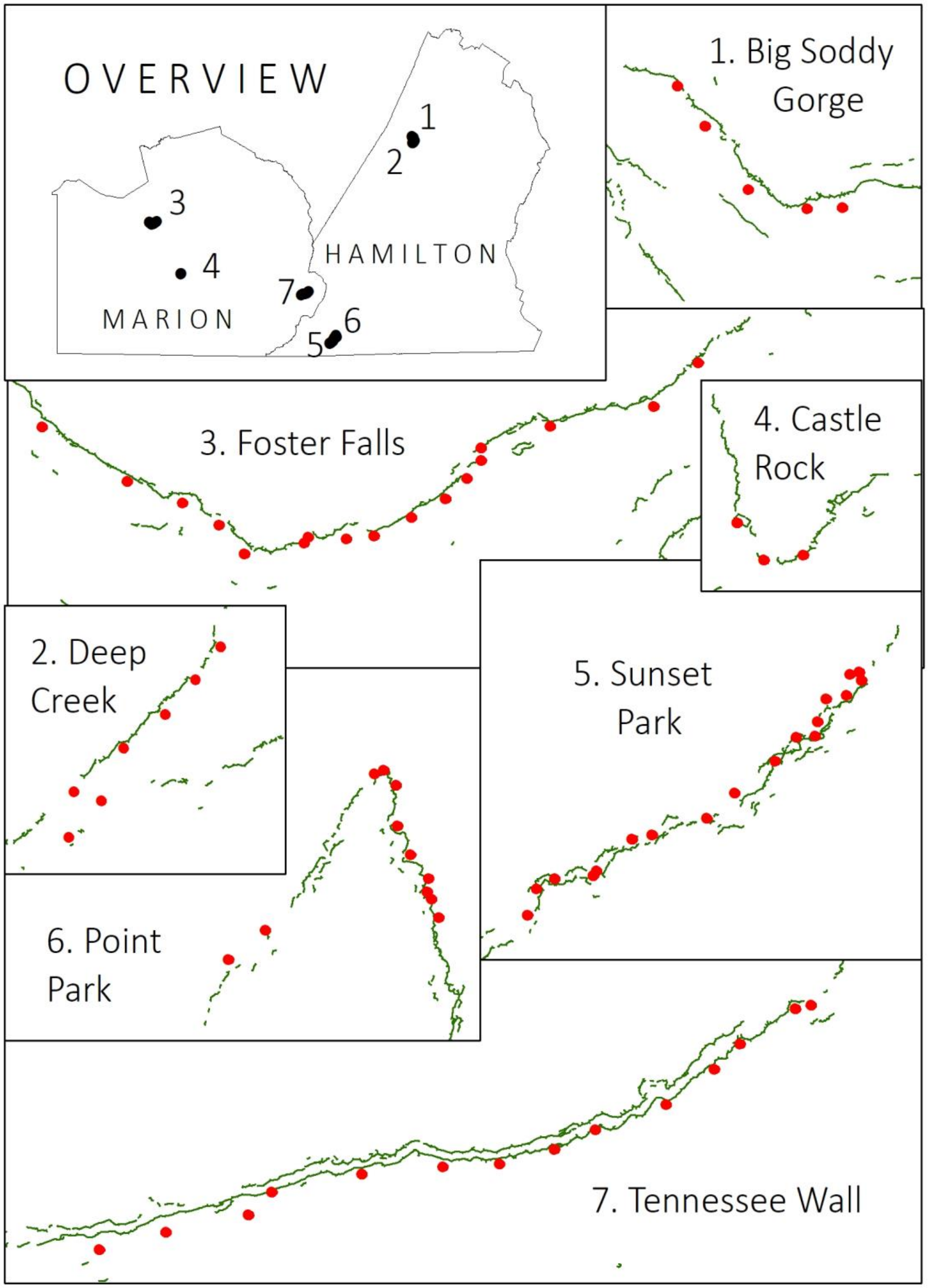

Figure 4.3

Maps showing the 71 GPS verification points recorded at 7 separate locations within the study area

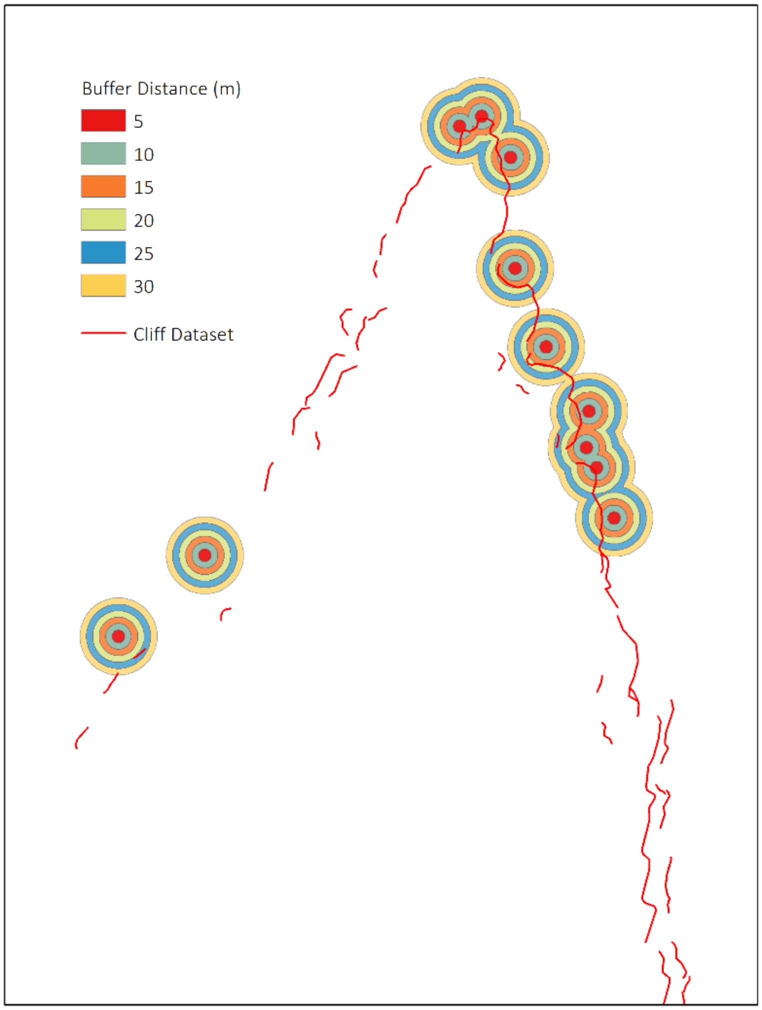

Figure 4.4

A map of the cliff model (red lines) at Point Park, Hamilton County; several (11 of 71) GPS verification points; and the corresponding, 5 m buffer rings around each point that were used to calculate the cliff model's accuracy (14 m)

A total of 9 individual GPS tracks were recorded in three separate locations across the study area. The resulting observed cliff lines, when compared to the corresponding stretch of modeled cliff line resulted in a RMSE of 91 m (Appendix A). Qualitatively, the tracks also conform well to the modeled geometry of the cliff dataset (Figure 4.5).

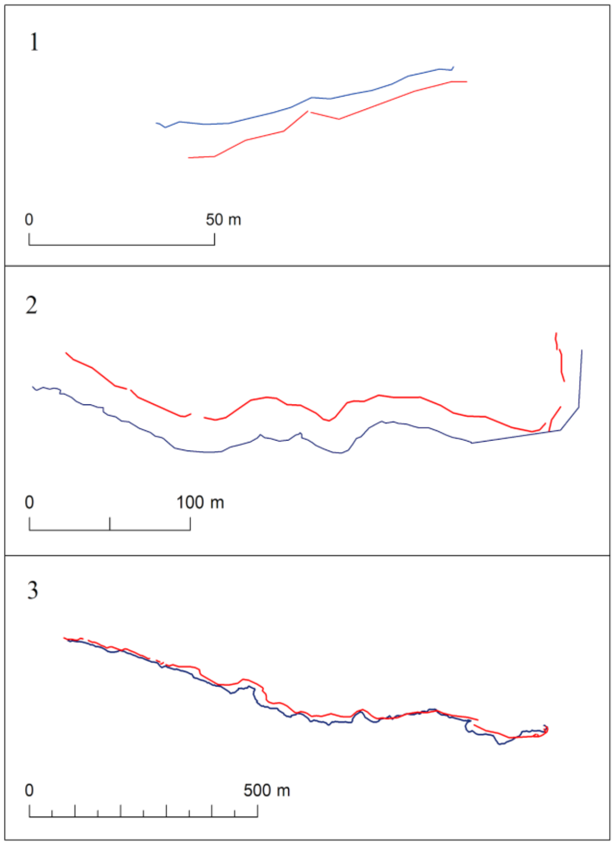

Figure 4.5

GPS tracks of various lengths were recorded to assess the accuracy of modeled cliff geometry and cliff segment length; the three examples shown above were acquired from Denny Cove, Marion County (red lines are the cliff model outputs, and blue lines are the observed cliff GPS tracks; cliff model length RMSE= 91 m)

In the analysis of cliff lines and their conservation status within they study area, over half (59%) of Hamilton County's cliffs are located on public/protected land (Table 4.3). In total, 36% of cliffs in the study area are located within public/protected lands. Both counties have a significantly higher percentage of cliffs located on public/protected lands as compared to the percentage of area that is protected for each county.

Table 4.2

Conservation Status of Cliffs Within the Study Area

County	Hamilton	Marion	Total Study Area
Length of Cliff within Protected Areas (km)	82	71	153
% of Total Cliff Line Protected	59	25	36
% of County's Area Currently Protected	8	13	10

Using the cliff dataset, every legal, publicly-accessible climbing area within the two-county study area accounted for a total of 28.5 km of cliff length (Figure 4.4) (Appendix A). This is just 5% of the total 515 km of potentially climbable cliff length within the study area. Conducting the same analysis for just public/protected lands yielded similar results (Table 4.4).

Table 4.3

Analysis of Current and Potential Rock Climbing Within the Study Area

County	Hamilton	Marion	Total
Established Climbing Areas on Public Lands (by Cliff Length) (km)	10.3	16.1	26.4
Established Climbing Areas Total (by Cliff Length) (km)	11.5	17.0	28.5
Cliff Line of Pennsylvanian Age Geology (km)	118.7	263.8	382.5
Percent of Legal Climbing Areas vs. Total Potential Climbable Rock (%)	10%	6%	7%

Figure 4.6

A map showing potentially climbable cliffs, current climbing areas, and public lands ('potentially climbable' is defined as having sandstone and/or conglomerate rock type, which was generated by selecting all cliffs above 1000' above mean sea level)

CHAPTER V

DISCUSSION

To my knowledge, the completion of this project marks the first exhaustive inventory of cliffs in the South Cumberland Plateau region of Tennessee. While any common observation of the SCP would conclude that cliffs are predominant throughout the region, quantifying the length of cliff line demonstrates the true significance of this geophysical feature in the SCP. If stretched out in a line, the total length of cliff line calculated within the study area, 428 km, is similar to the straight-line distance between Knoxville and Memphis, TN – an impressive length of cliff line for just two of the nineteen total counties that contain the SCP in Tennessee (Figure 5.1). While time and resources did not allow a thorough analysis and verification of the entire SCP, the extrapolation of this model to the remainder of the SCP would likely produce several thousand kilometers of cliff line in Tennessee alone. Combined with the enormous biodiversity and ecological value present in the SCP, the results of this study further support the argument made by Larson et al. (2000a) that cliffs are unique and occupy enough space on the planet to deserve the distinction of being recognized and studied as their own place.

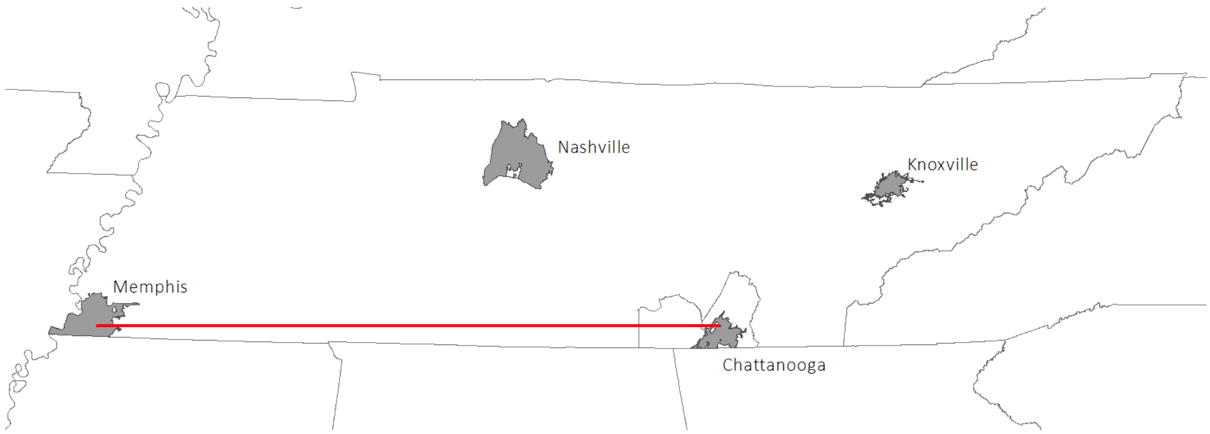

Figure 5.1

A graphical illustration of the total length of cliff lines contained within the Hamilton/Marion County study area, comparable to the distance between the Chattanooga and Memphis metropolitan areas

Within the context of having their own "ecology of place" (Larson et al., 2000a), examining the conservation status of cliffs results in some interesting observations. Cliffs and their associated ecosystems, especially those in Hamilton County, are afforded significantly more protection compared to the general percentage of protected areas throughout the study area. 56% of cliffs in Hamilton County are protected in just 8% of the total conservation area present throughout the entire county. Observation of the cliff map in Figure 4.1 reveals that the majority of protected areas within the study area are indeed located in and around the rugged escarpment edges and gorges where many cliffs in the study area are located. While it is beyond the scope of this project to dive deep into the ecology of the SCP, it is worth pointing out that despite this (seemingly) good news for cliff ecosystems also supports the theories (Shands and Healy, 1977) and studies (Scott et al., 2001) that point to the disproportionate representation of ecosystems in conservation. It should come as no surprise that ecosystem conservation is skewed towards those with higher relative elevations and poor soil productivity such as the SCP cliffs, leaving the lower elevation and limestone-based/productive soil ecosystems such as those that exist directly below these cliffs region vastly underrepresented (and unprotected).

While every effort was made to eliminate subjectivity in this analysis, several assumptions needed to be made that ultimately affected the outcome of the dataset and resulting calculations. Most of this subjectivity occurred in the selection of various weights and threshold values required of the cliff model. For example, the choice to use 70° off horizontal as the threshold value for the slope queries was not empirically based, but rather the angle that seemed to provide the best output when compared to multiple known cliff locations within the study area. Other examples of this include choosing to aggregate cliff areas within 5 m of each other, removing holes and other noise in the dataset, etc. Because cliffs are highly variable geophysical features, the values chosen for the accurate output of one cliff could also create error in the output of a separate cliff.

One of the biggest challenges in creating this dataset was determining an accurate method for validating the data. Despite the improvements in GPS technology in recent years, the inaccuracies evaluated in the dataset are more likely related to the limitations of using GPS waypoints as validation data than the dataset itself. While professional surveying of cliff lines would have provided a more robust set of validation data, time and resources did not allow for this.

Management Implications

Federal and state lands, land trusts, and conservation NGOs throughout the SCP region have the difficult responsibility of balancing the interests of the many stakeholders invested in these places. The growth of rock climbing in recent years is but one example of balancing the economic and recreational interests that the sport offers with the environmental stewardship of the areas these activities are located. The accurate, quantifiable information that this dataset provides could aid clear communication in stakeholder conversations or provide baseline data for adaptive management decision making.

Conclusion

Cliffs within Tennessee's South Cumberland Plateau significantly influence the area's economy and ecology, yet despite this, there has been little knowledge of the quantity and distribution of cliffs in this region. Using a new, high-resolution DEM dataset, this project created the first exhaustive cliff inventory dataset through a series of queries that identified and extracted areas of the SCP with the steepest slopes. Overlaying these cliff areas with elevation, and public/protected lands allowed a more in-depth analysis of the conservation and recreational status of cliffs within the study area.

Future Research

The intent of this project was to create a foundation from which future research efforts could apply this data to various applications. The dataset itself, while shown to be accurate concerning presence and location, could be further improved upon with a more custom, coded model for increasing the precision and accuracy of the dataset. Specific to rock climbing, one of the major weaknesses of this study's application in predicting rock climbing areas is the assessment of rock quality.

Future developments in technology, improved sensor resolution, etc. will create the opportunity for adding additional remotely-sensed attributes such as cliff height, aspect, and moisture; these could be applied to the cliff dataset to benefit future ecological and recreational studies in cliff research. For example, overlaying this cliff dataset with the USGS National Hydrologic Dataset could allow for a new dataset of waterfalls. This cliff dataset, combined with other landscape data, could aid floristics studies as well as identify critical habitat for species that reside on or near cliffs. Lastly, this dataset may be useful for geophysical research in landslide and slope stability studies.

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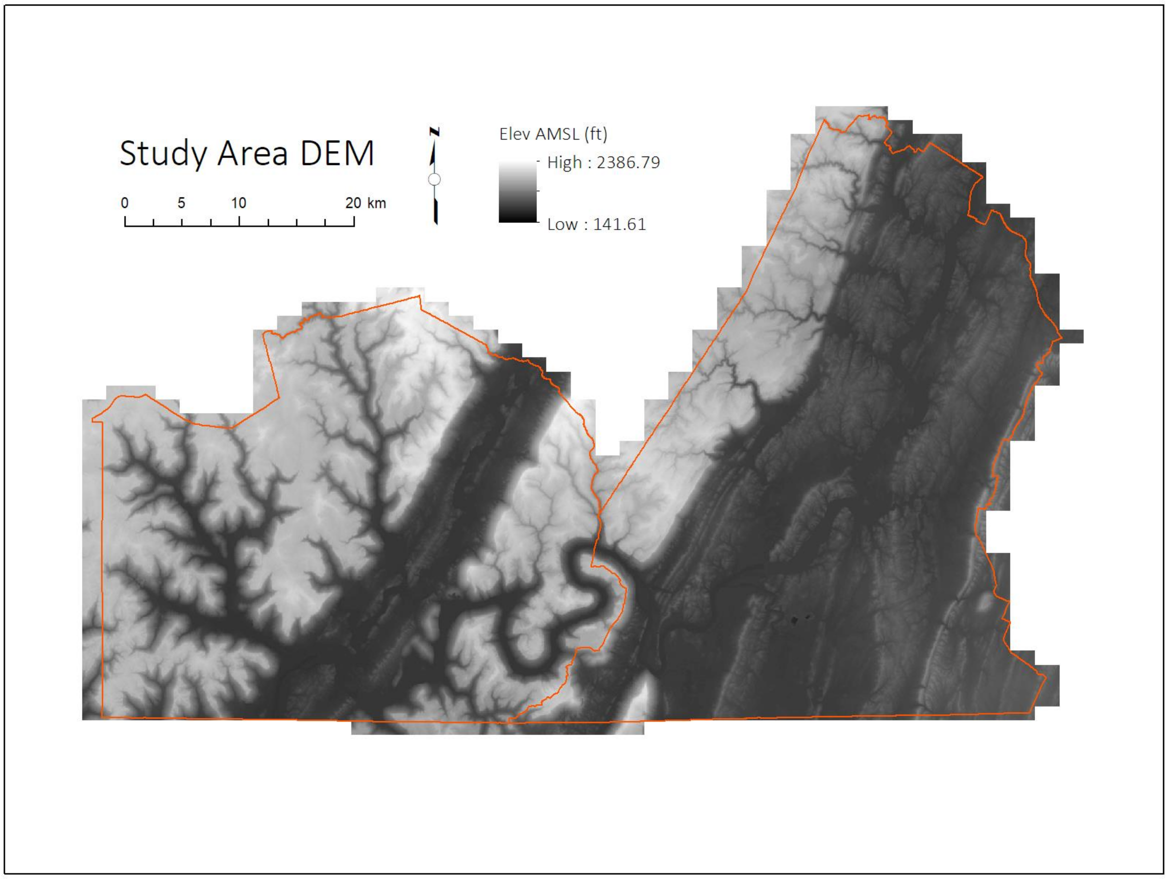
APPENDIX A

ADDITIONAL DATA



Cliff Length Accuracy Assessment

ID	Location	GPS Track Length (km)	Model Length (km)	Difference (km)
1	Sunset 1	0.221	0.221	0.001
2	Sunset 2	0.241	0.221	-0.021
3	Sunset 3	0.051	0.151	0.101
4	Sunset 4	0.081	0.261	0.181
5	Sunset 5	0.441	0.521	0.081
7	Point Park	0.401	0.361	-0.041
8	Denny Cove 1	0.421	0.361	-0.051
9	Denny Cove 2	1.281	1.161	-0.121
10	Denny Cove 3	0.081	0.061	-0.011
			RMSE =	0.865

RMSE Equations

Length Verification:

$$\sqrt{\frac{(1)^2 + (-21)^2 + (101)^2 + (181)^2 + (81)^2 + (41)^2 + (51)^2 + (121)^2 + (11)^2}{9}} = 86.5\ m$$

Climbing Areas Data Derived from Cliff Dataset

Climbing Area	County	Ownership	Cliff Length (km)
Big Soddy Gorge	Hamilton	Public	1.095
Castle Rock	Marion	Private	0.895
Deep Creek	Hamilton	Public	1.415
Denny Cove	Marion	Public	1.875
Foster Falls	Marion	Public	2.77
Leda	Hamilton	Private	0.445
Prentice Cooper	Marion	Public (TWRA)	4.755
Stone Fort	Hamilton	Private	0.77
Suck Creek Canyon	Hamilton	Public (WMA)	3.81
Suck Creek Canyon	Marion	Public (WMA)	4.635
Sunset Park	Hamilton	Public (NPS)	3.98
Tennessee Wall	Marion	Public (TWRA)	2.04
TOTAL	-	-	28.485

Verification of Cliff Locations

ID	GPS ID	Date	Location Name	Within 5m	Within 10m	Within 15m	Within 20m	Within 25m	Within 30m	Notes
1	2	3/2/2018	T Wall				Yes			
2	3	3/2/2018	T Wall			Yes				
3	4	3/2/2018	T Wall		Yes					
4	5	3/2/2018	T Wall	Yes						
5	6	3/2/2018	T Wall		Yes					
6	7	3/2/2018	T Wall			Yes				
7	8	3/2/2018	T Wall		Yes					
8	9	3/2/2018	T Wall			Yes				challenge
9	10	3/3/2018	T Wall				Yes			
10	11	3/3/2018	T Wall				Yes			
11	12	3/3/2018	T Wall		Yes					
	13	3/3/2018								data corrupted
	14	3/3/2018								data corrupted
	15	3/3/2018								data corrupted
	16	3/3/2018								data corrupted
	17	3/3/2018								data corrupted
12	18	3/4/2018	Big Soddy Gorge		Yes					
13	19	3/4/2018	Big Soddy Gorge					Yes		
14	20	3/4/2018	Big Soddy Gorge					Yes		
15	21	3/4/2018	Big Soddy Gorge			Yes				
16	22	3/4/2018	Big Soddy Gorge						Yes	
17	23	3/4/2018	Deep Creek				Yes			
18	24	3/4/2018	Deep Creek				Yes			
19	25	3/4/2018	Deep Creek				Yes			
20	26	3/4/2018	Deep Creek				Yes			
	27	3/4/2018	Deep Creek							data corrupted
21	28	3/4/2018	Deep Creek						Yes	challenge
22	29	3/4/2018	Deep Creek				Yes			challenge
23	30	3/9/2018	Sunset Park	Yes						
24	31	3/9/2018	Sunset Park		Yes					

25	32	3/9/2018	Sunset Park	Yes						
26	33	3/9/2018	Sunset Park			Yes				
27	34	3/9/2018	Sunset Park			Yes				
28	35	3/9/2018	Sunset Park	Yes						
29	36	3/9/2018	Sunset Park			Yes				
30	37	3/9/2018	Sunset Park			Yes				
31	38	3/9/2018	Sunset Park				Yes			
32	39	3/9/2018	Sunset Park	Yes						
33	40	3/9/2018	Sunset Park	Yes						
34	41	3/9/2018	Sunset Park		Yes					
35	42	3/9/2018	Sunset Park			Yes				
36	43	3/9/2018	Sunset Park			Yes				
37	44	3/9/2018	Sunset Park			Yes				
38	45	3/9/2018	Sunset Park		Yes					
39	46	3/9/2018	Sunset Park				Yes			
40	47	3/9/2018	Sunset Park		Yes					
41	48	3/9/2018	Sunset Park					Yes		challenge
	49	3/9/2018	Sunset Park							challenge (no cliff)
42	50	3/9/2018	Point Park	Yes						
43	51	3/9/2018	Point Park	Yes						
44	52	3/9/2018	Point Park		Yes					
45	53	3/9/2018	Point Park			Yes				
46	54	3/9/2018	Point Park			Yes				
47	55	3/9/2018	Point Park		Yes					
48	56	3/9/2018	Point Park			Yes				
49	57	3/9/2018	Point Park	Yes						
50	58	3/9/2018	Point Park			Yes				

51	59	3/13/2018	Point Park			Yes				
52	60	3/13/2018	Foster Falls				Yes			
53	61	3/13/2018	Foster Falls		Yes					
54	62	3/13/2018	Foster Falls	Yes						
55	63	3/13/2018	Foster Falls	Yes						
56	64	3/13/2018	Foster Falls			Yes				
57	65	3/13/2018	Foster Falls			Yes				
58	66	3/13/2018	Foster Falls		Yes					
59	67	3/13/2018	Foster Falls			Yes				
60	68	3/13/2018	Foster Falls				Yes			challenge
61	69	3/13/2018	Foster Falls			Yes				challenge
62	70	3/13/2018	Foster Falls	Yes						
63	71	3/13/2018	Foster Falls				Yes			
64	72	3/13/2018	Foster Falls				Yes			
65	73	3/13/2018	Foster Falls				Yes			
66	74	3/13/2018	Foster Falls		Yes					
67	75	3/13/2018	Foster Falls				Yes			
68	76	3/13/2018	Foster Falls	Yes						
69	77	3/15/2018	Castle Rock		Yes					
70	78	3/15/2018	Castle Rock			Yes				
71	79	3/15/2018	Castle Rock	Yes						
			Totals	14	15	21	16	3	2	
Weighted Average				13.94						

VITA

Kyle Jones was born in Charlotte, NC to Steven and Denise Jones. He grew up on the outskirts of Atlanta, GA with his younger brother Matthew. Kyle graduated from North Gwinnett High School in 2002 and went on to pursue an engineering degree at Clemson University in Clemson, SC. Kyle graduated from Clemson in 2007 with a BS degree in Civil and Environmental Engineering. While at Clemson, Kyle met Ashley Stumpff and they married shortly after graduating. Kyle worked multiple jobs in various industries, including environmental engineering, risk management, a sawyer, commercial photography, and landscaping. Having always loved maps and the sciences, Kyle began a self-study of geographic information systems in 2015, and after moving to Chattanooga, TN, he accepted a graduate research assistantship with the Cumberland Trail Conference and The University of Tennessee at Chattanooga in 2016. Studying under Dr. Henry Spratt, Kyle worked on multiple research projects at UTC, including ecological suitability modeling of potential conservation corridors, hyperspectral mapping of rock outcrops with unmanned aerial systems, and high-resolution mapping of cliffs within the South Cumberland Plateau region of Tennessee. Kyle completed his MS degree in Environmental Science in the summer of 2018.