# THE GEOMORPHIC NATURE OF MOUNTAIN BIKE IMPACTS ON SELECTED TRAIL SYSTEMS NEAR AUSTIN, TEXAS

By

Ross H. Martin, B.S., M.A.

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Committee Members:

David R. Butler, Chair

Richard Dixon

Colleen Myles

Jon Kedrowski

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# ABSTRACT

Mountain bike trails exist as physical manifestations of direct mountain biker forcing on the landscape. The geomorphic nature of these impacts was evaluated using innovative techniques with accelerometer data as a proxy for mountain biker forcing. Mountain biker forcing variables and landscape scale variables including topography, vegetation cover, and soil type and texture were evaluated in regard to their influence on trail morphology. Trail systems in the Austin, Texas area were used for the study. Each trail system had different trail user groups and management requirements. Trail morphology was found to be correlated with trail user forcing as documented by accelerometers and other movement variables such as speed and turn angles. Trail morphology was shown to be influenced by vegetation cover and soil type and texture. Trail morphology was also influenced by land management requirements introducing a political component to geomorphic change. Mountain biker generated forcing was most correlated with trail morphology at trails which had higher mountain bike traffic relative to other user groups. Overall use rates, independent of user type, were most influential on trail morphology. Further research is needed to gain better resolution for accelerometer data by sampling riders of various skill levels. As a proof-of-concept project this research provides an entry point for research about the geomorphic nature of mountain bike trails.

# I. INTRODUCTION AND PROBLEM STATEMENT

Mountain biking has become a popular recreational activity since the first production mountain bikes became available in the early 1980's. It is estimated that 8.5 million people (age 6+) went mountain biking in the US in 2014 (The Outdoor Foundation 2014). A popular trail user generated mapping and ranking website (www.mtbproject.com) lists 21,229 mountain bike trails in the United States. If the trend of increased outdoor recreation continues, understanding the impact that inevitably comes with increased trail use is important. Whereas, foot trails have existed for centuries in some places, mountain bike trails and the use of mountain bikes on trails previously reserved for hikers is a recent occurrence. Mountain biking introduced an entire new user group to trails. With increased trail use comes increased environmental impact. Understanding trail impact and morphological process is necessary for trail managers and trail builders so trails remain usable for many years to come. Trail management is as important to potential trail users as it is to the environment. Uninterrupted natural spaces are what outdoor recreation enthusiasts seek, and ironically, the impact of heavy use reduces the very characteristics that draw people to the wilderness in the first place.

The purpose of this study is to gain an understanding of mountain bike trail systems using a biogeomorphologic framework. Mountain bike trails, as biogeomorphic systems, are defined by the interplay between biotic and abiotic variables. This research employs a biogeomorphic framework to determine the most influential variables on mountain bike trail morphology and condition, and explores the utility of data collection methods, both in efforts to inform and guide trail stewards, trail crews, and land managers. The null hypotheses are that mountain bikers do not have a unique impact pattern, and that landscape scale variables are not responsible for variation in trail morphology. The alternative hypotheses include: the trail user (mountain biker) forcing can be quantified; mountain biker forcing will influence trail morphology; landscape scale variables such as soil and vegetation coverage will be appreciable factors in trail morphology; and that (at least some of) the data collection and analysis methods could be utilized to predict potential outcomes of trail building and maintenance activities for land managers and trail stewards.

This approach will seek to understand trail morphology as the combination of environmental or terrain sensitivity, and user generated forces. Limited research into the relationship between terrain variability and trail condition exists (Bryan 1977, and Morrocco and Ballantyne 2008). In addition to the environmental factors, trail user type plays a well-documented role in trail condition and morphology (Pickering et al. 2010). However, the literature lacks substantive quantitative research about the impact of mountain bikers (Pickering et al. 2010). This study asserts that by understanding both the environmental factors that most impact trail morphology and specific user type impact of mountain bikers, trail systems can be built and maintained more sustainably. The research presented herein could provide many groups with valuable knowledge about their trail systems.

The first phase of research was to explore how environmental and terrain variability affect trail morphology. The second part of this research was to describe and quantify mountain bike forces and impacts. To do this, it is first necessary to compare measurements of trail morphology (width, depth, soil compaction) to spatial data sets including soil properties, surficial geology, slope, aspect, elevation, and surface hydrology. This type of analysis will give insight into how spatial physical geographic factors influence trail condition and morphology.

Using a process geomorphology framework, I hypothesize that the forces from changes in direction and velocity that a mountain biker experiences create a unique pattern of impact. This type of analysis requires new methods for documentation. An innovative use of GPS with a 3-d accelerometer provides data about the forces that a biker exerts on a landscape. Accelerometers, instantaneous velocity, and trail curvature were used to quantify forces or proxies of forces that are induced by mountain bikers as they navigate a trail. The study compares the spatial patterns of these forces to trail condition and trail morphological measures. This analysis elucidates how trail design and layout might influence trail morphologic evolution and degradation. With this path of analysis, I hope to address a substantial gap in the literature about the specific impacts of mountain bikes.

The final phase of this research was to create and disseminate products to inform managers. This research project provides “proof of concept” for several novel methods. The methods and data that were chosen for this project are easily available to most people, with small monetary investment. The primary and explicit goal of this project is to understand the relationships previously discussed for trails in the Austin area. However, a secondary and equally important goal is to establish and test methods of data collection that can be adapted to other locations, and that can be adopted by trail stewards and other land managers. As such, publicly available data was sought. Land managers and trail steward groups are often under-funded and don’t have the capabilities to conduct or contract environmental assessments. This research provides a “proof of concept” where inexpensive data and methodologies can provide robust analysis. Data collection about trail maintenance and trail monitoring is time consuming which can result in no records being kept. This research project should highlight which trail variables and data collection methods are most indicative of overall trail condition. Monitoring only those most influential variables and methods could streamline and standardize trail monitoring efforts.

# II. LITERATURE REVIEW

First, this literature review will attempt to define what a trail is, in terms of physical properties, by describing general vegetation and soil impacts associated with trail use, and how those impacts vary over time and space. Then the discussion will focus on variations of impact amongst various user groups with emphasis on and comparisons to mountain biker impacts and research. The review will conclude with a general discussion about research paradigms utilized for trail-centric research. Research about trail impact can be dated back to the early 1970's with the Bayfield (1971) assessment of trampling pressure on paths being one of the first published studies specifically regarding trails. This area of recreational trampling research was born out of exploration of foot trail impact and in recent years has come to include horse, llama, and bike impacts, among others. Many trails have overlapping uses and impacts. The literature is heavily weighted towards foot trampling (Pickering et al. 2010). Environmental impact research is typically focused on impacts to vegetation and soils, and the complex feedback that exists between the two.

## Vegetation and Soil

Trails are curvi-linear features on the landscape devoid of vegetation (Cole 1995b; Cole 2004; Marion, Leung, and Nepal 2006). Many experimental trampling research papers have focused on determining trampling rates that denude previously non-impacted vegetation. These types of studies reflect the first phases of trail formation and evolution. For the research project proposed herein we are not concerned with initial trail formation. However, trampling of vegetation and the variable resistance of vegetation to trampling has major implications on trail conditions and off trail trampling, which results in trail widening and informal trail creation. Impacts to soil prevent vegetation growth and allow the trail to persist. Soil impacts also can induce overland flow erosion and muddiness. Soil impact and vegetation impact are closely coupled.

Vegetation species respond to trampling in similar ways but with different intensities. These responses include reduction in height, loss of percent vegetation cover and changes in species richness. Under experimental conditions in a Mediterranean environment Andres-Abellan et al. (2006) found that plant species had the greatest impact on response (decrease of percent vegetation cover, number of species and plant height) to trampling pressure, closely followed by trampling intensity. Most grasses and shrubs were not as tolerant to trampling when compared to native herbs (Barros, Gonnet and Pickering 2013). These authors found that several herb species positively respond to trampling, suggesting evolutionary adaptation to disturbance or the removal of competitive species by trampling. Cole (1995a) found that different species react differently to trampling in that the most resistant types of vegetation experience constant, nearly linear, rates of vegetation loss whereas less resistant species experience highly curvilinear rates of vegetation loss when compared to trampling intensity. Cole 1995(b) showed that vegetation stature and physiognomic type (shrubs, graminoids or forbs) explained the majority of the variance for the resistance to trampling. Whinam and Chilcott (2003) found that plant morphology was the major factor in determining the impact of trampling regardless of slope, aspect or altitude with a repeated trampling experiment over a four-year period. Pickering and Growcock (2009) found a reduction in species height because of trampling. They suggest that height directly affects the photosynthetic area of the plant which, if reduced, can impact the ability of the plant to flower. The potential for sexual reproduction can be reduced because of reduction in fruit production in trampled sites (Rossi et al. 2006; and Rossi, Parolo and Ulian 2009). Less resistant types of vegetation show a greater reduction in height and percent vegetation cover and they are eliminated first, thereby reducing the species richness by leaving only more tolerant species. Trampling and the reduction of vegetation cover exposes soil and results in impacts to soils and further response by vegetation. Korknac (2014) showed that short-term trampling pressure has minimal impact on most soil properties, however at higher trampling intensity (200-500 passes) there was decreased total porosity and increased soil penetration resistance.

Recreational trampling increases soil bulk density (Marion and Cole 1996; Waltert et al. 2002; Talbot et al. 2003; Kissling et al. 2009; Mingyu et al. 2009). The magnitude of increase depends on the amount of trampling and the soils (Ozcan, Gokbulak, and Hizal 2013). In general, a positive and linear relationship between soil bulk density and soil compaction exists (Tejedo et al. 2009). Perhaps the most commonly studied soil parameter in trail and trampling literature is soil compaction (Weaver and Dale, 1978; Bhuju and Ohswa 1998; Andres-Abellan et al. 2006; Mingu et al. 2009; Kissing et al. 2009; Pickering, Rossi, and Barros 2011). Soil compaction (as measured by a standard penetration test) is closely related to other soil properties including texture, porosity, organic matter content, aeration and infiltration of water (Soil Survey Staff 2006; Tejedo et al 2009). A negative relationship exists between soil bulk density and soil organic content (Sun and Walsh, 1998). The amount of soil compaction is dependent on a myriad of factors including trampling intensity, soil properties, trampling agent type, and contact pressure.

The consequences of soil compaction are varied. Compaction can impact vegetation growth, and subsurface microflora and fauna. Compaction of soils can lead to reduction in soil water availability which has been shown to impact tree transpiration (Komatsu et al. 2007). The compaction of soils is a detriment to root development and can impact tree and vegetation growth (Bhuju and Ohswa 1998). Compaction and the associated reduction in the leaf litter and humus layers decreases soil ventilation, water content, organic matter content and alters soil chemistry, which in most cases negatively impacts vegetation growth (Andres-Abellen et al. 2006). Subsurface geology plays a large role in soil development, which ultimately determines soil compaction rates. Basaltic soils were found to be less resistant to compaction than ryholitic soils during experimental trampling in a tropical rainforest environment (Talbot, Turton and Graham 2003). Morrocco and Ballantyne (2008) showed that granitic regolith with cohesionless particles lead to widening of the trail, and armoring by rock fragments limited incision. Meanwhile, incision and widening of trails on schist derived soils was limited by compaction of the soils (Morrocco and Ballantyne 2008).

After short term trampling, compaction begins to slowly decrease because of pedoturbation by earthworms and other organisms (Curry et al. 2008; and Kissling et al. 2009). However, continuous trampling prevents natural recovery of the soil (Liddle 1997). The amount of time it takes soils to recover from trampling varies greatly and is dependent on many factors. (Ozcan, Gokbulak, and Hizal 2011) found that in terms of bulk density, topsoil would recover in about 6 years, whereas if topsoil and subsoil were considered together, more time would be needed for recovery. In alpine and tundra environments, and other extreme environments, extremely long recovery times (>10 years) are needed, therefore temporarily closing and reopening tracks is not likely beneficial Whinham and Chilcott 2003; Monz 2002; Cole 1993).

Soil compaction leads to reduced infiltration rates and increased overland flow (Talbot, Turton, and Graham 2003; Ozcan, Gokbulak, and Hizal 2011). The consequences of overland flow are erosion and sedimentation, and the magnitude of both are dependent on the environment and climate. In high precipitation rainforests, Wallin and Hardin (1996) showed that hiking trails in the humid tropics can yield up to 40 times more overland flow than adjacent trail areas, and in their study, 12.7 km of trail on residual soils was responsible for 212.4 kg of sediment per 1 mm of rain, while 1.9 km of trail on alluvial soils provided 22 kg of sediment per 1 mm of rain. This shows that even a moderate rainstorm can produce large quantities of sediment. Even low volume rainfall events produced overland flow on trails, and rain splash erosion was significantly greater on trails than in the surrounding forest (Wallin and Hardin 1996).

Trail erosion provides the most visible evidence of impact. Trail systems with more erosion are seen as undesirable and negatively affect the trail user's experience (Jewell and Hammitt 2000). Erosion of a trail surface can be induced directly by the trail user, by wind, or by water. In general, erosion by wind and water is better documented than erosion by a recreationist (hiker or mountain biker). In the case of trail systems, the potential for aeolian or fluvial erosion is introduced or enhanced because of the existence of trails. Additionally, the trail user becomes a geomorphic agent. The amount of sediment erosion on trails depends on the amount of use, the user type, and environmental variables. The trail user, be it horse, hiker, or a biker can induce sediment erosion. Concentration of trampling pressure is often evidenced by truncated soil profiles (Greive 2000).

Vegetation, soil, and geology play an important role in trail cross-section morphology (Morrocco and Ballantyne 2008). Trail entrenchment, which is evidence of erosion, was greater in stone-free meadow soils, than in stony forest soils (Weaver and Dale 1978). De Gouvenain (1996) found that the soil of an impacted site had finer grains and more bare ground surface. Grieve (2000) found that un-vegetated trampled sites had increased stone abundance.

Aeolian transport of sediment as related to trail process is poorly understood, and does not seem to be documented. Personal observation has shown that in central Texas, during extreme drought conditions, trails with fine clays are subject to aeolian processes. This is especially true when the trail user initially entrains the sediment by speeding through a corner or skidding. Skidding and roosting are often glorified in the pages of popular mountain bike publications (Heil 2016).

Muddiness or standing water on trails is most often an issue in flat areas or valley floors (Leung and Marion 2000). The compaction of the trail surface slows infiltration and in areas with little relief, an entrenched trail may be the lowest point and therefore collect water. In wet soils, Wilson and Seney (1994) found that horses and hikers (hooves and feet) made significantly more sediment available for transport than motorcycles or mountain bikers (wheels). Leung and Marion (2000) also found that drainage features built by trail managers had little impact on occurrence of muddy areas, and suggested that this indicates management actions cannot undo what the landscape dictates. When trail users encounter standing water, they are likely to try to go around the muddy section.

This action can lead to trail widening (dependent on vegetation) and further soil compaction, which reduces infiltration and creates a potential for a bigger muddy area.

The trail user or trampling agent plays an important role in the magnitude and distribution of impact. The mechanical differences of different trampling agents (eg. hiker, mountain biker, horse) create differing spatial patterns of impact because of different ways they move across a landscape. Trampling interfaces (boots, tires, hooves) are also a cause of difference among trampling agents because of differences in how contact pressure is applied to the ground surface (Weaver and Dale 1978; Wilson and Seney 1994; Pickering, Rossi, and Barros 2011). Contact pressure is the amount of weight in contact with the ground surface and how that weight is distributed. Contact pressure is directly related to the trampling interface, and is expressed in the units of pressure (eg. $kg/cm^2$). Because of these factors, horses induce significantly more impact that hikers at the same trampling intensities (Mingyu et al. 2009).

## **Comparative Studies**

Because the mechanical forces that cause trampling vary between user types, distinction between trail use types is critical.  Cole and Spildie (1998) compared hiker, horse, and llama trampling. They found that horse trampling impact was higher than llama and hiker, which were similar. They found that vegetation type and trampling intensity played a role in vegetation cover loss, but if these two factors were accounted for, the horse impact on vegetation cover was substantially greater than either the hiker or the llama. Vegetation height after trampling was not significantly different between use type. They found that mineral soil exposure after trampling was dependent on vegetation type because the thickness of the soil organic-horizon was dependent on vegetation type. In shrub type vegetation, no mineral soils were exposed by hikers or llamas, but mineral soils were exposed by as few as 25 passes by horses. They concluded that because the weight of the horse was approximately six times greater than a person and the distribution of that weight by a hoof that was half the surface area of the boot of the person is responsible for the increased impact by the horse. Whinam and Chilcott (1999) compared horse to hiker trampling and found that after 30 passes the amount of broken biomass for hikers was 0.1% compared to 39.2% for horses. This suggests that the mechanics of the trampling force play a major role in magnitude of trampling impact. The mechanics of horse and hiker trampling are similar in motion, the up-down step wise progression, but varies in magnitude because of weight and the surface area of weight distribution.

In contrast, a mountain biker does not exhibit the up-down motion. Instead, a biker has nearly continuous contact with the trail surface with greater velocities and a weight 8-16 kilograms greater than a hiker. The weight distribution by the biker tires on a trail is also substantially different, in that a tire provides two small contact patches and one follows the other. On straight trail segments, the rear tire makes contact directly behind the front, however, in turns the tires become offset. The pattern of one tire following another is substantially different than a horse or hiker pattern where feet are oriented on the left or right of the body and contact the trail on their respective sides with a large gap between the footprints, depending on stride length. This difference in the mechanics of trampling pressure is thought to be critical to the difference between user type impacts.

Research into the impact of mountain bikers, specifically, has been limited in scope. Studies examining the impacts of mountain bikers have generally focused on soil erosion and trail condition (Marion and Wimpey 2007, Pickering et al. 2010). Mountain bike specific impacts have been identified, as increased erosion because of skidding and braking (especially on downhills and in corners), wheel slippage and rutting (Hawes 1997; Goeft and Alder 2001; Chiu and Kriwoken 2003; White et al 2006), and user-created technical features such as jumps and berms (Newsome and Davies 2009). Pickering, Rossi and Barros (2011) showed in experimental trampling conditions that mountain bike riding produced a reduction in vegetation percent cover and species richness. They found that the impact of bikes was higher on slopes compared to flat terrain. Cessford (1995) provided an analysis of mountain bike impact by considering the downward force placed on the trail by the user and shear forces placed on the trail because of wheel slippage. Vogler and Butler (1996) noted that an increased rate of erosion corresponded to the prevalence of bikers and suggested the cause was because of increased torque at the wheel. Hawes (1997) and Goeft and Alder (2009) both described significantly higher rates of soil loss around corners during mountain bike events. Burgin and Hardiman (2012) suggested that mountain bike races and 'downhill' biking, as opposed to recreational riding, have a greater physical impact because the racer is motivated by speed and is prone to making calculated risks while on the trail. Personal experience suggests that motivation for speed and calculated risk is not limited to a race course.

Comparative studies show that mountain bikers impact the trails in different ways from other trampling agents (Weaver and Dale 1978, Wilson and Seney 1994, Thurston and Reader 2001, Olive and Marion 2009). Weaver and Dale (1978) found that motorcycle impact was greatest when going uphill as opposed to flat or downhill, whereas horse and hiker impact was greatest going downhill. They noted the repetitious halting motion of horses and hikers as they go downslope was the cause of the increase in downhill impact. The increase in motorcycle impact going uphill is from the excess torque on the wheel. Wilson and Seney (1994) used experimental rain conditions to show that horse impacts are associated with greater sediment runoff yields than hikers, mountain bikers, or motorcycles. Thurston and Reader (2001) conducted experimental trampling conditions to study biker versus hiker impact and found that no significant difference existed between the two. However, their approach did not account for variations in speed, slope or cornering.

Each of these studies hints at the differences in trampling mechanics by bikes as a cause for increased or different impact. The wheel in nearly continuous contact with the ground at higher speeds produces different trampling forces than a stepping foot or hoof. Past studies have noted the effect of increased torque and wheel slippage. However, no studies known to this author related changes in mountain bike speed and momentum to trail morphology. A study did, however, find that the impact on vegetation of an 8-wheel military vehicle was dependent on speed and turn radius (Foster et al. 2006). Similar forces, but with two wheels, are unique to biking and they have not been accounted for in existing experimental trampling studies. Understanding these unique forces is crucial to understanding the environmental impact of mountain biking. A bike is not just a static object; when in motion, a bike is a steerage vessel for two large gyroscopes adorned in grippy rubber, and the forces that go along with it.

## Trail Research Paradigms

Biogeomorphology provides an appropriate lens through which the impacts of mountain biking can be studied. Biogeomorphology, like mountain biking, was introduced in the early 1980's. It was first formally defined by Viles (1988) as the study of the interaction between biological and geomorphic processes (Stine and Butler 2011). Trails are the physical manifestation of the interaction between a trail user and the environmental setting. The trail user induces impact, whereas vegetation sensitivity and environmental variation influences how that impact will be reflected on the landscape. Trail morphology is a direct reflection of the interaction between the user and the environment. To understand the processes that determine trail morphology, it is necessary to understand both sides of the biologic-geomorphic interaction.

A few studies have used a holistic approach to understand environmental system and trail feedbacks (Bryan 1977, Morrocco and Ballantyne 2008, Wimpey and Marion 2010). Bryan (1977) explored the relationship of soil composition to trail erosional features, finding that the texture, grain size, and particle composition of the ground surface played an important role in the onset of erosion. Morrocco and Ballantyne (2008) described the need for a biogeomorphological assessment of trail morphology in their investigation on the impact of vegetation and substrate composition on trail morphology on footpaths in Scotland. These authors found that surficial geology and vegetation mat strength were determinants of trail width and depth. In their attempt to classify and describe environmental influence on trails, Morrocco and Ballantyne (2008) termed their combination of factors a "terrain sensitivity" index. Wimpey and Marion (2010) found that trail surface type plays a role in trail width, but the trail surface types were all man-made surfaces (gravel or stone) with one “natural surface” category encompassing all other natural trail surfaces. Barros, Gonnet and Pickering (2013) found that braided trails in meadows were twice as wide as trails in steppe sites. They deduced that the woody vegetation in the steppe sites restricted trail users to narrower paths, however the meadow vegetation does not restrict the user resulting in lateral spreading of the users. Bayfield (1979) and Wimpey and Marion (2010) both noted the importance of trail surface roughness on trail erosion and morphology.

# III. METHODS

This methods section will be first be divided into methods for the pilot study, followed by the methods for the main study. Data collection for this project includes point sampling and spatial analysis. To understand how trail morphology reflects user impact and terrain sensitivity, data collection efforts describe each; trail morphology, user impact, and terrain variability. User impact was described by mapping the forces that a user places on the landscape with accelerometers. Because the main study lacks the time component of the pilot study, some of the methods were altered. However, the pilot study and main study results were combined where the data and methods allowed.

## Pilot Study

The pilot study was conducted to test methods and the veracity of the hypothesis that environmental factors and user forcing impact trail morphology. A trail was built specifically for a series of three short track mountain bike races. This presented an opportunity to collect "before" and "after" data in a controlled environment from inception of trail design until after the race series was completed.

The trail at the focus of this study was purpose built for the Dirt Remedy Race Series. The location of the pilot study is privately-owned land which makes it unique within this research project. The course was constructed for a 3-race series at Quest ATX, near Creedmoor, Texas, southeast of Austin (see Figure 1). The land cover at Quest ATX is a mix of mesquite and grass (Texas Ecological Mapping System TPWD TNRIS 2016), and a continuous coverage of clayey backland prairie soils (National Soil Survey USDA NRCD 2016).

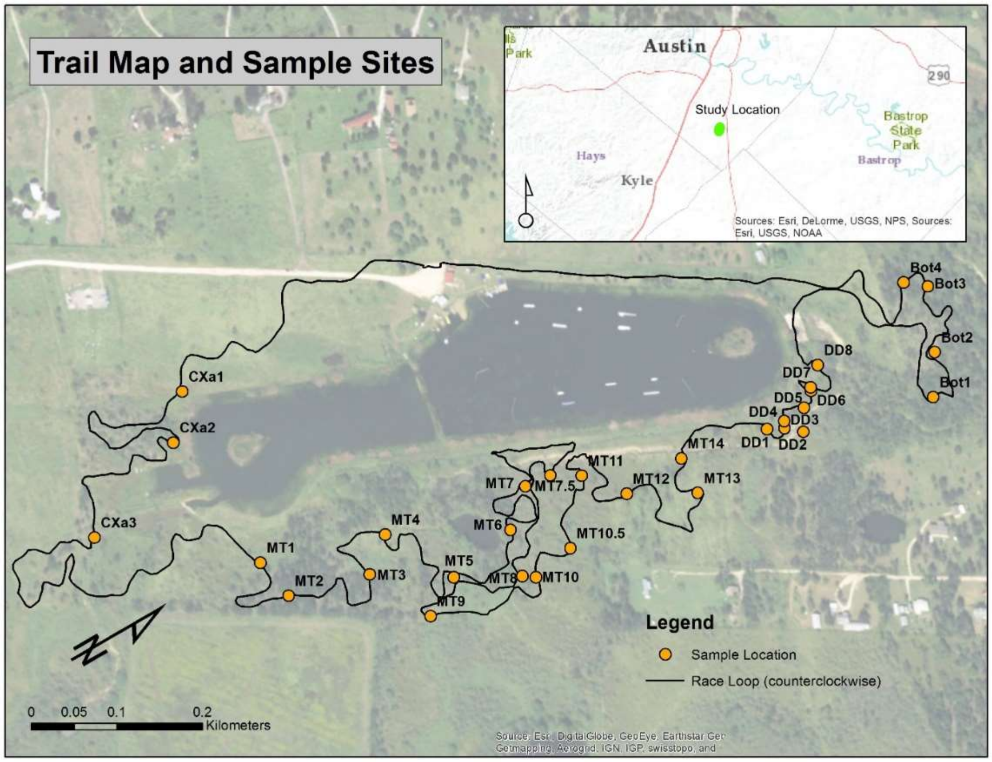


Figure 1. Map of Pilot Study Locations

The initial route was marked by walking through the property. The area has little topography so any hilly area that might provide a challenge for cyclists was of high value. Low lying and flat areas were avoided both to avoid mud and "boring" trail segments. Once the initial route was marked, a lawnmower followed the route to remove vegetation and make the route visible. Overhanging branches and other woody vegetation were removed; however efforts were taken to avoid cutting down trees. Motorcycles were used to expedite the trail formation process by further removing vegetation and compacting the trail surface. Eight motorcyclists rode the approximately ~six loops each resulting in ~48 laps. These laps occurred before cross-section sample locations were chosen, as such the 'before' results represent conditions after motorcycle impact, but before the race occurred.

## Sampling Methods

The entire trail was mapped with an accelerometer equipped GPS. A Garmin Virb was used to collect GPS tracks with georeferenced 3-D accelerometer data and video. The trail route GPS information and accelerometer data was recorded at one second intervals as the author completed the one race loop on a Santa Cruz Highball 29er hardtail mountain bike. The GPS with accelerometer data was uploaded and imported into Excel and ArcMap shapefiles. The GPS points documented both the sample locations and the trail route. The georeferenced three-dimensional accelerometer with G-forces data in the x, y, and z directions, were imported into Excel.

Sampling stations were placed throughout the race course. The samples were spaced apart from one another and effort was made to place sampling stations in each vegetation type and on various slope inclines. The initial sampling strategy was to place stations approximately 150 meters apart, however once in the field additional samples were collected to document the variation in the terrain. The straight stretch on the northwest side of the lake was not documented because it is a gravel access road sometimes used by pickup trucks for maintenance operations and to access the storage area in the field between the four BOT sampling locations and the lake. The CXA-1 location as shown in Figure 1 marks the beginning of the built trail and sampling strategy. Several of the original sampling location were lost to a last minute reroute. Each sample location was photographed before and after the mountain bike races. Repeat photographs provided documentation of trail condition.

Cross-section measurements were taken at each sample location. Cross-section stations were established by placing a wooden stake on both sides of the trail creating a transect line perpendicular to the trail direction. Most cross-sections were 3 meters in width, however four (MT-6, MT-9, MT-14, and DD-1) were 4.5 meters to allow for potential lateral migration of the trail. Cross-section measurements were collected twice. A tape measure was stretched taught between the two stakes. The height of the stakes was recorded. The distance from the tape measure to the ground surface was measured at 30 cm intervals along each transect. Measurements were recorded to the nearest centimeter. The 'before' measurements were taken after the trail was formed (after motorcycles) but before mountain bike racing, such that the first measurements include impacts from initial trail building and motorcycle use. The 'after' data was collected after three mountain bike races were completed.

Soil compaction measurements were also taken before the races and again after three races were completed at each of the cross-section locations. Compaction was measured with a standard pocket penetrometer. At each cross-section site five soil compaction measurements were taken from the center of the trail tread, and five measurements were take adjacent to the trail. This paired set of measurements was collected for both the before and after conditions.

### Analysis Methods

Cross-section measurements were tabulated, and corrections were applied to transform the measurements from the depth of tread to elevation. The area between the before and after curves was calculated to show the amount of change. The soil compaction measurements consisted of both before and after data with values from the center of tread and adjacent areas. The mean of the five measurements for each sample was calculated so that one number was representative for each of the four conditions (before center of trail, before adjacent, after center of trail, after adjacent).

The GPS data were post processed with the “Pathmetrics” tool from Geospatial Modeling Environment software (http://www.spatialecology.com/gme/). The output of this analysis provided turn-angles and step-length for each point (at one second intervals) along the trail route. Because of the one second sampling interval, step length is easily converted to instantaneous velocity. The slope at each point was derived from a Digital Elevation Model (DEM). The accelerometer data and the GPS data with turn-angles, velocity, and slope were extracted to each of the cross-section sample locations.

### Statistical Analysis

Based on process geomorphology perspectives, it is hypothesized that force distribution patterns as documented by accelerometer data should correlate with trail morphology measures. Independent variables describing how mountain bikers ‘flow’ through the trail include three-dimensional G-forces, velocity, and turn angle. The dependent variables describing the trail morphology include the change in cross-sectional area and soil compaction measurements. A Pearson Correlation was used to test the hypothesis that g-forces induced by the mountain bikers are reflected in trail morphology. For Pearson’s Correlations, such as these, the values range from -1 to +1. A zero value represents no correlation, whereas -1 or +1 would be a perfect negative or positive relationship, respectively.

## Main Study

The main study was conducted at established trails instead of a purpose-built trail. The pilot study took advantage of a unique opportunity to document early trail impacts with a before and after scenario. Some of the methods were altered to better suit established trails, and a study that would not have a before and after component.

The analysis for this research project consisted of several steps: The first was to understand environmental and terrain variability that affect trail morphology. The second part of this research describes and quantifies the mountain bike impacts. The final phase of this research project was to aggregate the most influential variables that determine trail morphology into a conceptual model that can inform trail builders and land managers.

User rates were assessed and the trail systems were qualitatively evaluated. Rider velocity and g-forces induced by trail users and trail curvature were recorded. Terrain variability was modeled by utilizing spatial data sets of soil classifications, land cover, and topography. Soil resistance to compression, and bulk density were also used to characterize terrain variability and sensitivity. The dependent variables are those that describe the trail morphology. The independent variables describe the terrain variability and forces induced by the biker. A correlation table and scatter plots were created for analysis to establish relationships between dependent and independent variables.

### Site Selection

The trails chosen for this research, consist of Walnut Creek Metropolitan Park, Slaughter Creek Preserve, Barton Creek Greenbelt, and Emma Long Motorcycle Park (See Figures 2a, 2b, 2c, 2d, 2e) which are popular trails in the Austin, Texas area. These trail systems are managed in part by the Austin Ridge Riders (http://www.austinridgeriders.com/), a volunteer based organization that provides trail advocacy, trail maintenance, and fund raising for mountain bike trails in the Austin, Texas area. In full disclosure, the author is a member of Austin Ridge Riders and the trail steward for Slaughter Creek Preserve.  Additionally, the results from the pilot study were included in analysis where data compatibility allowed. The goal was to select trails which would exhibit regional trail characteristics. The trails were chosen because they are relatively close to one another and therefore share similar environmental conditions. All the trails are located along the Balcones Escarpment. They are also all accessible from the City of Austin and surrounding suburbs.

A brief description of the developmental and political history of the trail systems gives insight into how trail management might influence trail condition. The rate of trail use is a difficult parameter to establish because no records exist. Using game cameras or parking lot counts were considered, but some trails have multiple trail heads and some trail systems have multiple routes, making accurate assessments difficult. For this study, Strava was used to obtain relative rates of mountain bike use between the trails. Strava is a computer application (app) that records rides and ranks users on user created segments. Segments were selected on the trails used in this study. The total number of attempts (the total number of times a segment has been ridden by Strava users) and the number of riders (the number of unique riders, many riders complete multiple attempts over time) on those segments gives insight into the use patterns. By monitoring the change in attempts and riders over time, a rough estimate of user rates is estimated. The percentage of mountain bikers that use Strava is unknown, but this study assumes that the percentage of Austin area mountain bikers that use Strava remains reasonably consistent between different trail systems. Video documentation of the trails, multiple site visits, and years of participant observation will inform a qualitative assessment of trail use rates and patterns. Details concerning the usage rates and history of each trail system are discussed in the results section.

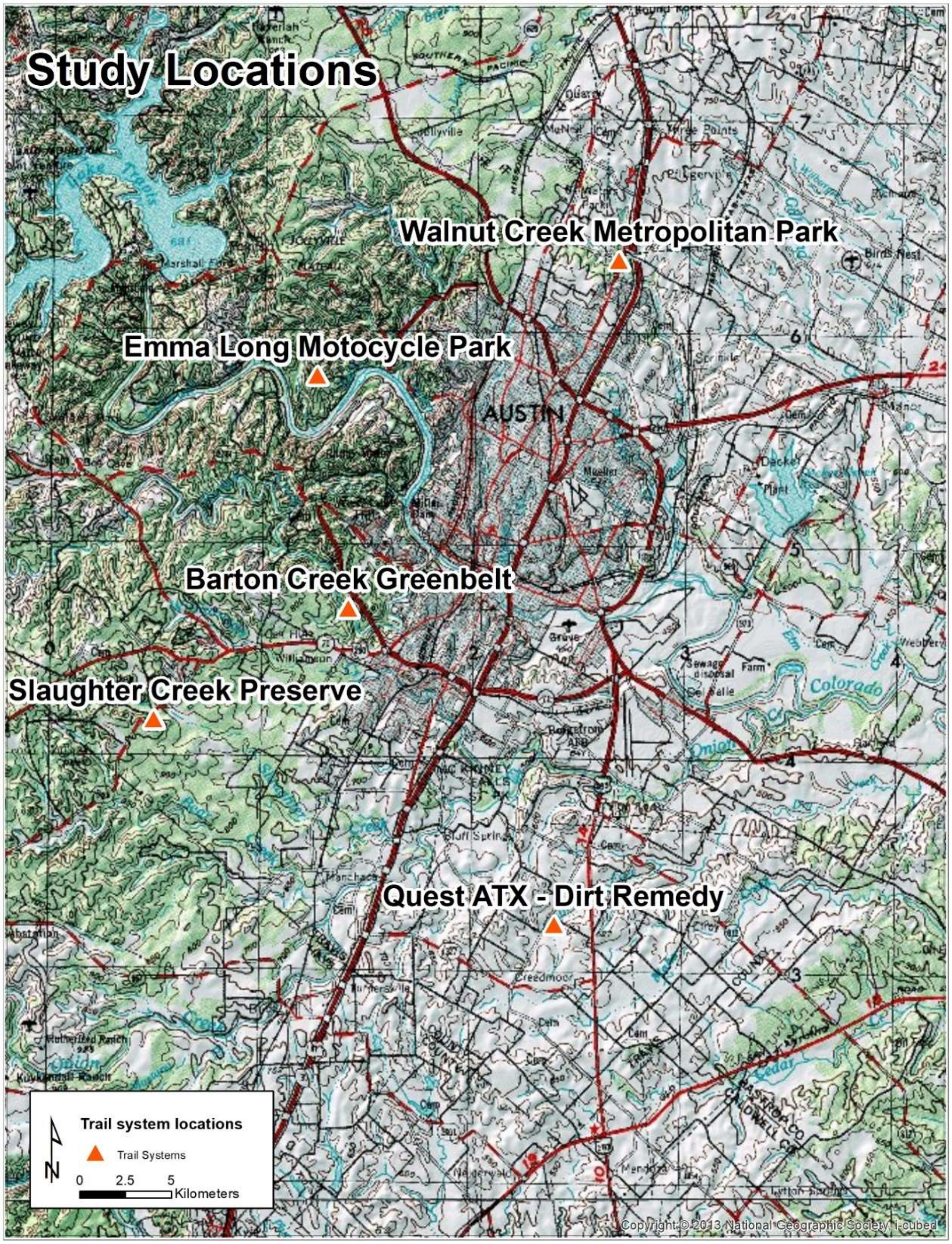
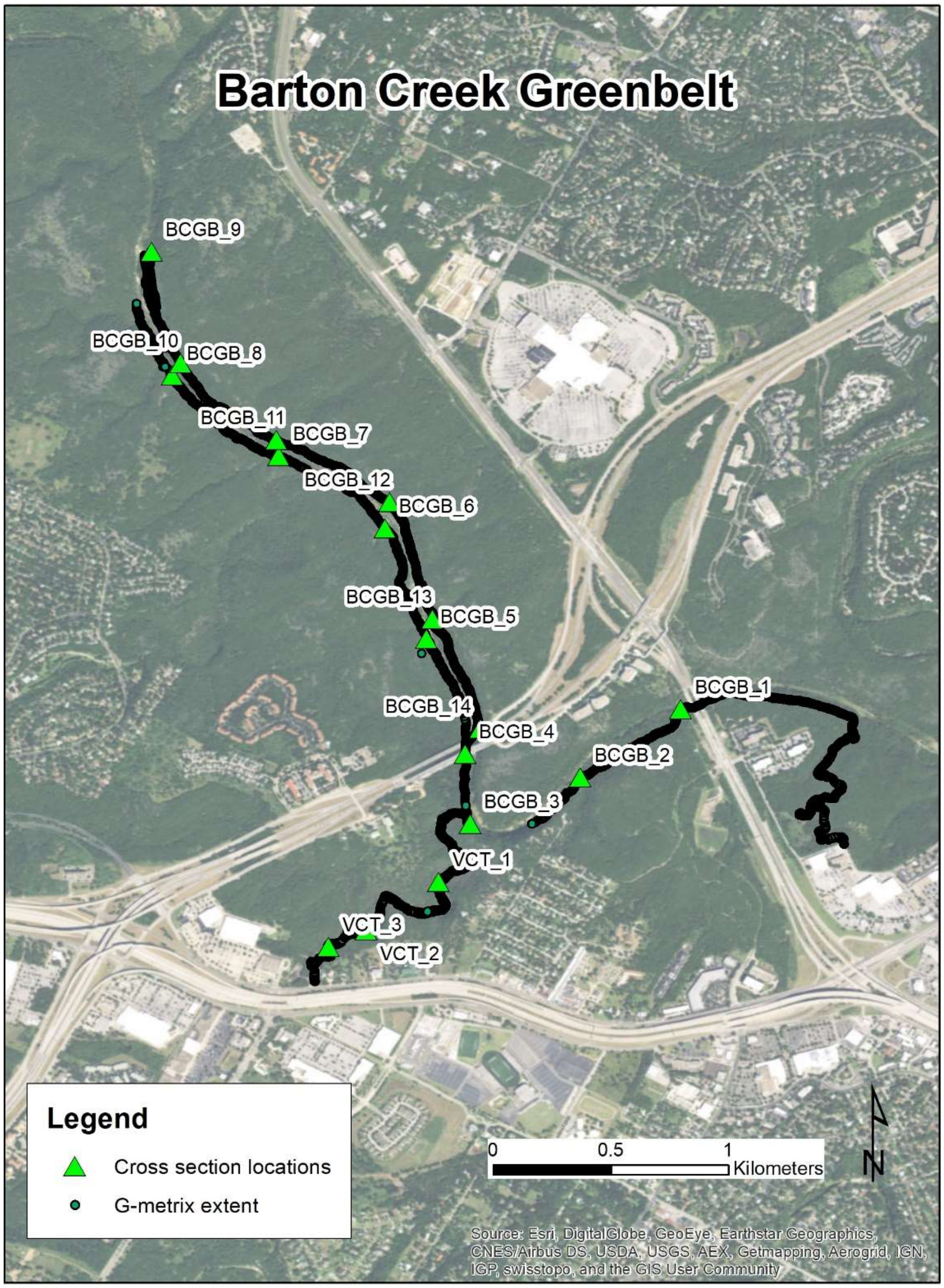


Figure 2a. Trail system locations map



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 2b. Barton Creek Greenbelt study area map

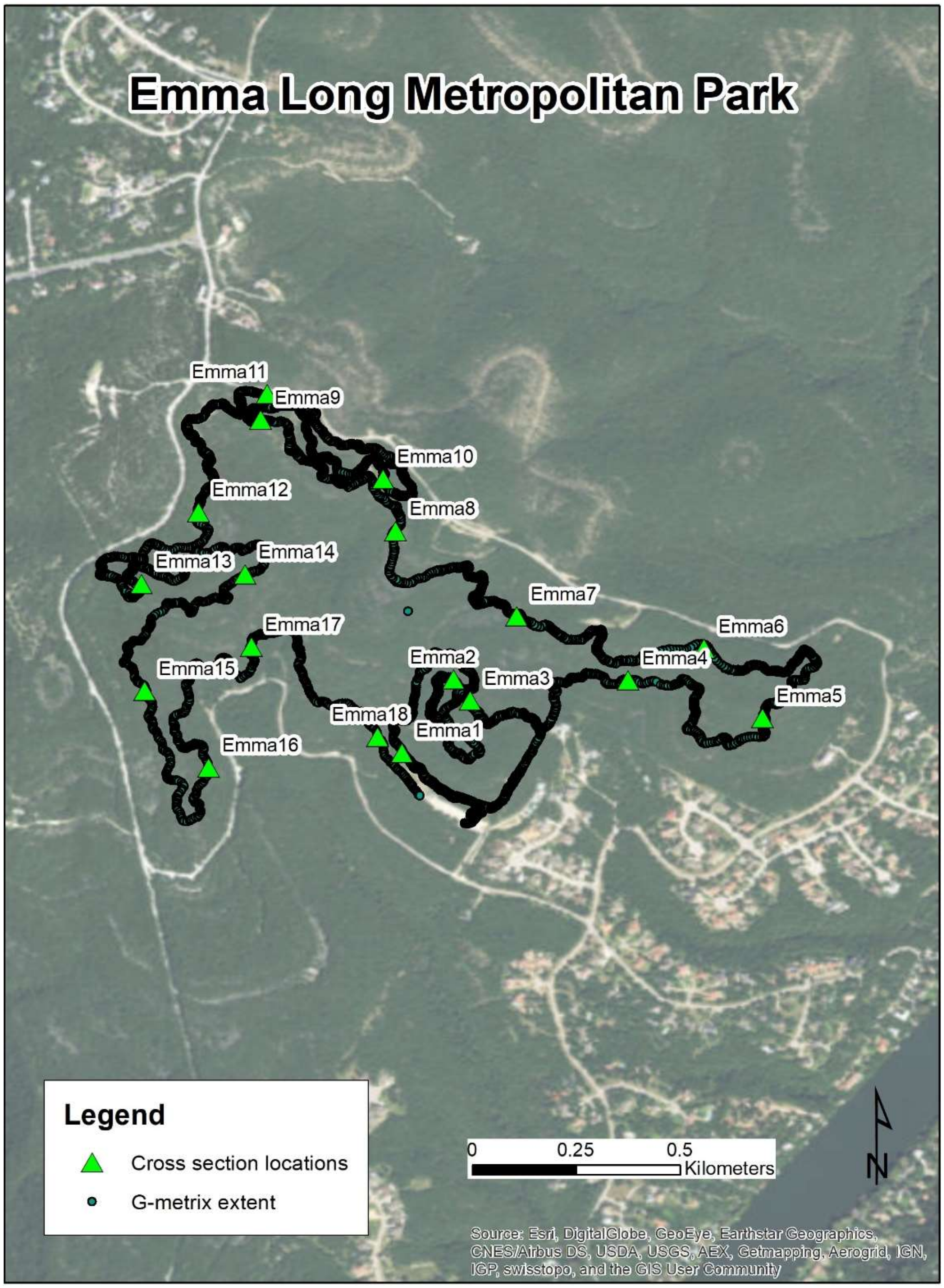


Figure 2c. Emma Long Metropolitan Park study area map

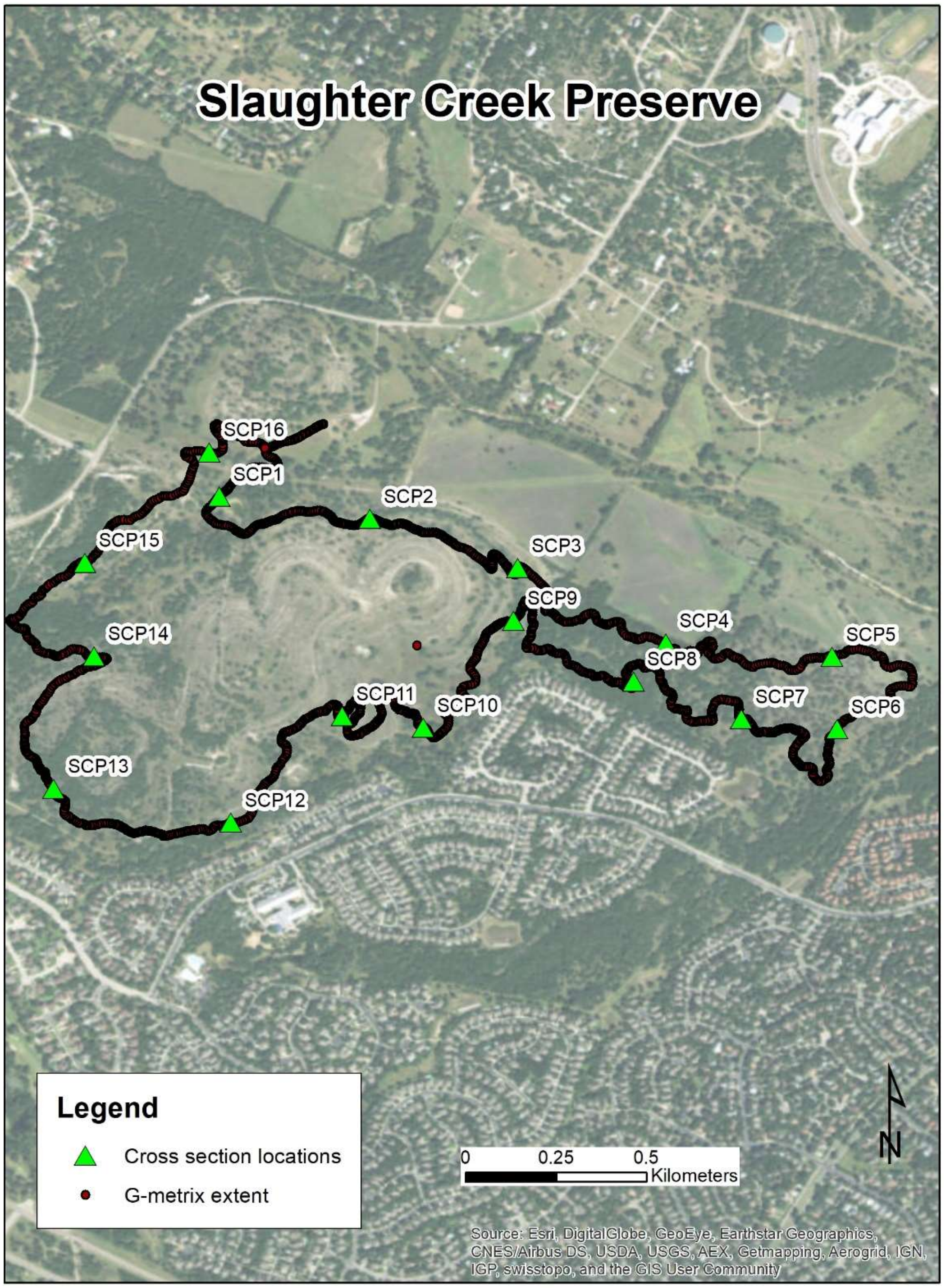
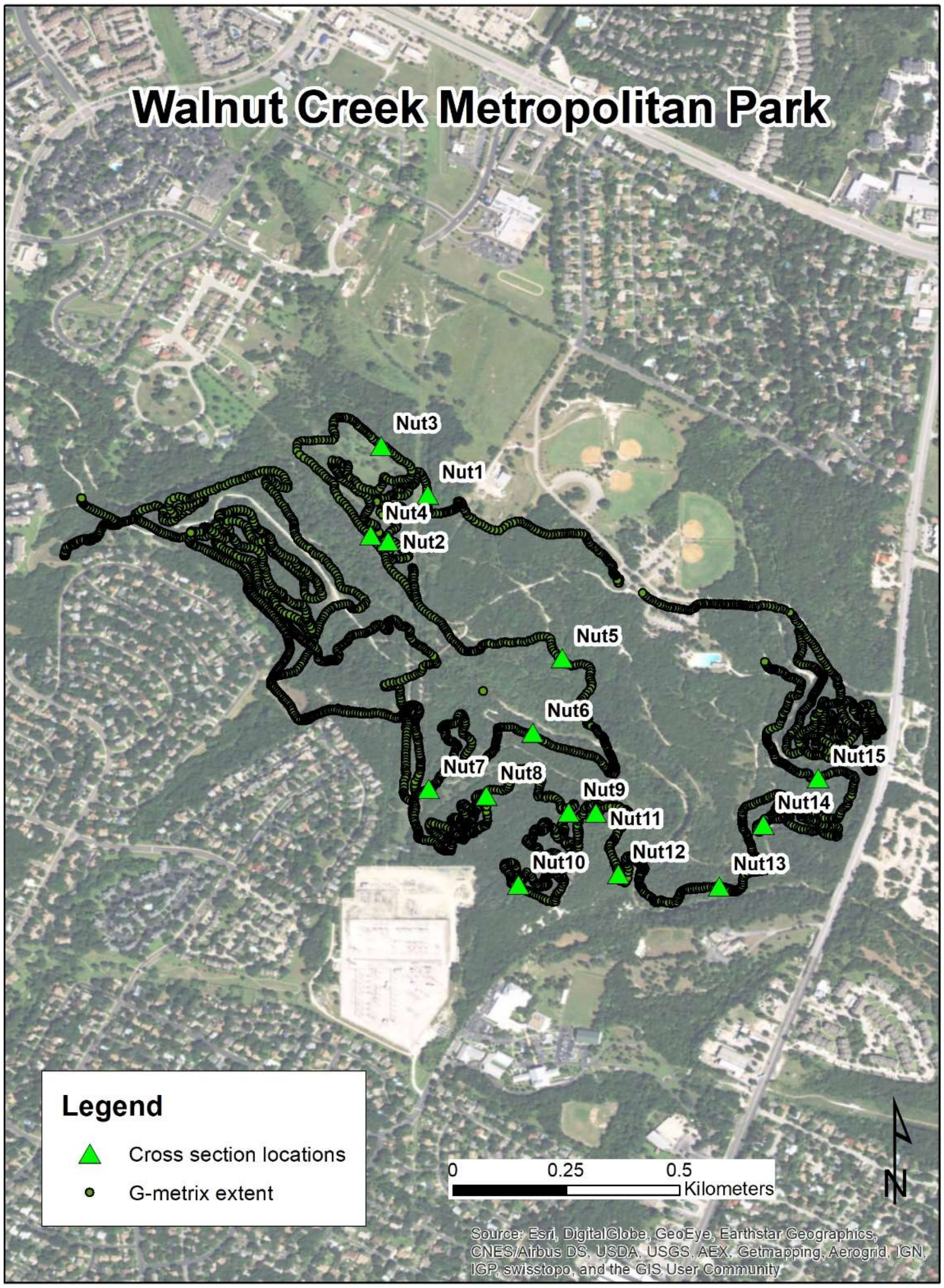


Figure 2d. Slaughter Creek Preserve study area map



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 2e. Walnut Creek Metropolitan Park study area map

### Point Sampling

Samples were collected along each trail segment at approximately 500-meter intervals. At each sample location trail morphology data; including trail width and depth, soil compaction, tread roughness, and soil bulk density, were collected. The coordinates of each of the point sampling locations was recorded with a GPS. The measurements were tabulated in Excel and imported into GIS. Trail width as measured was determined by assessing the trampled width of the trail, denoted by the extent of vegetation growth and/or damage along the edges of the trail. The depth was measured as the maximum incision depth within the trampled width. The ground surface level from which maximum incision is measured, often stretched beyond the measured trail width. See Figure 3 for explanation of with and depth measurements.

Soil compaction was measured with a pocket penetrometer in the center of the tread and adjacent to the trail. Five samples were taken in both center and adjacent locations at each point sample location. The adjacent location was one meter from the center of the tread. The median and average of those five samples was used to characterize the point sample location. Bulk density samples were taken approximately every 1 km (every other sample). At each location, bulk density samples were taken in the center of the trail and adjacent to the trail, by hammering a small cylinder with a known volume into the soil. The dry weight of the samples was divided by the volume of the cylinder to determine bulk density (USDA NRCS 2016). Bulk density and soil compaction measurements were paired in an attempt to distinguish a relationship between soil bulk density and compaction.

Figure 3. Depiction of trampled width and maximum incision depth measurements.

Trail tread roughness was measured in an innovative way, by laying a one-meter chain along the trail surface and measuring the distance between the ends of the chain (see Figure 4). Two samples were taken perpendicular to one another, in the center of the trail. The chain has small (~5 mm) links and it is laid down to conform to the microtopography of the trail surface. The average of the total chain length to the end-to-end length gives an approximation of the tread roughness at each point sampling location.

Figure 4. Demonstration of chain-length method of measuring roughness. Note the chain in front of the tape measure with orange tape at the ends.

Rider Forcing

For this study, I employed a new approach to understand the impact of mountain biking. To the knowledge of the author, there have been no attempts to empirically document and understand the influence of speed and acceleration (especially around corners) in relation to mountain bike impact on trails. The new approach will document the unique forces exerted by a mountain biker onto a trail. The primary mode of data collection was the georeferenced video camera, Garmin Virb. The Garmin Virb creates a GPS track with a point every second. These GPS tracks will be used to calculate the turn angle and speed along the trail. The Garmin Virb is also equipped with a georeferenced 3-d accelerometer. The 3-d accelerometer gives g-force measurements along the X, Y and Z axes in the units of g ($1g = 9.8m/s^2$). Accelerometer data was collected at roughly 1/10th of a second interval along the trail, while the GPS collected the location coordinates once every second. Each reading at one-second intervals includes approximately 10 g-force measurements for each of the 3 directions (x, y, z). This left either the option of manually creating GPS points for each of the 1/10th intervals, or reducing the data to each collected GPS point. The latter option was chosen because either way the data would have to be aggregated before it was compared to other variables, it was easier to aggregate this way, and it did not require the creation of possibly inaccurate data points. The average, the maximum of the absolute value, and the standard deviation were used to reduce the roughly 10 accelerometer data readings at each collected GPS point. In theory, these g-force measurements are proportional to the force that is placed on the trail surface by the bike rider. It is hypothesized that trail morphology will reflect these force parameters.

### Spatial Terrain Characterization

The spatial datasets that were used to model the landscape variability included DEMs, landcover, and soil data. The DEM was accessed and downloaded from the USGS National Map (USGS 2016). The DEM (1/3 arc-second spatial resolution) was used to calculate slope and a flow accumulation model in ArcMap. The flow accumulation model is a raster layer where the value of each cell reflects the number of cells that flow downstream into it.

Landcover classifications were described by the ecoregion classifications from the Texas Ecological Mapping System (TPWD MoRAP TNRIS 2016). These land classification maps (10-meter spatial resolution) were created as part of the Texas Comprehensive Wildlife Conservation Strategy for the Texas Parks and Wildlife Department. The “Common name” is given for vegetation types, and a second “Econame” which describes soil types based on ecological units. For example, a given vegetation cover (Common name) may exist on more than one soil based ecological unit (Econame) and any given Econame may house multiple vegetation types.

Soil data and descriptions were gathered from the Soil Data Viewer from the National Soil Survey (USDA NRCS 2016). The soil data viewer provides access to soil maps (1:24,000) with physical descriptions about the soils, and maps of soil characterization and interpretations. This study used the soil classifications of surface texture, and hydrologic group.

### Statistical and GIS Analysis

Statistical analysis was used to analyze the effect of rider-induced forces on trail morphology. Pearson Correlation analysis was used to determine which independent variables have an impact on trail trampled width and maximum incision depth. The independent variables included measures of user generated forces. This analysis is a test of the methods as much as it is a test of the relationship between the variables. The average, standard deviation, and maximum of the absolute value of the g-forces measurements were calculated at each cross-section sample location by using the "nearest" tool in ArcGIS. Additionally, trail surface slope, absolute value of the turn-angle, and velocity (steplength) were calculated with the "Pathmetrics" command from the Ecological Modeling Environment tool for ArcGIS and were calculated at each cross-section location. The turn-angle data yields results showing the degree of turn from the previous point with a straight trail having a value of zero. The absolute value of the turn-angle was used because this study does not need to distinguish between left and right turns. The chain-length was used as an estimate for trail roughness. Trail surface roughness is an environmental condition, but it also alters the pattern of impact by a mountain biker via bouncing and deflection of tires over obstacles.

A Pearson Correlation was used to discern the influence of each of the rider forcing independent variables on the dependent variables of trail width and depth. The entire data set was analyzed and each trail system was analyzed for comparison. The assumptions required for Pearson Correlations which include level of measurement, related pairs, and normality were fulfilled. Scatter plots illustrated the assumptions of linearity and homoscedasticity and resulted in the exclusion of some correlations. The assumption of the absence of outliers was met by calculating the outlying values by adding 1.5 to the 1st and 3rd quartiles. Outliers were calculated and removed from the combined trails dataset and then applied to the individual trail datasets. Outlier removal reduced the sample sizes for the individual trails data. Because it is unlikely that the outliers are measurement error, Pearson Correlations were calculated for duplicate datasets, one containing all data and one with outliers removed.

# IV. PILOT STUDY RESULTS

## Race Description

The summer of 2015 in Austin, TX, was notable for being very wet and then very dry. March received 128 mm of rain and April 117 mm. May received 348 mm of rain compared to an average of 68 mm. June received 82 mm compared to its average of 111 mm. July received 0.3 mm of rain compared to its average of 62 mm (https://www.climate.gov/maps-data/dataset/daily-temperature-and-precipitation-reports-data-tables). The races occurred June 13, 20, and 27. Data was collected March 16th and 17th (before); and July 18th and 19th (after races were completed). Table 1 shows the days since the last precipitation event and the accumulation over the week previous s to the sampling dates.

There were several racing categories including A (expert class) and B (intermediate class) for both men and women. These categories were further separated by age group. Each of the different categories were required to do a different number of laps so the totals were tabulated to acquire an estimate of trail usage (Table 2). The total number of laps completed during the races was 255. Several riders did warm-up or practice laps so the actual number of laps completed is higher. The race course was not open to the public when races were not occurring. However, trail builders and employees of the wake board park were known to ride laps to check trail conditions. Thus, 300-350 laps are assumed to be a reasonable estimate of the total number of laps ridden on the race course.

Table 1. Precipitation information for sampling dates.

| Trail Name | Date of sampling | Day since previous rain | Rain in previous week (mm) | Station ID |
|---|---|---|---|---|
| Barton Creek Greenbelt | 7/18/2016 | 19 | 0 | US1TXTV0160 |
| | 8/3/2016 | 6 | 60 | US1TXTV0160 |
| Slaughter Creek | 8/2/2016 | 37 | 0 | US1TXTV0111 |
| Walnut Creek | 8/9/2016 | 12 | 0 | US1TXTV0142 |
| Emma Long | 9/6/2016 | 6 | 10.5 | US1TXTV0117 |
| Quest ATX (Before) | 3/16/2015 | 6 | 20.5 | US1TXTV0218 |
| | 3/17/2015 | 7 | 0 | US1TXTV0218 |
| Quest ATX (After) | 7/18/2017 | 18 | 0 | US1TXTV0218 |
| | 7/19/2017 | 19 | 0 | US1TXTV0218 |

Table 2. Quest ATX rider tally

| Race Categories | Laps per rider | Number of Riders | | | Total Laps |
|---|---|---|---|---|---|
| | | 13-Jun | 20-Jun | 27-Jun | |
| Men A U39 | 4 | 9 | 4 | 5 | 72 |
| Men A 40+ | 4 | 7 | 3 | 6 | 64 |
| Men B U39 | 3 | 1 | 6 | 4 | 33 |
| Men B 40+ | 3 | 4 | 2 | 5 | 33 |
| Women A | 3 | 3 | 3 | 5 | 33 |
| Women B U39 | 2 | 2 | 1 | 3 | 12 |
| Women B 40+ | 2 | 0 | 1 | 3 | 8 |
| Total Riders | | 26 | 20 | 31 | **255** |

The author rode the course to collect the g-force data. Since the g-force data is dependent on speed, it is probable that different lap speeds have different g-force signatures. The differences likely occur in intensity rather than location. For example, if you make a turn at 30 kilometers per hour versus 15 kilometers per hour, the turn may dictate the location of the g-forces, but the velocity likely determines the intensity of the forces. Further research should use g-force data from riders with different skill levels.

Before and after data was collected at 29 sample sites throughout the course (see Figure 1). Sample site naming conventions separate the site into four areas: the main trail (MT); the hilly section that goes up and down the back of the levee, double down (DD); the lowland area below the dam or bottomlands (BOT); and a small section of trail cleared for a cyclocross bike race the year before this study was conducted and not a part of the trail building activities for this project.

## **Photo Documentation**

Photographs were used to characterize the dominant vegetation of each cross-section. Classifications included; graminoids or grasses, forbs and herbs, and mixed (grasses and forbs). The photos captured the growth of vegetation through the spring, with mostly dormant vegetation before the race, and abundant green vegetation about a meter tall after the race. As shown in Figure 1 (map) there was some tree cover, but the trail avoided thickets of trees and shrubs, therefore those vegetation types were not used as a classification. From the repeat photography, the grasses appear more resistant to impact than the forbs. Figure 4 shows photos taken before and after the race that typify each vegetation characterization; sample site MT-2 shows grass dominant areas where grasses are impacted, but still present in the trail tread. Sample site MT-13 shows forb dominant areas where vegetation is completely removed from the trail tread. Sample site DD-4 shows mixed vegetation, where there are some grasses in or near the trail tread, but the trail center is mostly devoid of vegetation.

Observations about soil condition were taken in field notes, photographs and first-person video from the race. The change in soil moisture is evidenced by mud cracks found throughout the study area on trail surfaces and adjacent to the trail (Figure 6). After the race, in some sample sites there were pockets of loose soil, with low resistance to compaction values surrounded by a hard-pack trail surface (Figure 6). This occurred where the soils were dry and had mud cracks. The action of mountain bike tires broke or crumbled the edges of the mud cracks and the trail surface.

5a. MT-2 Before (3/16/2015) and After (7/18/2015)

5b. MT-13 Before (3/16/2015) and After (7/18/2015)

5c. DD-4 Before (3/16/2015) and After (7/18/2015)

Figure 5. ‘Before’ and ‘After’ Photos of selected sample stations at Quest ATX.

Figure 6. Trail surface conditions, an example from MT-4. Before 3/16/2015 (left) damp soils show motorcycle tread, note dormant vegetation. After 7/18/2017 (right) mud cracks and loose material on the trail surface, with green vegetation.

## Compaction

During the first sampling event, the soil was characterized as medium dense, moist, moderately stiff silty clay with a simple hand test. After the race, the same soils were characterized as dense, dry, hard silty clay, also with a hand test. Before the races, the center of tread compaction values were higher than the adjacent values. This shows that the mountain bikes effectively compacted the soil. The compaction data collected after racing shows an increase in compaction of both adjacent and center of tread values, because of drying soils. Several of the samples taken after the races exceeded the measurement capability of the pocket penetrometer (~5.0 kg/cm$^2$).

Soil resistance to compaction changed drastically over the course of the race series. The adjacent samples were intended to show the control conditions of undisturbed soil, in contrast to the center of tread samples. However, the adjacent samples showed a greater amount of variation when comparing before and after samples, than the samples at the center of the trail tread. Figure 6 compares the adjacent to center of tread results for the before and after conditions. Figure 7 illustrates that soil compaction did increase after the race series. Center of trail compaction values increased from the before condition, and the center of tread samples were generally more compacted than the adjacent samples. Compaction values from after the races were higher than before. This includes the adjacent sampling locations that should not have been impacted by mountain bike use. This suggest that another variable, soil moisture, had an impact on soil resistance to compression. Unfortunately, no soil moisture data was collected.

The amount of compaction caused by mountain bikes is difficult to differentiate from the changes in soil moisture on soil compaction. However, mountain bike impact was responsible for increased soil compaction. Figure 8 shows that the before values for soil compaction were generally lower than the after data collected after the race. This figure also shows less variation between the adjacent and center of trail samples before the races, as compared to compaction values after the races. Figure 9 shows the same data plotted differently, and it illustrates that the average difference between the adjacent and center of trail samples was greater before the races, whereas the average difference after the race is negligible.  This shows that dehydration of soils and mountain bike activity may be responsible for similar scales of impact on soils.

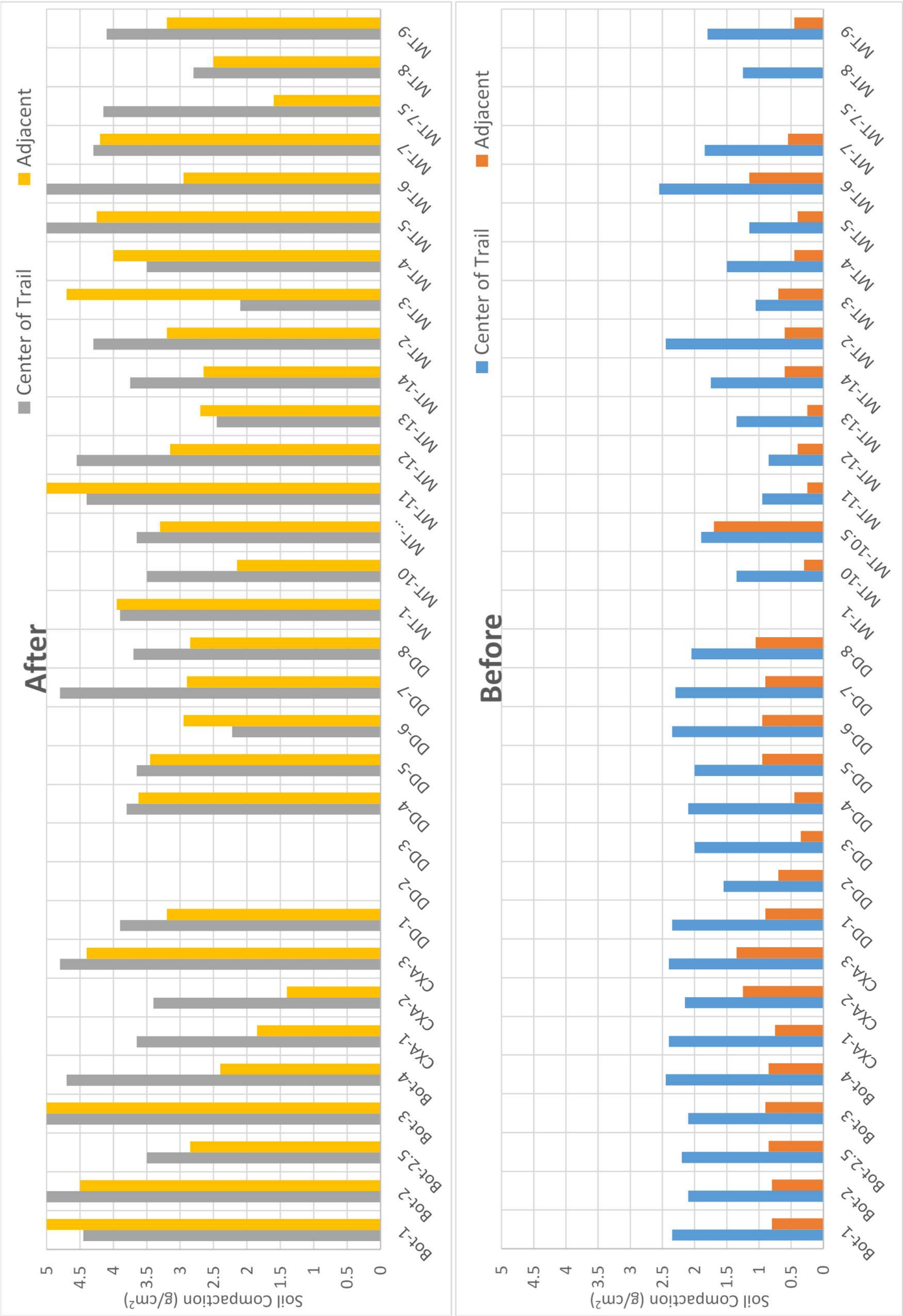


Figure 7. “Before” and “After” soil compaction measurements. Note: 5 g/cm$^2$ is the maximum measurement of the pocket penetrometer.

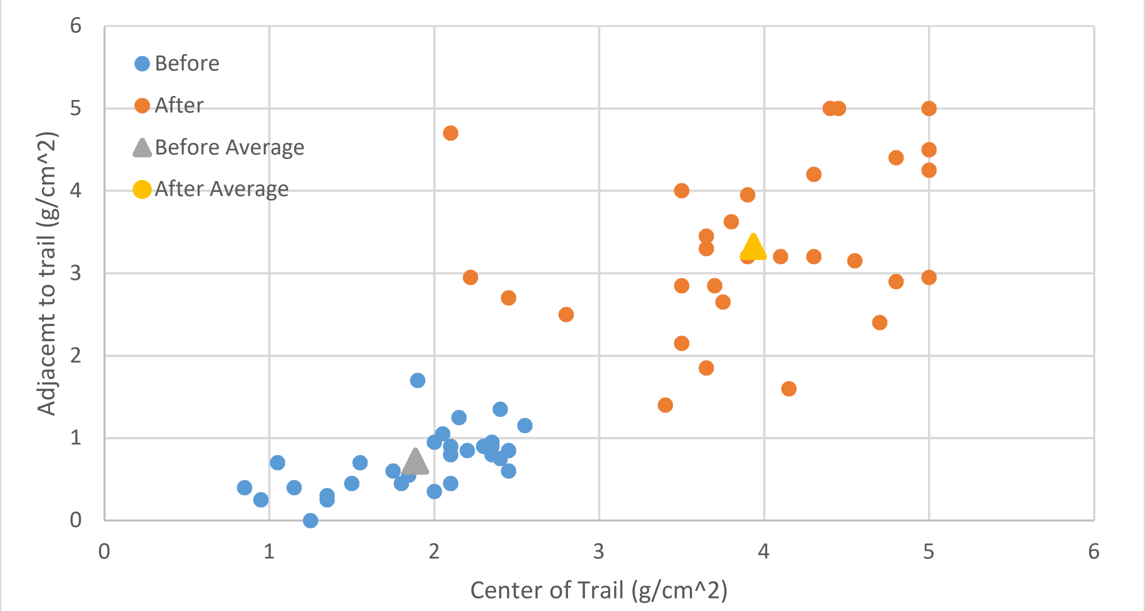


Figure 8. Center of Trail and Adjacent to trail soil compaction scatter plot.

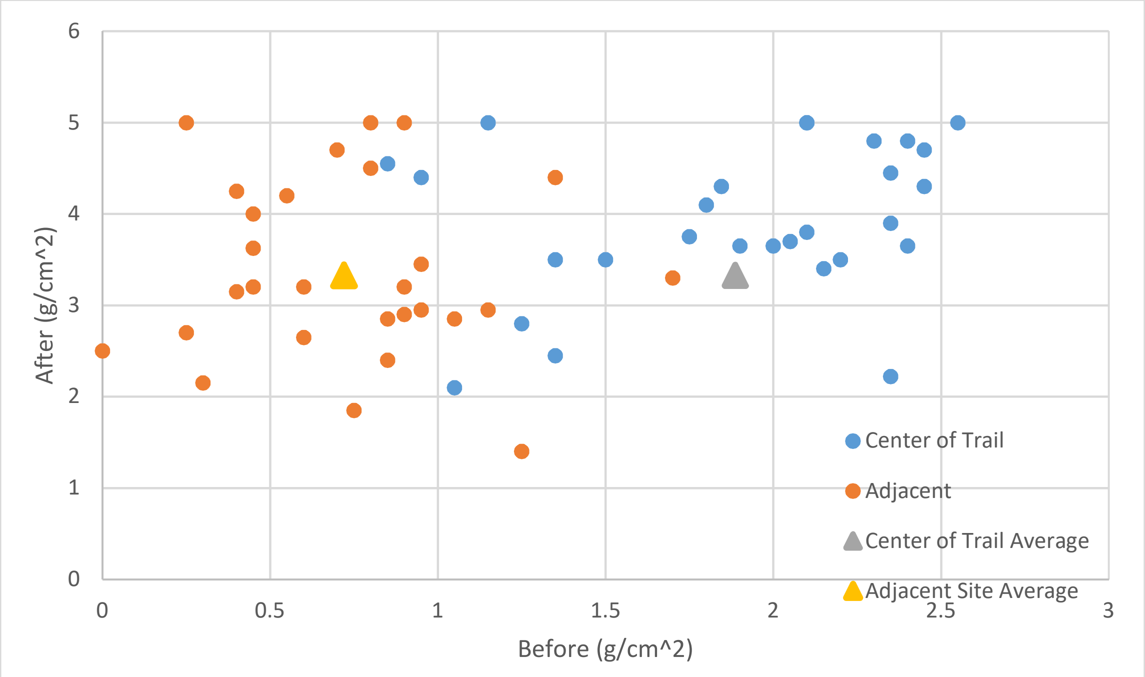


Figure 9. ‘Before’ and ‘After’ soil compaction values scatter plot.

## Cross-Sections

There were not any visible signs of overland flow, so soil compaction and dehydration were responsible for altering surface elevation. As previously discussed, the soil became much drier during the duration of the study. The height measurement of the stakes placed at the endpoints did not differ in most cases, suggesting that change was because of the mountain bike traffic. However, at some cross-sections the endpoints had different height measurements suggesting that the shrinking of the soils because of dehydration is responsible for some change.

The change in cross-sections showed a general trend of a lowering of the ground elevation. The amount of change varied widely. The average difference in cross-sectional area was 272 cubic centimeters, with a standard deviation of 304 cubic centimeters. The maximum change was 855 cubic centimeters and minimum was -377 cubic centimeters. There were only 5 sites that showed an aggradation or increase in trail surface elevation. Negative values indicate net aggradation or an increase in ground-surface elevation. The explanation for why some areas show aggradation is unclear.

Figure 10 shows the cross-section profiles. Sample site BOT-2 has a profile with two peaks and aggradation in the troughs or ruts. These ruts may act as a sediment sink for the material dislodged by bike tires. Sample site DD-1 shows an opposite condition where the ruts are being accentuated. DD-1 is on a downhill slope, and it is likely that as bikers brake, the increased shear stress further erodes the ruts and moves sediment downslope and to the edges. The changes in MT-10.5 and MT-13 are likely due to sedimentation processes that may or may not be related to the mountain bike race; the data collected and the repeat photography offers no explanation. The sample site MT-14 was across a pre-existing erosional gully. The aggradation occurred at the bottom of the gully, on the opposite side from where bikers rode. This aggradation is likely a consequence of processes that pre-existed the trail.

No correlation could be found between compaction and cross-section changes. The soil did not vary greatly across the site; however, vegetation cover did. Vegetation type was characterized and evaluated as a potential cause for the variation in cross-section area change. Figure 11 shows a scatter plot of the total change in compaction after the races against cross-sectional area change. The samples adjacent to the trail can represent no impact, so the difference between those values and the measurements in the center of the trail, after the races, approximate the net change in soil compactness. Soil in grassy (graminoid) dominant areas varies less in both compaction and cross-section area change, than either of the other vegetation covers.

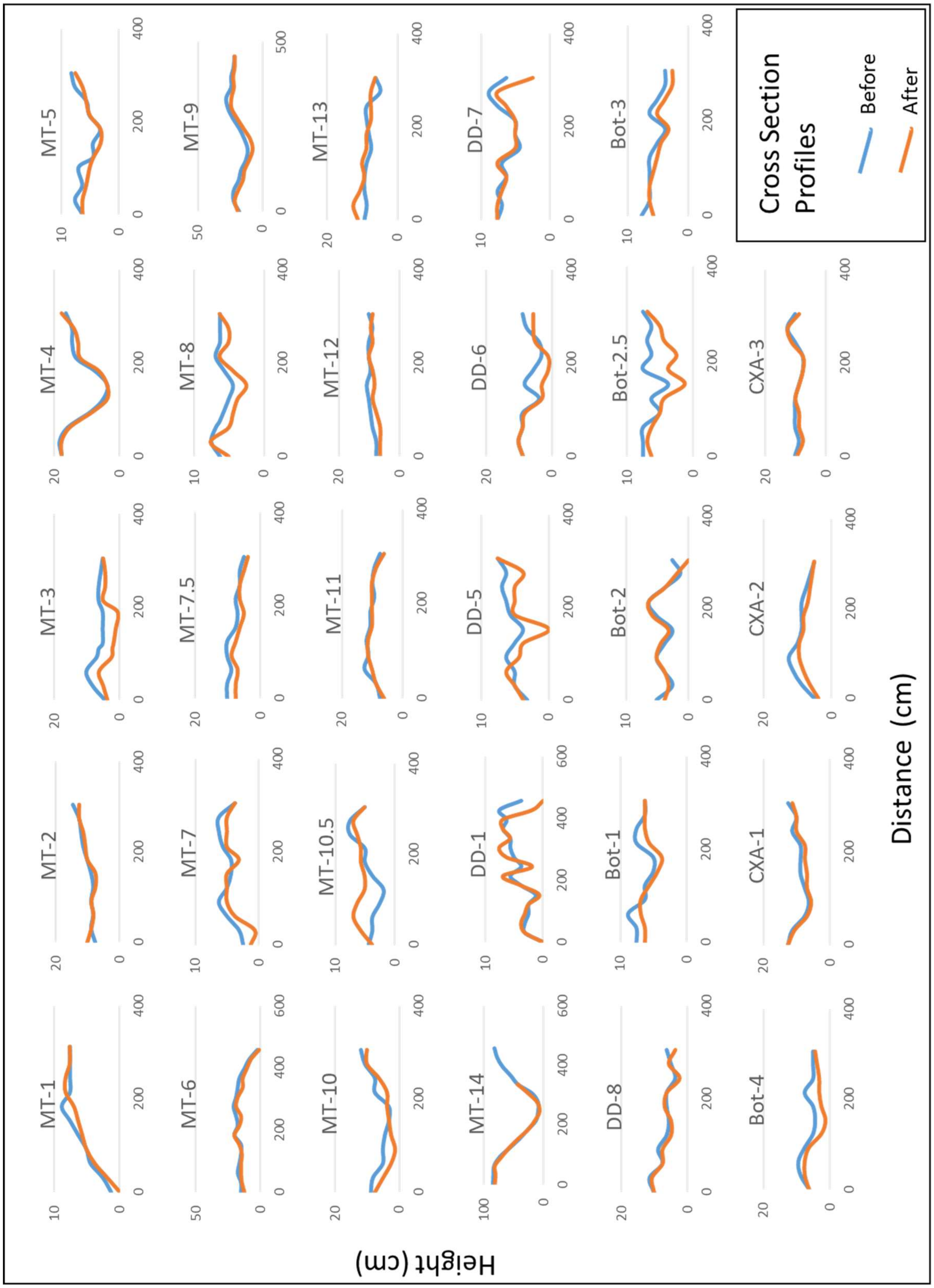


Figure 10. Cross-section profiles.

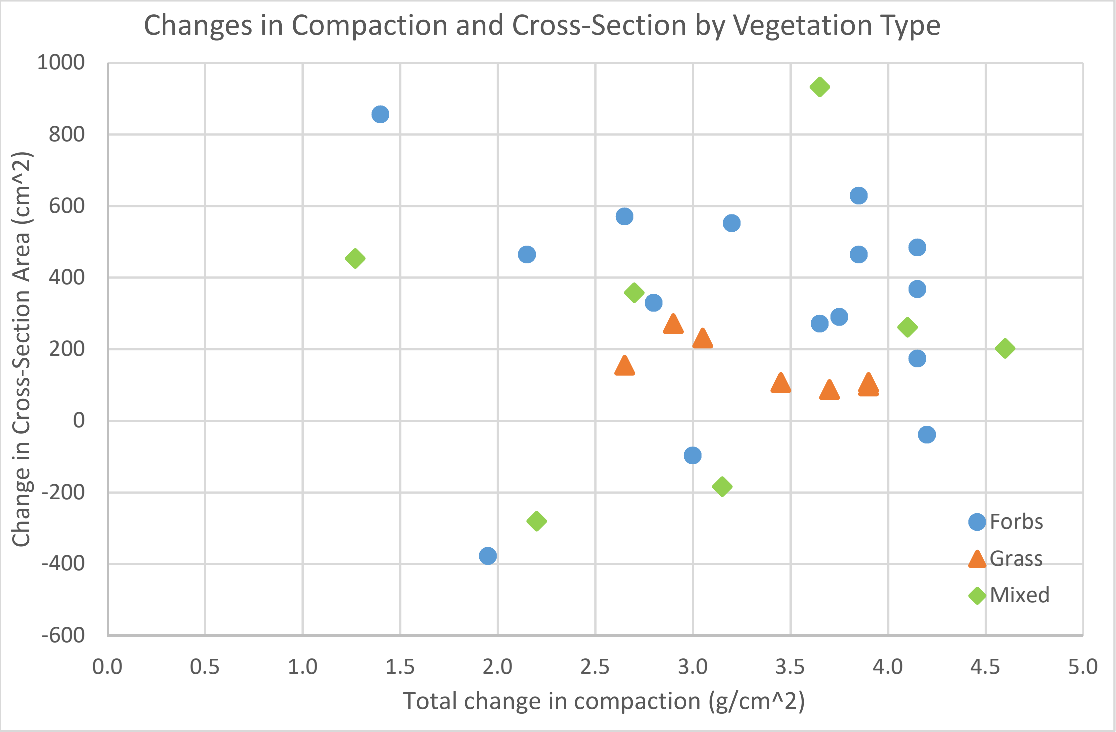


Figure 11. Cross-sectional area change vs compaction, by vegetation type.

## G-force

The correlation matrix shows that correlation exists between some of the biker forcing variables (see Table 2 for variable definitions). Table 3a shows the correlation values and Table 3b the significance of the t-values for the correlation coefficients for the 0.05 level for 28 degrees of freedom. The T-test showed that the following correlation coeffecients were significantly different than zero; change in cross-sectional area (AreaChange) with the G-force in the X-dimension, and change in soil compaction in the center of the trail (CntrDiff) with velocity (StepLength) and G-force in the Y-dimension. See Table 3 for variable definitions. This suggests that rider velocity and g-forces in the X and Y dimensions play an important role in trail morphologic evolution.

Table 3. Definitions of variables.

| Variable Name | Definition |
|---|---|
| Area Change | The change in cross-sectional area in $cm^2$ |
| Soil Comp CntrDiff | The difference between ‘before’ and ‘after’ soil compaction measurements in the center of the trail in $kg/cm^2$ |
| Turn Angle | The turn angle from GPS track point to the next (one second intervals). Zero is straight ahead, negative is left, positive is right in degrees |
| Abs (Turn Angle) | The absolute value of the turn angle in degrees |
| Net G-force | The total g-force from X, Y, and Z directions in g |
| Velocity | The instantaneous velocity at each GPS track point (one second interval), in m/s |
| Gx-force | The g-force in the X direction oriented horizontally and parallel to the trail in g. |
| Gy-force | The g-force in the Y direction oriented horizontal and perpendicular to the trail in g. |
| Gz-force | The g-force in the Z direction oriented vertically intersecting the trail perpendicularly in g. |
| Slope | The slope of the trail surface from a GPS track point to the next in degrees. |

Table 4a – Correlation Matrix

| Correlation | Area Change | Soil Comp CntrDiff | Turn Angle | abs (Turn Angle) | Net G-force | Velocity | Gx-force | Gy-force | Gz-force | Slope |
|---|---|---|---|---|---|---|---|---|---|---|
| Area Change | 1.000 | | | | | | | | | |
| Soil Comp CntrDiff | -0.130 | 1.000 | | | | | | | | |
| Turn Angle | 0.034 | 0.050 | 1.000 | | | | | | | |
| abs (Turn Angle) | 0.137 | -0.033 | 0.067 | 1.000 | | | | | | |
| Net G-force | -0.262 | -0.217 | 0.251 | 0.323 | 1.000 | | | | | |
| Velocity | -0.312 | 0.323 | -0.074 | -0.341 | 0.177 | 1.000 | | | | |
| Gx-force | -0.413 | 0.089 | 0.132 | -0.104 | 0.392 | 0.208 | 1.000 | | | |
| Gy-force | -0.203 | 0.116 | -0.176 | 0.009 | 0.367 | 0.130 | -0.051 | 1.000 | | |
| Gz-force | -0.198 | 0.364 | -0.431 | -0.494 | -0.334 | 0.236 | -0.020 | 0.479 | 1.000 | |
| Slope | 0.106 | 0.107 | 0.034 | 0.279 | -0.216 | -0.411 | -0.062 | -0.233 | -0.095 | 1.000 |

Table 4b – T-test results for correlation matrix. Yellow highlights show the t-values that are significantly different than zero at a 0.05 confidence level.

| T-test | Area Change | Soil Comp CntrDiff | Turn Angle | abs (Turn Angle) | Net G-force | Velocity | Gx-force | Gy-force | Gz-force | Slope |
|---|---|---|---|---|---|---|---|---|---|---|
| Area Change | | | | | | | | | | |
| Soil Comp CntrDiff | -0.67 | | | | | | | | | |
| Turn Angle | 0.17 | 0.26 | | | | | | | | |
| abs (Turn Angle) | 0.71 | -0.17 | 0.34 | | | | | | | |
| Net G-force | -1.39 | -1.13 | 1.32 | 1.74 | | | | | | |
| Velocity | -1.68 | 1.74 | -0.38 | -1.85 | 0.92 | | | | | |
| Gx-force | -2.31 | 0.46 | 0.68 | -0.54 | 2.18 | 1.09 | | | | |
| Gy-force | -1.06 | 0.60 | -0.91 | 0.05 | 2.01 | 0.67 | -0.26 | | | |
| Gz-force | -1.03 | 1.99 | -2.43 | -2.90 | -1.81 | 1.24 | -0.10 | 2.78 | | |
| Slope | 0.55 | 0.55 | 0.17 | 1.48 | -1.13 | -2.30 | -0.32 | -1.22 | -0.49 | |

# V. MAIN STUDY SITE BACKGROUND AND DESCRIPTIONS

Each of the trails chosen for this study has different land management strategies. Each of the trails in this study has a different political history that must be noted. Trail user types, use rates, and patterns are highly influential on trail morphology. As a frequent user of these trail systems, the author can provide valuable observations from years of participant observation.

## Trail Descriptions

Walnut Creek Metropolitan Park has an approximately 18-kilometer loop along the banks of Walnut Creek in north Austin. The Walnut Creek trails are heavily used by hikers, their dogs, and mountain bikers. Although the 18-kilometer “main loop” is a common route for mountain bikers, many cut-through and short-cut trails connect different points of interest throughout the park. Walnut Creek Park is under the purview of the City of Austin Parks Department, and Austin Ridge Riders manages and maintains the trails through an agreement with the city. The “Metropolitan Park” designation means that this park is open to receive the most recreation based development. In addition to the trail system, there is a swimming pool, multiple playgrounds, several baseball fields, and multiple picnic tables. Walnut Creek trail receives the highest management activity and budget through the Austin Ridge Riders, and therefore the trail contains many mountain biking specific built features such as berms and jumps.

Slaughter Creek Preserve is a carefully managed 8-kilometer loop trail. It is managed by Austin’s Water Quality and Protected Lands and the Austin Ridge Riders. This preserve was created in 2009, making it the youngest trail in the main study. The purpose of the preserve is to protect water quality, and as such, trail use is carefully managed. Horses, hikers, and mountain bikers are all active users. The Slaughter Creek site is a directional trail with hikers and horses directed counter clockwise, and bikers clockwise. The entrance gate for vehicles closes access to the trail, after rains. Off-trail trampling is highly discouraged and short-cut or rouge trails are absent, because managers are quick to respond. The Austin Ridge Riders do not build jumps, berms, or any other mountain bike specific features, instead trail work efforts are focused on in-filling entrenched areas and covering exposed roots. Prescribed burns are common, with the goal of thinning juniper trees to restore a post-oak savanna. In full disclosure, at the time of writing, the author is the Austin Ridge Rider's trail steward for Slaughter Creek Trail.

Barton Creek Greenbelt (BCGB) can be accessed directly from downtown Austin, and its 11 (official) kilometers follow Barton Creek upstream. Barton Creek Greenbelt is likely the oldest trail system. The portions of the trail in this study are located along either side of the creek. It is very likely that these trails have existed in some form for hundreds of years, since they originate from near Barton Springs, which is the reason Austin is located where it is. Currently, Barton Creek trail is a very popular trail for tourists and locals alike. During the summer each weekend hundreds of people flock to the several swimming holes along the creek. Because of the accessibility of BCGB and the frequent pools along the creek, it gets very heavy pedestrian traffic, especially in the summer. Mountain bikers are also frequent trail users, who because of the traffic, have developed an extensive un-official trail network that exploits the land that doesn't have water access. The Barton Creek Greenbelt stretches from Zilker Park which is a few minutes' walk from downtown Austin, up the creek where it widens and is surrounded by residential areas. This research project surveys portions of the official main trail in the central part of the Greenbelt. The City of Austin's "greenbelt" designation for Barton Creek Greenbelt means that the land's primary purpose is flood control with recreational trails allowed. At the time this study was conducted the City of Austin had not approved the trail maintenance partnership with the Austin Ridge Riders, which left large portions of the trail without adequate management.

Emma Long Motorcycle Park only allows mountain bikers, dirt-bikers and trials motorcycle riders. See Figure 12. Dirt bikes (left) are built for speed with large engines suspension, and knobby tires; mountain bikes (center) are powered by the rider and often have suspension for comfort; and trials motorcycles (right) are small and lightweight, built for balance with wide tires at low psi, and with no seat they are meant to be ridden standing up at slow speeds. (Pantin 2015). No pedestrian use is allowed, which is rare. Emma Long is a directional trail, for safety reasons, with traffic only allowed in a counter-clockwise direction. Emma Long trail consists of rocks and ledges in juniper forest cover in the hills west of Austin. It is home to the endangered golden-checked warbler during mating season and the land access disputes that go with it. Access by motorcycles and mountain bikers was 'grandfathered' when the City of Austin became owners of the land in the 1970's. The Friends of Emma Long and Austin Ridge Riders work together to maintain and manage the trail. Because of the presence of the endangered Golden-Cheeked Warbler, the Balcones Canyonlands Preserve has oversight to maintain habitat. Often the City of Austin and Balcones Canyonlands Preserve are at odds with the mountain biker and motorcycle communities about trail closures and trail use.

Figure 12. Emma Long trail user types

## Trail Observations

Over the last several years, the author rode each of these trails many times. Based on approximately 6 years of riding these trails, video review, and intimate knowledge of these trails, the author makes the following observations: Walnut Creek trail is the most heavily used by mountain bikers and dog walkers are frequent. The high use rates at Walnut Creek are apparent by wide trails and subsequently it receives the most trail work. The frequent trail work also has a secondary impact because groups of volunteers often trample off trail when working on it, and dirt borrow pits are excavated to provide dirt for eroded areas, jumps and berms. Several organized group rides typically meet at Walnut Creek every week, which can easily have 30 or more riders, but are often between 10-20 riders. Group rides often mean that people stop and wait for stragglers in the group, and this results in off trail trampling and trail widening. One particular type of trail widening is trail braiding, where the trail temporarily diverges into two or more parallel threads. The trail-braiding planform occurs as users (any user type) take different “lines” commonly around an obstacle such as a tree or large rock. It can occur without such obstacle if users desire to walk or ride side by side. Trail braiding was present on some of the trails in the study area; at Barton Creek Greenbelt and Walnut Creek. However, trail widening was not present at any of the sample sites. If trail widening had occurred at the sample locations, the width and depth measurement methods would have to be altered, likely by measuring the cumulative trampled widths. Future research could evaluate conditions leading to trail braiding.

Barton Creek Greenbelt is overrun with pedestrians on the weekends and during the summer and, also has very wide trails. Large groups of college age people toting coolers is not infrequent. Many mountain bikers will not even consider riding the main trail portions of the Barton Creek Greenbelt during the weekend in the spring and summer, because there are too many people. Barton Creek Greenbelt is a rocky trail and is not the most beginner friendly trail, so the population of riders that chooses to ride there is smaller than some other easier trails like Slaughter Creek and Walnut Creek. Barton Creek Greenbelt has multiple trailheads and access points.

Slaughter Creek is the most well-managed and receives moderate use. The rather small parking lot serves as a control to how many people can ride, and a sign states, if the lot is full you should come back later. Trails alongside the road link Slaughter Creek Trail to other trails in South Austin, and many people, the author included, do not drive there, so the parking lot as a control on capacity is limited. Slaughter Creek Preserve is closed when the trail is wet. Given the loop layout and the lack of any attractive resting spots along the trail, most pedestrians are fitness hikers or runners. Although allowed, horse traffic is very low, especially after for-profit tours groups were banned in 2016. Slaughter Creek Trail is a relatively easy trail which is beginner friendly, however, over the author's six-year experience riding this trail, it has become more difficult as roots and rocks are exposed.

Emma Long is arguably one of the most challenging trails in central Texas. Trail traffic is moderate to low for mountain bikers. Emma Long is a hard trail. The route and technical features of the trail were created for and by motorcyclists, so everything seems bigger than a typical mountain bike trail. Emma Long can be dangerous and is only suitable for experienced riders, preferably in groups. Motorcycle traffic includes dirt bikes and trials bikes. Trials bike riders go slow and seek to 'clear' very technical terrain. Trials riders might spend an hour or more on one small section of trail, repeatedly practicing technical maneuvers. Dirt bikes are speed oriented and produce excess torque which results in erosion. Many sections of Emma Long have eroded to limestone bedrock providing a halting point for erosion, and supplying technical features.

In conclusion, the author's experience riding these trails, conversations with other riders, and general riding experience suggest that Emma Long is the most challenging trail, Walnut Creek is the most purpose-built trail for biking, but overuse has ruined the aesthetic in many areas, Slaughter Creek is the most well managed from an ecological perspective, and the Barton Creek Greenbelt trail is in poor condition in many areas.

## Trail Use Rates

In an effort to substantiate the claims from personal experience and provide trail use rates, Strava was used to calculate the average use rates over 4 months. Strava is a data recording app that many runners and cyclists use. Users can create "segments" which are as it sounds, segments of trails which are timed within the app. Users can then see how they rank amongst all other users for any segment that any user has created. The total number of attempts and users who have traversed a segment are recorded on the Strava website. The number of riders and attempts was recorded on March 30th, 2017, and then also on June 25th, 2017. The total number of riders and attempts show the relative use patterns between segments. The change in users and attempts over the 117 days was used to calculate the average number of users and attempts per day. It is important to stress that these rates are only relative, since the proportion of mountain bikers that use Strava is unknown, but it is assumed that the proportion doesn’t change significantly at different trails in close proximity.

Table 5 shows the selected segments and the numbers of users and attempts. The entire loop segments were used for Emma Long and Slaughter Creek. Multiple segments were chosen for Walnut Creek and Barton Creek, since there are many access points and interconnecting trails. A short segment that leaves the main parking lot at Walnut Creek had the highest numbers of attempts, users, and rates. This approximately 500-meter section has had 45,270 attempts as of July 25th 2017, with an average of 40 riders per day since March 30, 2017. The full loop at Walnut Creek showed much lower rates, but because of the diversity of routes available resulting from numerous cut-throughs and short-cuts. A segment of Barton Creek that trail users must cross shows the highest total attempts at 13,635 with an average of seven attempts per day. Slaughter Creek Trail had the next highest total attempts with a total of 11,359 attempts, but a higher rate of 15 attempts per day. Emma Long has the lowest rates with 3460 attempts and an average of 2.6 attempts per day. The averages per day are only a relative estimate and do not represent actual use trends, because traffic is higher on the weekends and it also varies seasonally and with weather These rates and number of attempts are only relative because many users don’t use Strava. These rates of use are in accordance with the author’s observations about each trail system.

Table 5. Strava segment user rates in study area

| Trail System | Strava Segment Name | Type | Length | Attempts 3/30/17 | Users 3/30/17 | Attempts 7/25/17 | Users 7/25/17 | Attempts/ Day | New Users/Day | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| Emma | Emma Long Full Loop from Parking Lot | bike | 5.6 | 3152 | 672 | 3460 | 718 | 2.6 | 0.4 | Loop, one direction |
| | | | | | | | | | | |
| SCP | Slaughter Creek Trail - Updated | bike | 4.8 | 9577 | 1127 | 11359 | 1356 | 15.2 | 2.0 | Loop, one direction |
| | Slaughter Creek Trail 5 Mile | run | 4.9 | | | 926 | 206 | 7.9 | 1.8 | |
| | | | | | | | | | | |
| Walnut | Walnut Creek Intermediate Loop | bike | 8.5 | 3673 | 684 | 3797 | 724 | 1.1 | 0.3 | |
| | Walnut Creek Full Loop | bike | 8.9 | 3701 | 666 | 3842 | 696 | 1.2 | 0.3 | |
| | Puncher's Demise | bike | 0.3 | 40647 | 3373 | 45270 | 3705 | 39.5 | 2.8 | First section out of parking lot, good indiactor |
| | Point 6 | run | 0.4 | | | 1050 | 315 | 9.0 | 2.7 | |
| | | | | | | | | | | |
| BCGB | Greenbelt - Mopac to Pumphouse | bike | 0.5 | 7942 | 1573 | 8539 | 1679 | 5.1 | 0.9 | oposing direction pair |
| | Pump House Exit to MoPac | bike | 0.4 | 8300 | 1363 | 9151 | 1453 | 7.3 | 0.8 | oposing direction pair |
| | Top o' Elephant's Butt to Seismic Wall | bike | 0.3 | 8101 | 1732 | 8973 | 1909 | 7.5 | 1.5 | |
| | Sue me Schumi | bike | 0.4 | 12804 | 2089 | 13635 | 2252 | 7.1 | 1.4 | Must-use section, good indicator |
| | Barton Creek Greenbelt Trail Climb | run | 0.2 | 3312 | 915 | 3950 | 1079 | 5.5 | 1.4 | |
| | | | | | | | | | | |
| Quest | Fast turns | bike | 0.5 | 169 | 35 | 177 | 37 | 0.07 | 0.02 | |

# VI. ENVIRONMENTAL FACTORS RESULTS

## Trail System Variability

Some variability existed among the trail sites. This section will detail the variations between the study sites including the pilot study site where data compatibility allows. Table 5 show how trail conditions varied between the trail sites. Trail width was greatest at Barton Creek Greenbelt with a mean trail width of 175 cm. Emma Long and Walnut Creek were similar (131 cm and 143 cm) and Slaughter Creek (71 cm) had the narrowest trails. Trail Depth was greatest at Emma Long because of the motorcycles with a mean trail depth of 14.4 cm. Walnut Creek and Barton Creek Greenbelt (14 cm and 13.6 cm) were in a close second and Slaughter Creek had the shallowest trails (9.8 cm) and Quest (the pilot study) had the least depth at 2.4 cm.

Table 5. Descriptive statistics for variables by trail sites.

| | | ***BCGB*** | ***Emma*** | ***Nut*** | ***SCP*** | ***Quest*** |
|---|---|---|---|---|---|---|
| **Depth (cm)** | Mean | 13.6 | 14.4 | 14.0 | 9.8 | 2.4 |
| | Median | 11.0 | 14.0 | 9.0 | 8.5 | 1.9 |
| | Std. Dev. | 11.4 | 5.6 | 14.9 | 5.7 | 1.4 |
| **Width (cm)** | Mean | 175.6 | 130.8 | 142.7 | 71.0 | 107.0 |
| | Median | 190.0 | 127.5 | 140.0 | 66.0 | 115.0 |
| | Std. Dev. | 69.6 | 32.2 | 38.9 | 27.3 | 34.7 |
| **Width to Depth Ratio** | Mean | 18.2 | 10.8 | 14.5 | 10.4 | 49.6 |
| | Median | 15.2 | 9.1 | 13.8 | 7.4 | 42.1 |
| | Std. Dev. | 21.8 | 5.9 | 6.0 | 8.7 | 28.1 |
| **Slope (degree)** | Mean | 9.0 | 7.0 | 5.1 | 2.8 | 2.2 |
| | Median | 7.4 | 6.5 | 4.1 | 2.1 | 1.8 |
| | Std. Dev. | 7.2 | 2.4 | 3.5 | 1.8 | 2.0 |
| **Flow Accumulation (# cells)** | Mean | 88.5 | 17.8 | 26.9 | 13.7 | 21.5 |
| | Median | 9.0 | 6.0 | 2.0 | 4.0 | 2.5 |
| | Std. Dev. | 325.7 | 40.7 | 67.3 | 22.3 | 85.9 |
| **Chain Length Roughness (ratio)** | Mean | 97.0 | 98.3 | 98.7 | 97.5 | - |
| | Median | 98.3 | 98.5 | 99.0 | 97.6 | - |
| | Std. Dev. | 2.6 | 1.0 | 0.4 | 1.4 | - |
| **Bulk Density Adjacent to Trail (kg/cm^2)** | Mean | 0.82 | 0.86 | 0.76 | 0.79 | - |
| | Median | 0.89 | 0.83 | 0.85 | 0.83 | - |
| | Std. Dev. | 0.21 | 0.15 | 0.21 | 0.23 | - |
| **Bulk Density Center of Trail (kg/cm^2)** | Mean | 1.16 | 1.23 | 1.34 | 1.16 | - |
| | Median | 1.14 | 1.20 | 1.31 | 1.12 | - |
| | Std. Dev. | 0.09 | 0.07 | 0.18 | 0.23 | - |

Recall that paired, center-of-trail and adjacent-to-trail, bulk density samples were gathered at selected samples sites. The adjacent-to-trail bulk density is similar on average for each of the sites, but Walnut Creek and Slaughter Creek had a relatively wider range and the lowest sampled bulk densities. Barton Creek Greenbelt had the highest average and the lowest standard deviation of adjacent bulk density samples. Walnut Creek trail has the highest average, the widest range, and the biggest difference between center and adjacent samples. Slaughter Creek has the highest overall data point, the mean of Slaughter Creek is equal to Barton Creek Greenbelt. Emma Long has the second highest center-of-trail bulk density and a very narrow standard deviation. Slaughter Creek has the roughest sample sites on average, and Barton Creek Greenbelt had the greatest range of values as approximated by the chain method. Flow accumulation values at the study sites varied. Barton Creek Greenbelt sites had the greatest flow accumulation followed by Walnut Creek, then Quest, Emma Long, and Slaughter Creek Preserve with the least flow accumulation. Emma Long and Slaughter Creek are both located at the top of a watershed, whereas Barton Creek Greenbelt trails are located parallel to Barton Creek.

## **Terrain Variability and Sensitivity**

Terrain variability was evaluated by comparing spatial data sets as independent variables to trail condition (dependent) variables from point sampling stations. This analysis show which terrain units are more sensitive to impacts. The relationships between trail condition and soil classifications are visualized in Figures 13-18. Trail width and depth were compared to surface texture (Figure 13). Trail depth, at this scale of analysis, does not correlate with surface texture. Trails in clayey soils are generally narrower, whereas coarser gravely soils produce wider trails. This result is likely because of the relative mobility rates of gravel on the surface in contrast to compacted cohesive clay particles. Gravel surface trails also produce a less well-defined ideal line amongst the trail surface, whereby riders may choose slightly different lines when traversing the trail. Choosing "lines" is an important concept for mountain biking, because a rider can take multiple paths within the trail surface. Because trails range from about 70 to 175cm in width, and a bike tire is typically about 4-5cm in with, there are multiple lines a rider can choose. A skilled rider will choose the smoother line.

Soil hydrologic group seems to influence trail widths and depths (Figure 14). These groups describe run-off and infiltration capacity. Group A is defined by low runoff and high infiltration capacity, Group B is moderate infiltration and drainage, Group C is low infiltration, and Group D has the highest runoff potential with high and perched water tables or nearly impervious clays. This analysis suggests that higher run-off potential (Group D) may lead to deeper and narrow trails. This trend may be explained by observations by Wallin and Hardin (1996) about the influence of overland flow as a secondary erosive force on trail surfaces. If an area is more likely to experience overland flow, the flow may concentrate on the trail surface and result in downcutting, similar to a stream in a confined channel. Hydraulically, the slight depression that is the trail surface initiates rill development. The sample sizes between the four hydrologic groups (A, B, C, D) are inconsistent and call for further research.

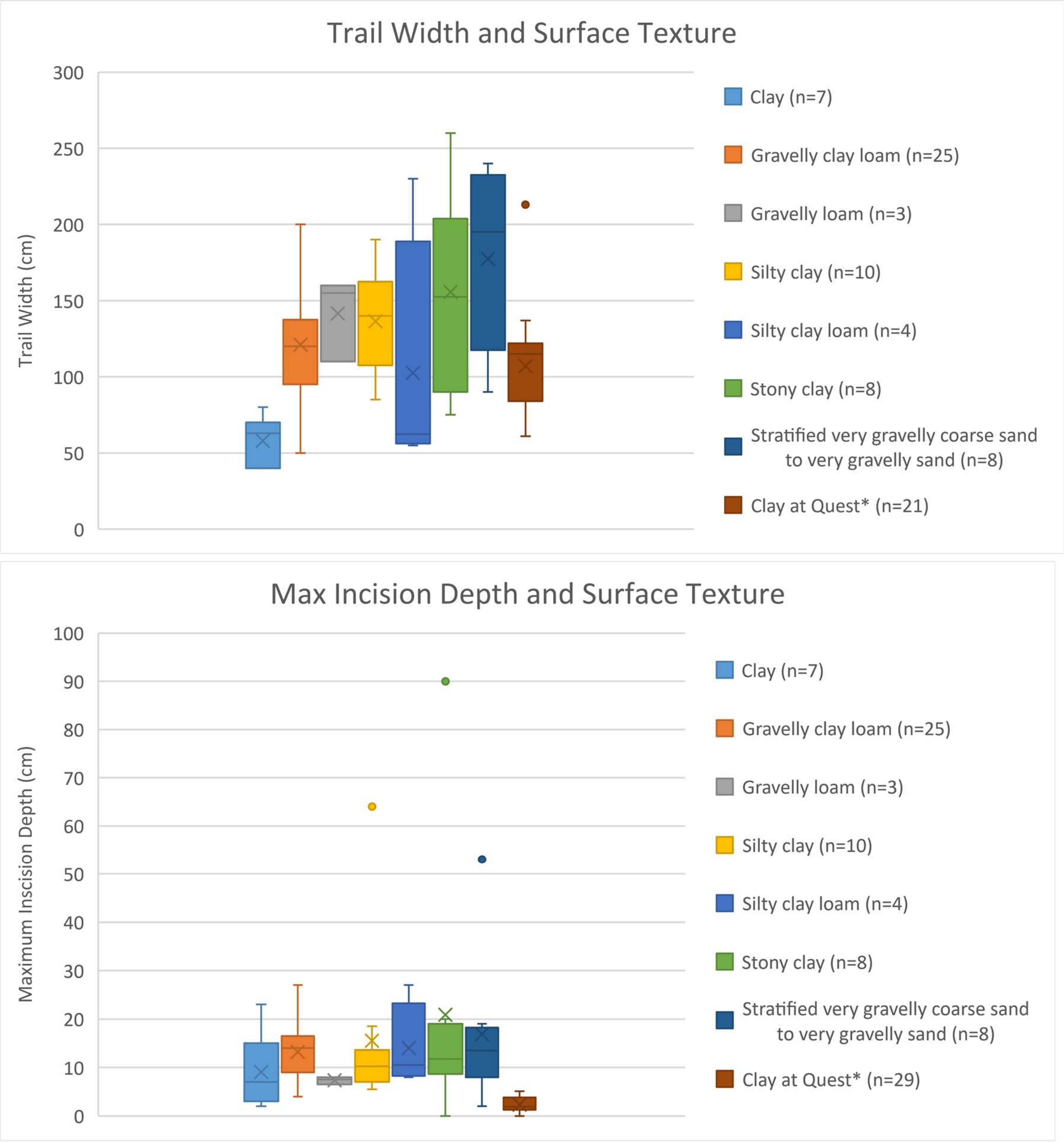
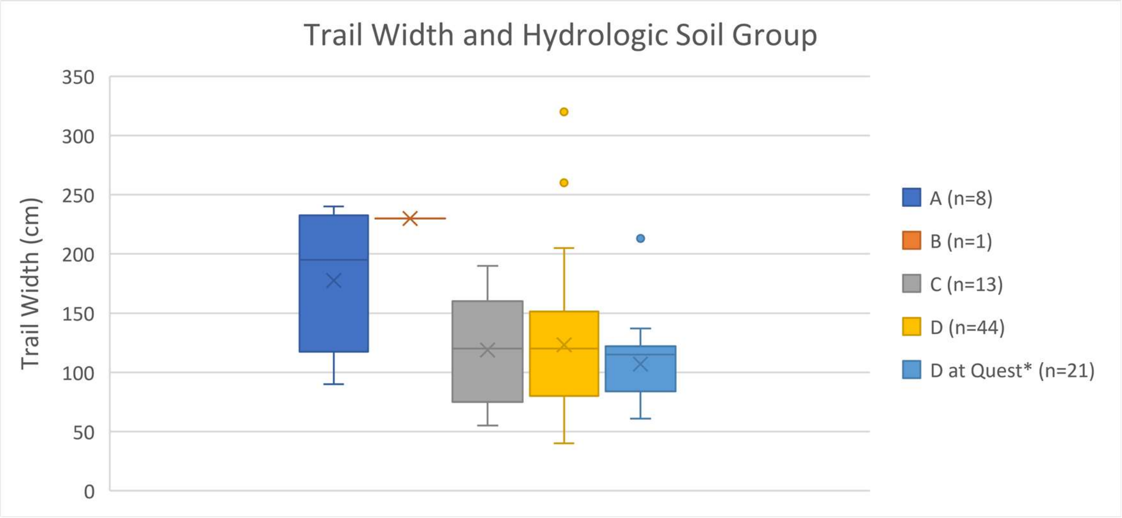


Figure 13. Surface texture and trail width and depth.



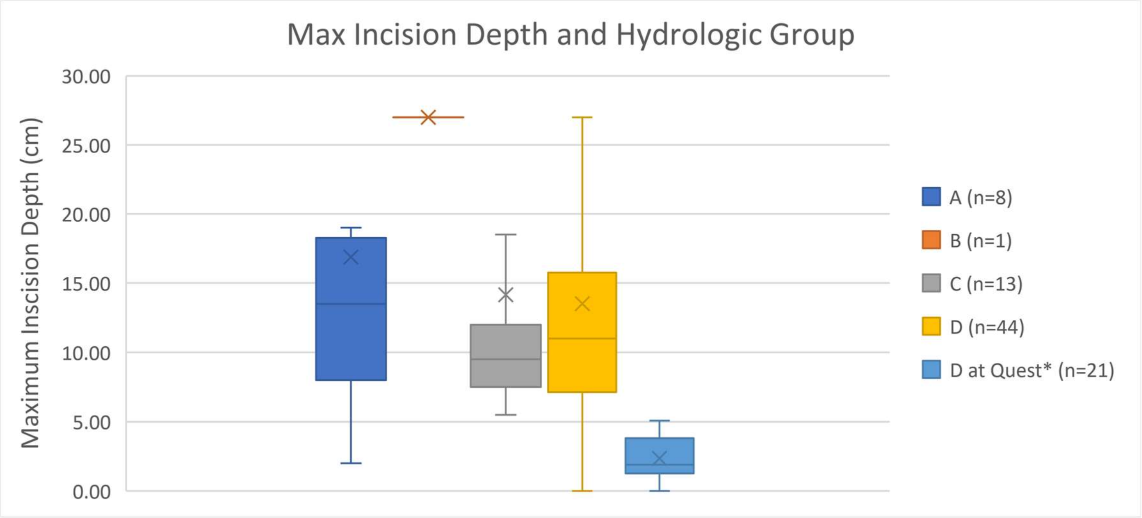


Figure 14. Hydrologic group and trail width and depth

Ecoregions are described by the Texas Parks and Wildlife Ecological Monitoring Systems (TPWD MoRAP TNRIS 2016), as being a combination of vegetative land cover and abiotic variables. The downloaded shapefiles give two classifications; one is the landcover described by dominant canopy type (Common Name), and the second is an ecological description of soil types (Econame). Tables 7 and 8 give descriptions of each of the categories used for both spatial datasets.

The terminology; "Common Name" and "Econame" were the designations given in the downloaded data, so they will also be used in this report. The Econame soil descriptions should not be confused with the surface texture soil descriptions. The "Econame" soil classifications include soil type and organic composition. The several clayey soils; Adobe, Blackland, Clayey Loam, and Clayey Bottomland all exhibit narrower trampled trail widths when compared to relatively coarser Loamy Bottomland and Steep Rocky (Figure 15). This confirms the previously documented effect that surface texture seems to have on trail widths. The "Common name" vegetation classification does not give any definitive insight into influence of plant communities on trail conditions. It is most probable that the scale and resolution of vegetation analysis is too coarse. The relationship between vegetation type and trail condition has been rigorously documented by many researchers, as previously noted. The results presented here (Figure 16) suggest that trail morphology might not vary drastically between different ecological units, meanwhile inter-community variation exists, as seen in the pilot study. Slight evidence exits that hardwood areas produce narrower trails than coniferous areas, and areas with Ashe Junipers have deeper trails than other areas.

Table 7 – Definitions of Common Name categories (TPWD MoRAP TNRIS 2016).

| Common Name | Description from TEAMS |
|---|---|
| Ashe Juniper Motte and Woodland | Common, closed woodlands on limestone uplands on the Edwards Plateau and adjacent ecoregions. *Juniperus ashei* (Ashe juniper) is the clear dominant in the canopy and shrub layer |
| Deciduous Oak / Evergreen Motte and Woodland | intermediate between areas dominated by evergreens *Juniperus ashei* (Ashe juniper) and *Quercus fusiformis* (plateau live oak), and deciduous components *Quercus buckleyi* (Texas Oak), *Quercus sinuata* var. *breviloba* (white shin oak), and *Quercus laceyi* (Lacey oak) |
| Floodplain Hardwood / Ashe Juniper Forest | A mix of deciduous and evergreen canopy species |
| Floodplain Hardwood Forest | Deciduous species dominate the canopy |
| Live Oak Motte and Woodland | Common woodland throughout Edwards Plateau with dominant *Quercus fusiformis* (plateau live oak), typically grass dominates openings between mottes |
| Native Invasive: Deciduous Woodland | Broadly defined, may have one of several species including *Ilex vomitoria* (yaupon), *Liquidambar styraciflua* (sweetgum), *Prosopis glandulosa* (honey mesquite) with other species present |
| Native Invasive: Mesquite Shrubland | *Prosopis glandulosa* (honey mesquite) is dominant with other species present |
| Oak / Ashe Juniper Slope Forest | Forest with slopes greater than 20 percent on rocky sites with co-dominated canopy by *ashei* (Ashe juniper) and one of several deciduous oak species |
| Oak / Hardwood Motte and Woodland | Upland areas with dominant deciduous canopies with *Quercus buckleyi* (Texas oak), *Celtis* spp. (hackberries), and *Ulmus crassifolia* (cedar elm) |

Table 8 – Definitions of Econame categories (TPWD MoRAP TNRIS 2016).

| Econame | Description |
|---|---|
| Adobe | Shallow gravelly clay loams underlain by limestone, with limestone outcrops giving a stair step topography; Low water capacity. |
| Blackland | Clay soils with some silty clay, clay loam, or gravelly clay; High to low water capacity; Prone to sheet, rill, and gully erosion |
| Clay Loam | Shallow soils overlying chalky limestone; low water capacity. |
| Clayey Bottomland | Deep clayey soils along streams; flooded regularly; high water capacity |
| Deep Redland | Deep soils with stony surface and substrate; low to high water capacity |
| Loamy Bottomland | Loamy to sandy bottomlands and low terraces; low to high water capacity |
| Steep Rocky | Very shallow stony and clayey soils in ravines and along steep breaks; low water capacity |

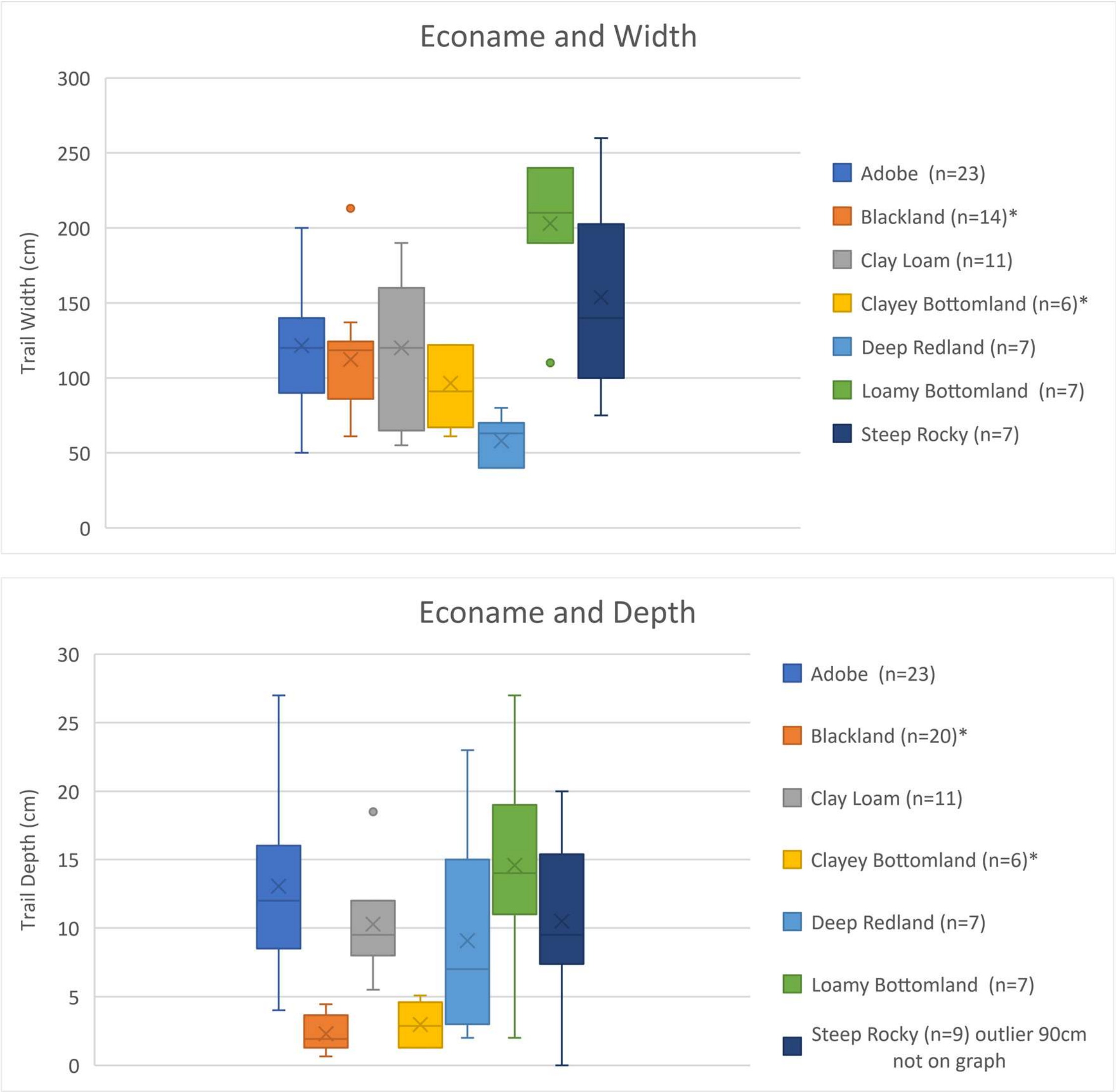


Figure 15. Econame and trail width and depth

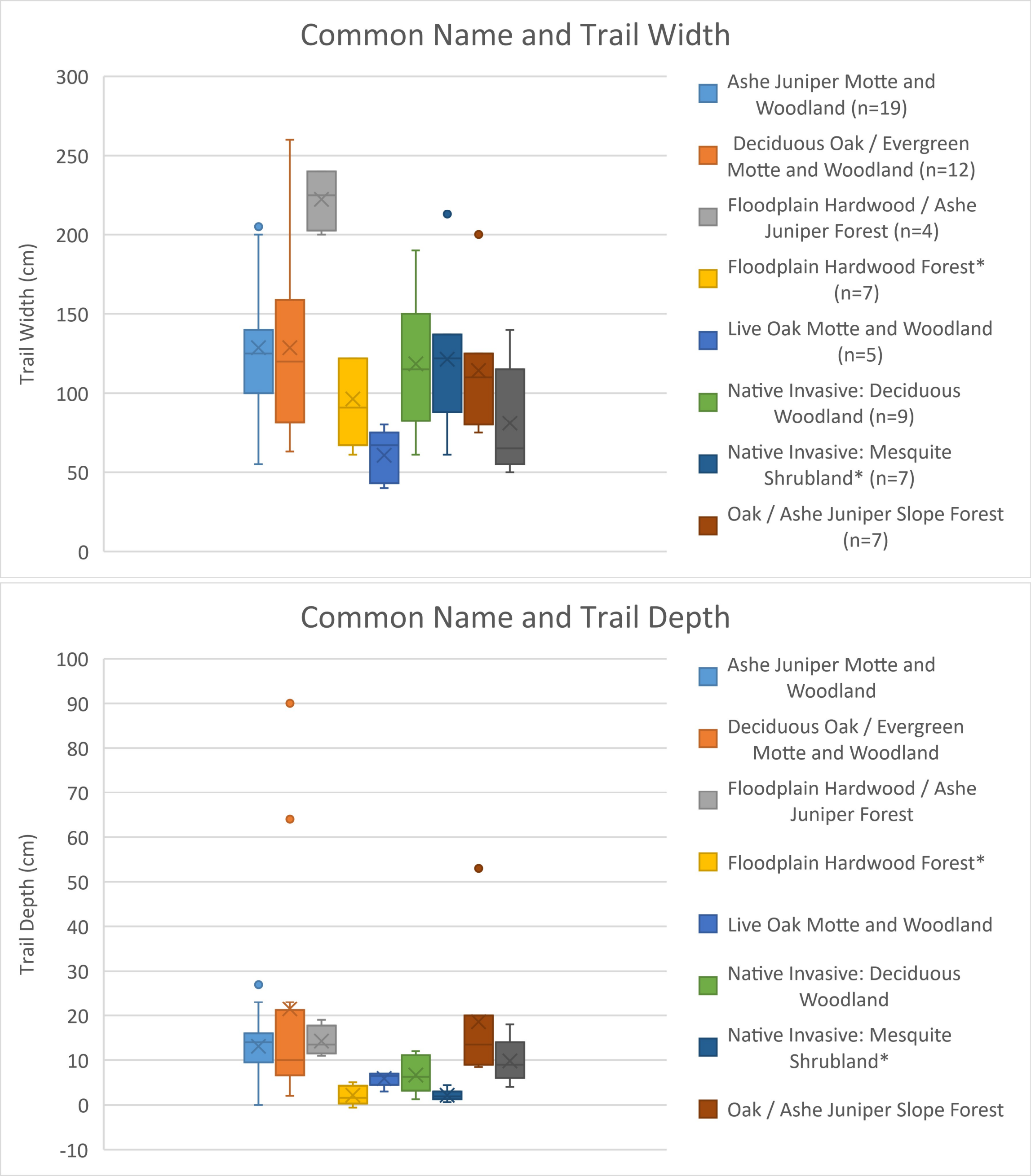


Figure 16. Common name and trail width and depth

Slope and flow accumulation were calculated from a 1/3 arc second DEM. The slope modeling gives the percent hillslope for each grid cell. The flow accumulation modeling assigns each cell with a value representing how many upstream cells flow downstream into the cell. The slope in this case is the overall, or average slope for each cell. This slope is not the trail surface slope which will be discussed in subsequent sections. Slope was compared to width, depth, and the width to depth ratio (Figure 17). Slope is weakly positively correlated with trail depth, and shows no correlation with width (Table 9). This relationship, as visualized in Figure 15 might be best represented by an envelope with linear upper and lower bounds. The minimum widths and depths at a given slope shows a positive linear trend suggesting that slope has some influence on width and depth. The width-depth (w-d) ratio shows that trails with less slope have a wide range of w-d ratio, and as the slope increases the w-d ratios become less and the range of w-d ratios converges. Flow accumulation of grid cells does not provide insight into trail condition (Figure 18). The resolution of the raster (1/3 arc second = ~10 meters) is too coarse when compared to trails widths and depths which are generally sub-meter in scale. It is likely that higher resolution lidar imagery would be better for this type of analysis.

Table 9. Correlation and $r^2$ values for slope and flow accumulation versus width and depth scatter plots in Figures 15 and 16.

| *Correlation r values* | *Depth_cm_* | *Width_cm_* | *Depth/Width* |
|---|---|---|---|
| Slope_degree | 0.39 | 0.04 | -0.31 |
| Flow_accumulation | 0.07 | 0.15 | -0.05 |

| *Trendline r-squared values* | *Depth_cm_* | *Width_cm_* | *Depth/Width* |
|---|---|---|---|
| Slope_degree | 0.154 | 0.002 | 0.098 |
| Flow_accumulation | 0.005 | 0.022 | 0.002 |

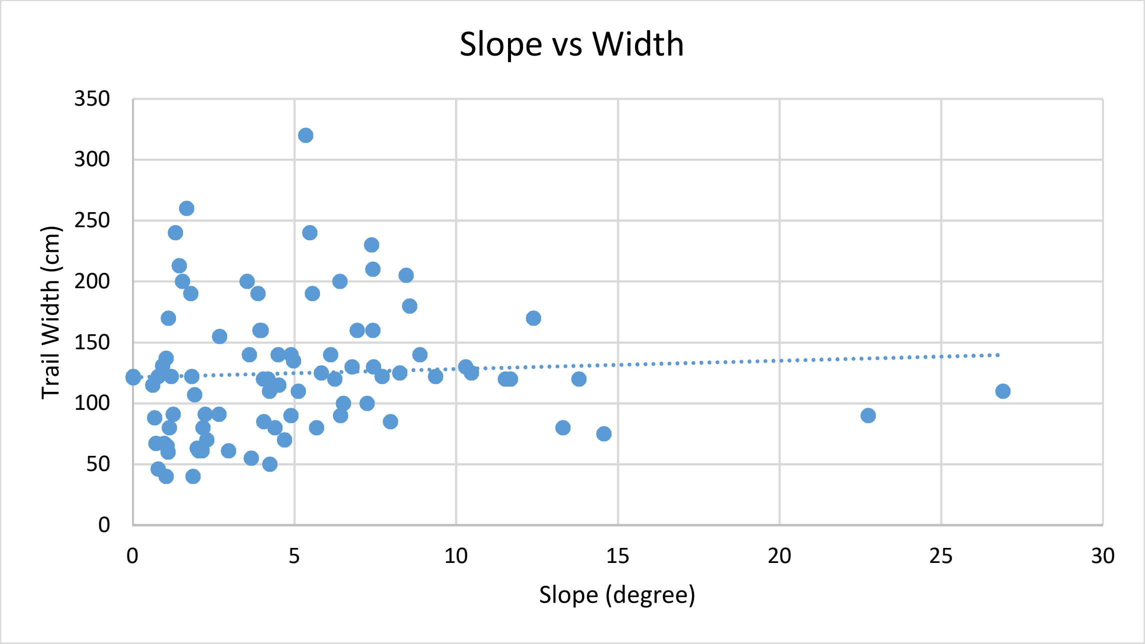


Figure 17a. Slope and trail width scatter plot

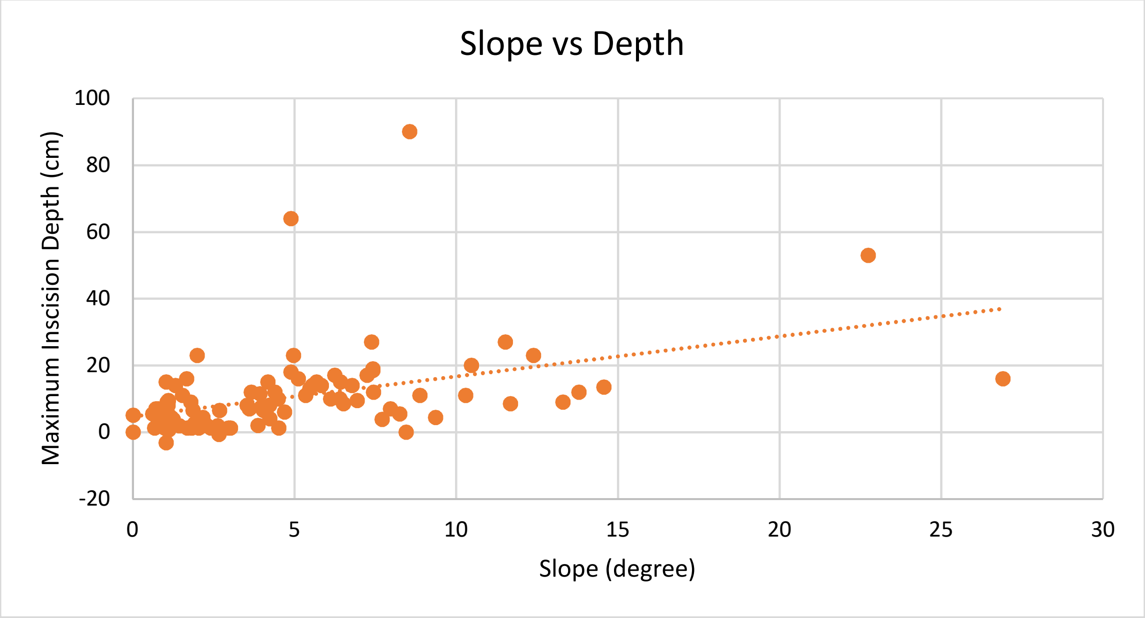


Figure 17b. Slope and trail depth scatter plot

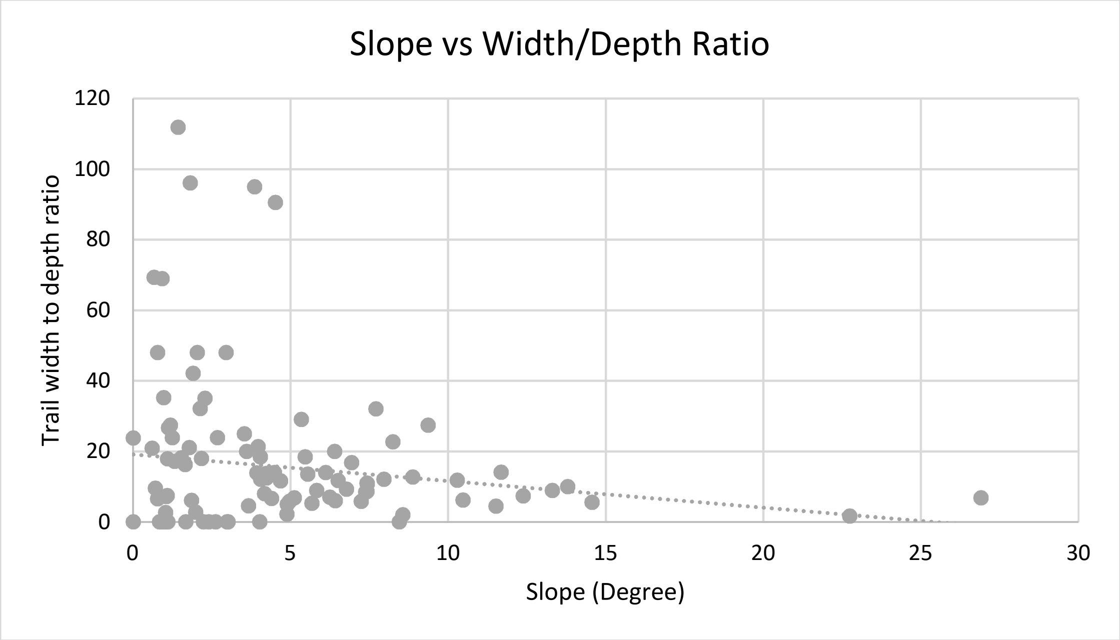


Figure 17c. Slope and trail width/depth ratio scatter plot

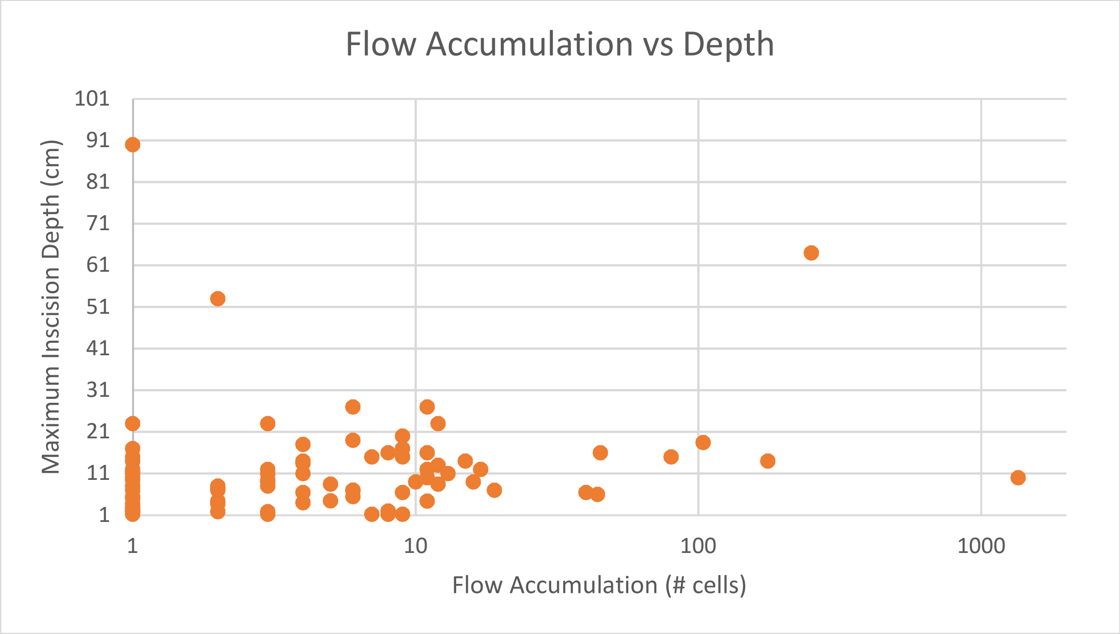


Figure 18a. Flow accumulation and trail depth scatter plot

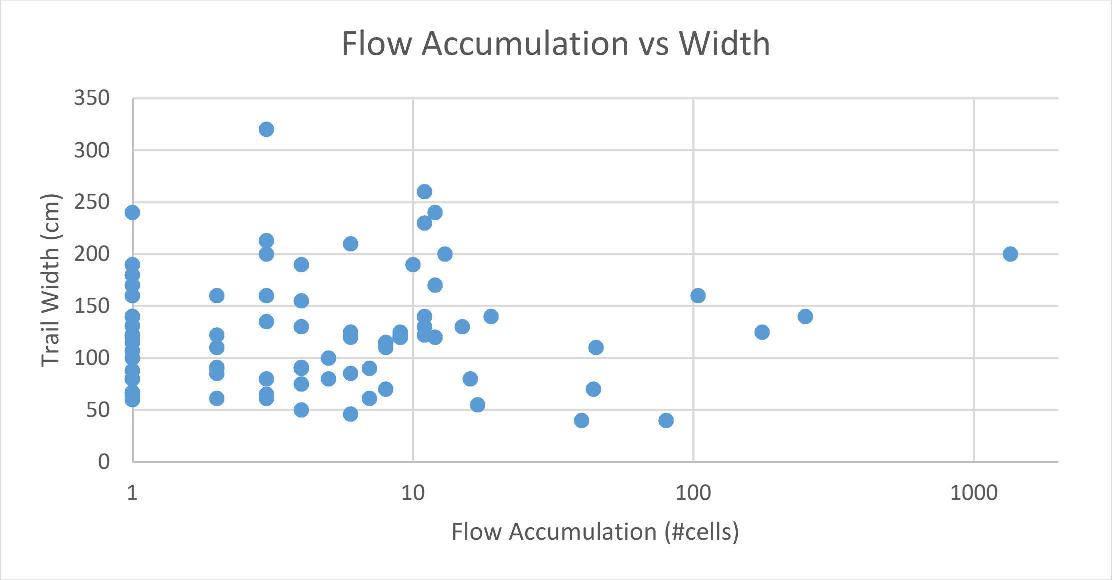


Figure 18b. Flow accumulation and trail width scatter plot

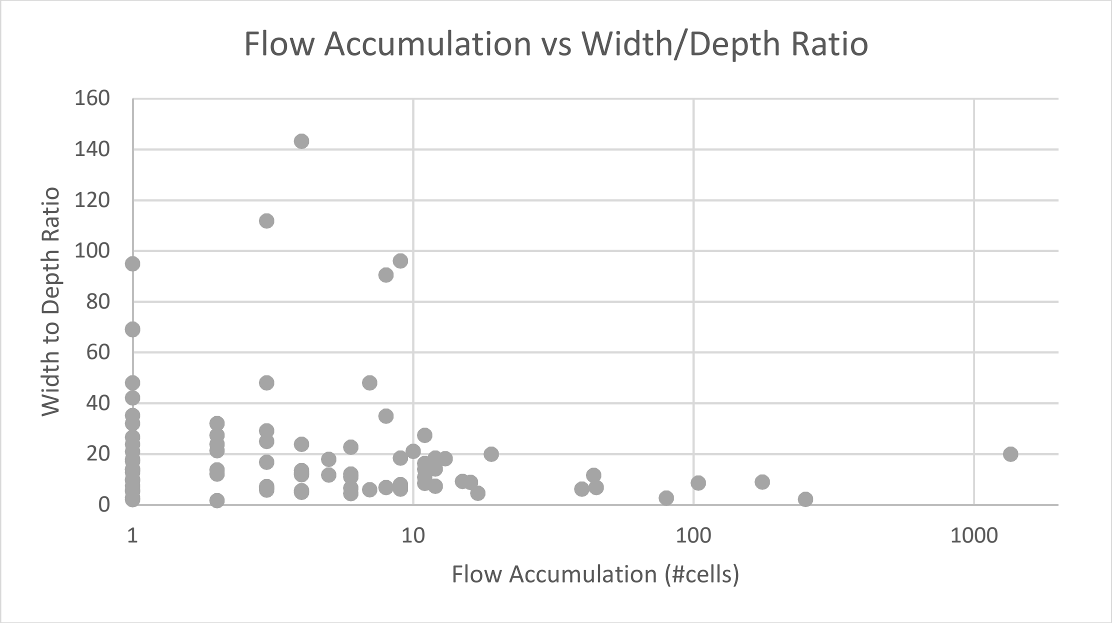


Figure 18c. Flow accumulation and width/trail depth scatter plot

# VII. RIDER FORCING RESULTS

The influence of the forces that a mountain biker exerts on the landscape was tested by proxy with three-dimensional g-force measurements. The pilot study suggested that g-forces produced as a mountain bikers traverses terrain are correlated to some trail impacts. Because the pilot study was a unique study of the initial impacts of solely mountain bike use on a trail, here we seek to explore that relationship in the more established multi-use trail systems.

Turn angle, trail surface slope, chain length roughness, and velocity were also considered as rider forcing factors because they each affect how a rider responds and acts on a section of trail. Turns force riders to slow and shift their weight as they lean, and their tires track along two different lines. Slopes are associated with braking when going downhill, and excess torque at the tire when going up-hill, both of which are tractive forces that dislodge sediment and exacerbate erosion. Trail surface roughness is an indicator of soil and geologic conditions, but from a trail user forcing perspective, trail roughness changes the way that the mountain bike interacts with the trail itself. A rougher trail will result in tire and suspension compression and decompression. As the mountain bike tires and suspension vary, so does the rider’s impact. As a mountain bike rider bounces or vibrates along a rough trail surface, the impact to the trail surface varies spatially. The alternative condition, a smooth trail, does not result in a constant alteration of pressure applied to the trail surface because the tires, suspension, and the body of the mountain biker are relatively static.

When the trail systems were analyzed with Pearson Correlations, the degree of correlation between the variables was varied. The initial correlations consisted of width and depth as the dependent variables, with trail surface slope, absolute value of turn angle, velocity (steplength), chain length roughness, and the average, standard deviation, and maximum of the absolute value for each X, Y, and Z g force directions as the independent variables. This analysis produced correlations tables for the combined trail data set and each of the individual trails (see summary Table 9). Using a general rule, potential correlations were assumed to at least have correlation values less than -0.3 and greater than 0.3. For each data set (all trails and individual trails), a secondary analysis which included the creation of scatter plots was conducted for all variables with correlation values less than -0.3 and greater than 0.3 (See Appendix 1 for plots). The scatter plots were used to omit some correlation value because of lack of linearity or homoscedasity. Summary Table 10 shows the final results for all data sets for both complete datasets and those with outliers removed, and only contains correlation values less than -0.3 and greater than 0.3, with less than -0.6 and greater than 0.6 in bold. In the subsequent discussion, "weak" will be used to describe relationships with correlation confections less than -0.3 and greater than 0.3, and "strong" for those less than -0.6 and greater than 0.6.

When all trails were analyzed together and no outliers were removed, trail depth was weakly positively correlated with trail surface slope, and weakly negatively correlated with velocity and chain length roughness. Width was weakly negatively correlated with velocity. This suggests that higher slopes may be associated with increased incision which is logical given that trail incision can channel surface water flow and induce erosion. The negative correlation between velocity and both width and depth suggests that higher speeds are associated with narrower and less incised trails; which can be explained by understanding that at higher speeds the gyroscopic forces associated with wheels are less likely to wander side to side, and braking and excess torque forces are not as pronounced. The weak negative correlation between chain length roughness and depth suggests that rougher trails may be more incised, which is likely because of erosive forces removing fines and partially exposing larger rocks and roots, and sometimes bedrock.

Slaughter Creek Trail width and depth had more strong and weak correlations than any other trail system. Depth was weakly negatively correlated with turn angle and strongly negatively correlated with chain length roughness for analysis with and without outliers removed. With outliers removed, Xavg was weak negatively, and Yavg was weakly positively correlated with depth. Without outliers removed there was a weak positive correlation with Zabmax. Width without outliers was correlated strongly positively with slope, strongly negatively with velocity, strong positively with Zavg, and weakly negatively with chain length roughness. Without outliers removed width correlated strongly positively with Zabmax, weakly negatively with velocity and chain length roughness, and weakly positively with Xstd and Ystd.

Walnut Creek showed several strong correlations. Trail depth was strongly, negatively correlated with velocity, and weakly positively correlated with chain length roughness

when no outliers were removed. Without outliers depth was weakly negatively correlated with Xavg and Xabmax. Width was strongly negatively correlated with Xavg and Xabmax, and weakly correlated with turn angle when outliers were removed. When outliers were not removed, width was weakly correlated with Ystd, Xabmax, and Yabmax.

At Emma Long trail depth, without outliers removed, showed weak negative correlations with velocity and Yabmax, and weak positive correlation with trail surface slope. When outliers were removed, there was a strong negative correlation between depth and chain length roughness, and a weak negative correlation with Yavg. Width at Emma Long was weakly positively correlated with Zavg before outliers were removed, and with outliers removed, weak positive correlated with Xavg and Zabmax.

Barton Creek Greenbelt showed no correlations with depth before outliers were removed. Once outliers were removed, the correlations with depth included a weak positive correlation width and slope, and weak negative correlations between depth and velocity and Yabmax. There was a strong negative correlation between width and slope both with and without outliers. Width was weakly negatively correlated with Xavg and weakly positively correlated with Ystd before outliers were removed. Without outliers, there was a weak negative correlation between width and chain length roughness.

At Quest-ATX, there were weak negative correlations between depth and Xavg, Yavg, and Xabmax, and weak positive correlations between depth and slope, before outliers were removed. Once outliers were removed depth was weakly negatively correlated with Xavg. Width was weakly positively correlated with Zavg and weakly negatively correlated with Xabmax, with outliers removed.

Slope correlated with depth when all trails were combined, and at Emma Long, Barton Creek, and Quest. Slope correlated with width at Slaughter Creek and Barton Creek both of which were strong correlations. Turn-angle correlated with depth at

Slaughter Creek and Barton Creek, and with width at Walnut Creek. Velocity correlated with depth when all trails were combined, at Walnut Creek, and Emma Long. Velocity correlated with width when all trails were combined, and at Slaughter Creek. Chain length roughness correlated with depth when all trails were combined, at Slaughter Creek, Walnut Creek, and Emma Long. Chain length roughness correlated with width at Slaughter Creek and Barton Creek Greenbelt.

The correlations with G-forces included: Xavg with depth at Slaughter Creek, Walnut Creek, Barton Creek, and Quest; Xavg with width at Walnut Creek and Emma Long; Yavg with depth at Slaughter Creek, Emma Long, Barton Creek, and Quest; Zavg with width at Slaughter Creek, Emma Long, and Quest; Zavg with depth at Barton Creek; Xstd with width at Slaughter Creek; Ystd with width at Slaughter Creek, Walnut Creek, and Barton Creek; Xabmax with width and depth at Walnut Creek and Quest; Yabmax with width at Walnut Creek, and depth at Emma Long; Zabmax with width at Slaughter Creek and Emma Long, and with depth at Slaughter Creek.

General observations about the correlations results may yield some insight. Slaughter Creek trail had the most weak and strong correlations with 17 total including both analysis with and without outliers removed. Walnut Creek and Barton Creek Greenbelt had 10 correlations each, although the variables correlated varied. Emma Long had eight and Quest had seven. Unexpectedly, all of the trails combined produced fewer and weaker correlations that any of the individual trails. This effect could be a result of the Simpson’s Paradox, where aggregate statistics differ from analysis at a finer scale (Wagner 1982).

Some independent variables were more consistently correlated that others. Xavg and Yavg were correlated with depth at four of the five trail systems. Chain length roughness was correlated with depth when all trails were considered and at three of the five trails, and width at two trails. Slope was correlated with depth when all trails were considered, and at three of the five trails.

Table 10. Summary correlation table, cont. Bold indicates strong correlation greater than 0.6.

| | | | Slope (degree) | Turn Angle (absolute value degree) | Step Length (velocity) | Chain Length Roughness |
|---|---|---|---|---|---|---|
| All Trails | Depth | All | 0.42 | | -0.45 | -0.45 |
| | | No outlier | | | | |
| | Width | All | | | -0.32 | |
| | | No outlier | | | | |
| Slaughter Creek | Depth | All | | -0.42 | | **-0.67** |
| | | No outlier | | -0.36 | | **-0.58** |
| | Width | All | | | -0.45 | -0.49 |
| | | No outlier | **0.65** | | **-0.78** | -0.42 |
| Walnut Creek | Depth | All | | | **-0.79** | 0.33 |
| | | No outlier | | | | |
| | Width | All | | | | |
| | | No outlier | | 0.30 | | |
| Emma Long | Depth | All | 0.42 | | -0.49 | |
| | | No outlier | | | | **-0.62** |
| | Width | All | | | | |
| | | No outlier | | | | |
| Barton Creek Greenbelt | Depth | All | | | | |
| | | No outlier | 0.31 | 0.36 | | |
| | Width | All | **-0.70** | | | |
| | | No outlier | **-0.60** | | | -0.31 |
| Quest | Depth | All | 0.32 | | | |
| | | No outlier | | | | |
| | Width | All | | | | |
| | | No outlier | | | | |

Table 10, continued. Summary correlation table, cont. Bold indicates strong correlation greater than 0.6.

| | | | X avg | Y avg | Z avg | X std | Y std | Z std | X abmax | Y abmax | Z abmax |
|---|---|---|---|---|---|---|---|---|---|---|---|
| All Trails | Depth | All | | | | | | | | | |
| | | No outlier | | | | | | | | | |
| | Width | All | | | | | | | | | |
| | | No outlier | | | | | | | | | |
| Slaughter Creek | Depth | All | | | | | | | | | 0.33 |
| | | No outlier | -0.39 | 0.43 | | | | | | | |
| | Width | All | | | ***-0.70*** | 0.33 | 0.37 | | | | **0.64** |
| | | No outlier | | | ***0.66*** | | | | | | |
| Walnut Creek | Depth | All | | | | | | | | | |
| | | No outlier | -0.31 | | | | | | -0.35 | | |
| | Width | All | | | | | -0.42 | | -0.44 | -0.36 | |
| | | No outlier | **-0.69** | | | | | | **-0.70** | | |
| Emma Long | Depth | All | | | | | | | | -0.31 | |
| | | No outlier | | -0.51 | | | | | | | |
| | Width | All | | | 0.55 | | | | | | |
| | | No outlier | 0.36 | | | | | | | | 0.36 |
| Barton Creek Greenbelt | Depth | All | | | | | | | | | |
| | | No outlier | 0.31 | **0.61** | -0.50 | | | | | | |
| | Width | All | -0.49 | | | | 0.35 | | | | |
| | | No outlier | | | | | | | | | |
| Quest | Depth | All | -0.44 | -0.40 | | | | | -0.32 | | |
| | | No outlier | -0.38 | | | | | | | | |
| | Width | All | | | | | | | | | |
| | | No outlier | | | -0.30 | | | | 0.38 | | |

# VIII. DISCUSSION AND CONCLUSIONS

This study shows that mountain bike trail morphology is influenced by both environmental factors and user generated forces. This research project can begin to define a conceptual framework about the interplay between mountain bike trails and environmental conditions. More research is needed, but this type of framework can be used to inform land managers and trail stewards. This project also provides “proof of concept” for the utility of these research methods, most prominently, that g-force measurements are valuable data about forces generated by mountain bikes. In addition to providing insight about the processes that drive mountain bike trail morphology in the Austin area, this project begins to define a framework that can be applied to other areas, and it provides accessible methods for future research. While the accelerometer methods need more development to be used in any management capacity, the spatial data comparisons to trail width and depth could easily be applied to many other locations. The accelerometer methodology may show more response and significant findings on mountain bike only trails since the “signature” of a mountain bike on a landscape is likely to be more prevalent, but more research is need to establish its utility. The spatial data such as vegetation cover and soil characteristics will influence the morphology of any trail, so these methods could be applied to multi-use or single use trails.

From the Pilot Study, we learned grasses are more resistant to trampling and it appears that their root structure limits compaction and erosion (i.e. loss of cross-sectional area). The finding that grasses are more resistant and resilient to trampling is supported by the literature, however this research project suggests that the resistance of grasses to trampling plays a role in trail morphology. This presents a biogeomorphic system where mountain bikers induce soil compaction and erosion, but the extent to which bikers can induce change is mitigated by vegetation. As discussed previously, trail compaction creates depressions in the ground surface, which can become conduits for overland flow. This adds to the tiered geomorphic effect of mountain biking. Since the vegetation type plays a role in compaction and change in cross-sectional area, vegetation may be determinant in the capacity of a trail to channelize overland flow. Overland flow results in fluvial erosion and transport (Martin 2016), which leads to another tier or layer, that being the initial impact creating conditions for different geomorphologic processes. The reduction in vegetation and the channelization of flow can induce or allow both aeolian and fluvial erosive processes.

For the Main Study, ecological units and soil types from publicly available GIS data sets instead of photograph interpretations as in the pilot study, show that environmental conditions play an important role in trail morphology. Soil type and texture are important factors. Finer grains result in smoother trails, which allows mountain bikers to hold a steadier line. Rougher and rockier trails provide more obstacles which force riders to choose multiple lines, which results in wider trails as people ride around rocks and roots. Additionally, gravelly or rocky trail surfaces are prone to particle movement, in contrast to clay trail surfaces that compact. Hydrologic group D, which has high runoff potential, is linked to increased width. Clay and steep slopes can both contribute to runoff potential. This research shows that slope is also associated with trail incision. High runoff in an incised trail yield the tiered impact of fluvial erosion. The ecological unit analysis shows that trail morphology varies some among ecological units (common name). However, the analysis does not reveal any processes or causal factors. An interesting finding about ecological units comes from the potential for induced landcover change in Slaughter Creek Preserve. Prescribed burns seek to change Ashe Juniper forests to native Live Oak motte interspersed with grasslands. According to the ecological unit analysis, this landcover change could result in conditions favorable to narrower and shallower trails.

The user generated forcing results showed that rider forces are correlated with trail morphology. As a proof of concept, this analysis was successful, and shows that user forcing is associated with trail morphology. However, more research is needed to understand the influence of rider skill and mountain bike style on g-forces. The results from rider-generated forcing can be interpreted two ways. One is to evaluate the variables with high correlations, and the other is to evaluate which trails had higher correlations. In evaluating the variables that seemed to be most influential, the average g-force in the X was correlated with trail morphology at each trail, whereas the Y and Z directions were correlated at each trail except Walnut Creek. This suggests that with more research, accelerometers like the Garmin Virb could be valuable tools to predict trail impact. As suggested in the environmental analysis, trail roughness was correlated with morphology, as was trail surface slope. The results are not conclusive, but suggest that in areas of flatter areas with higher velocity the trail is less likely to be incised and more likely to be narrow, than in sloped areas with slower velocities. This may seem counterintuitive, but one must consider the mountain bike wheel as a gyroscope, if rotational velocities are higher it requires more force to make the bike attached to the wheel deviate from its path. Additionally, it is supported by earlier research that observed higher erosion because of braking and when going uphill, two actions associated with slower movements. The increased torque while climbing, even on low grades, and the increased tractive forces associated with braking result in sediment movement, erosion, and evidently increased trail incision. In summation, the following guidelines are suggested for future trail building and trail management actions in the Austin, Texas region:

- Route trails in grass rather than herbaceous or forb type vegetation
- If trail widening is a concern avoid rocky terrain and low-lying clay areas that may accumulate water.
- Avoid steep slopes especially when soils have high runoff potential.
- Avoid areas with poor soil development and/or little surface vegetation that are more prone to erosion.
- Take user generated forces into account.
    - Avoid features that slow or interrupt the flow of bikers in sensitive terrain.
    - Avoid downhill sections that require intense braking.
    - Avoid trails on loosely consolidated slopes.

If considering the political history of each trail with the user generated forces, some interesting hypothesis and interpretations emerge. Slaughter Creek trail has more weak and strong correlations between width and depth and the various user generated forces. Slaughter Creek is also the youngest trail (besides the pilot study) and it gets the most concentrated mountain bike activity. It seems like because of these circumstances, the ‘signature’ of mountain bike impact is most apparent. Emma Long had few correlations, but motorcycles provide the predominant impact. Motorcycle impact is similar to mountain bike impact, but more exaggerated because of increased power, torque, and weight, and therefore the motorcycle impact outweighs that of mountain bikes. The pilot study had the fewest and weakest correlations, but it was a new trail, and the process of trail alteration by mountain bike had just begun. Barton Creek showed correlations with slope, but lacked many strong correlations with the g-force data. This finding is likely because of the overwhelming impact of pedestrians along the trail. Walnut Creek had fewer correlations with turn angle and velocity, but showed several correlations with g-forces. On trails with mountain bike specific features such as Walnut Creek, berms are built to allow riders to maintain higher speeds, and the g-forces that go with them, around turns. These trends suggest that in addition to environmental factors and user forces, political dimensions of land management play an important role in trail condition.

Future research could focus on the environmental impacts of trail building and maintenance processes. For example, as the trail steward of Slaughter Creek the author participated in trail work efforts to fill incised trails where roots were exposed. This required moving dirt from one area of the land to the area of concern. Trucks were used to transport the fill material. Thus, the initial impact by the mountain bikers threatened the trees by exposing roots, but the corrective action introduced trampling and likely soil compaction adjacent to the trail in the area of concern. Also, driving trucks across the area and moving the dirt present some impact, therefore trails in sensitive environments present multiple tiers of potential impacts. Another example of how politics influences trail condition, is the concentration of work efforts and financial investment at Walnut

Creek. The trails at Walnut Creek have been built and adjusted especially for mountain bikers, and they are the only trails in the Austin area that offer this. Berms, jumps, and flowy trails are sought after by many riders, and since Walnut Creek is the only trail that readily offers these features it gets a much higher concentration of riders than trails that do not offer those amenities.

Considering these findings in aggregate suggests a framework for understanding trail condition and morphology. Impacts by mountain bikers, and other user types, are realized differently depending on environmental circumstances. Variations in soil type and texture, vegetation types, and topography result in different trail morphologies. Impacts and alterations of the trail surface can induce secondary geomorphic processes; including overland flow and erosion, and aeolian erosion when dry. Trail surface slope and curvature are an effect of trail building, layout, and planning; a socio-political system. Maintenance and management paradigms impact trail conditions by controlling use rates and which user types are allowed on trails. Impacts by mountain bikers, in particular, do not seem to be greater in scale than impacts imposed by management decisions. This study cannot make a distinction about whether mountain bike impacts are greater than or less than other trail user types, but it does show that trail condition is strongly influenced by both political and environmental factors. This suggests that many degraded trail segments, often blamed on mountain bikers, in realty could be a result of the environmental conditions and the politics surrounding management actions.

## Conclusions

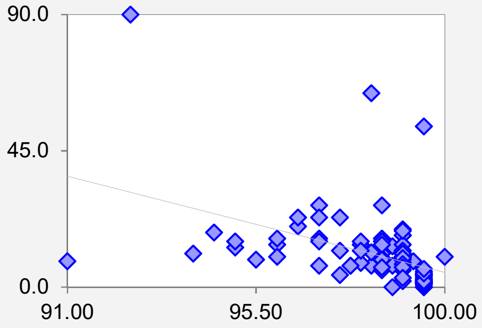
As hypothesized mountain bike trail morphology and condition are dependent on user generated forces and environmental sensitivity. This presents the conditions for a classic biogeomorphologic system. An interplay of biotic (vegetation) and abiotic (soil and sediment) components play an important role in trail morphology. Anthropogeomorphic forces provide the primary mechanism for erosion, which brings a component of direct human agency to geomorphic change. These geomorphic systems are housed in a context of cultural and political intervention in the form of land management and trail maintenance, which presents a topic for future research. Future research could help to understand the relative scale of influence that environmental factors, user impacts, and political management structures have on trail condition and morphology.

Future research should utilize accelerometers on a variety of mountain biker skill sets and styles. This study showed the utility of accelerometers, but future research could vastly improve the utility of these devices by testing sampling intervals and data aggregation methods. Future research should also ground truth spatial vegetation datasets to test the hypothesis that inter-ecological variation (as seen in the pilot study) has a larger impact on morphology than the more generalized ecological units.

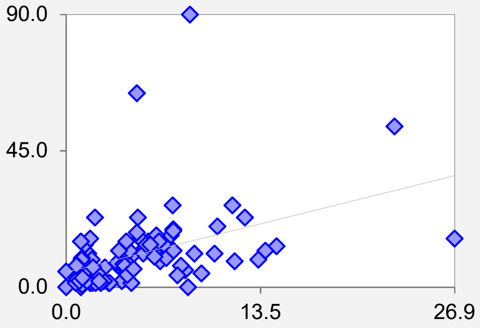
# APPENDIX SECTION

Scatter plots for width or depth with variables that had a correlation value greater than 0.3 or less than -0.3. Plots with light blue background and include outliers, and plots with orange background (darker grey if greyscale) omit outliers.

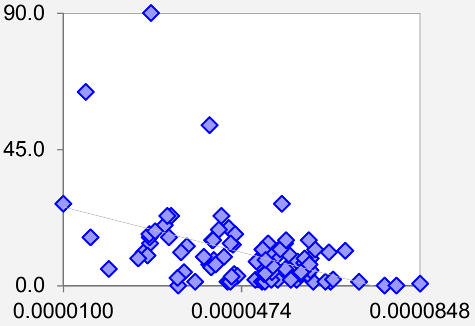
Scatter plots for all trail systems: n=94, including all data (outliers not removed)



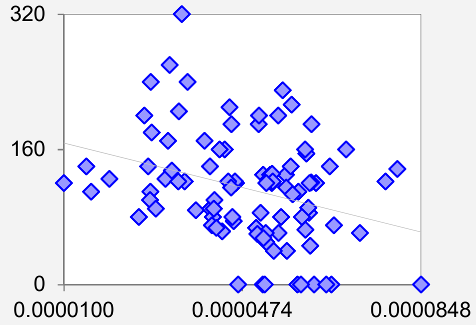
Depth_cm_ vs.
ChainAvg
r = -0.446,  r-squared = 0.199



Depth_cm_ vs.
Slope_degree
r = 0.422,  r-squared = 0.178

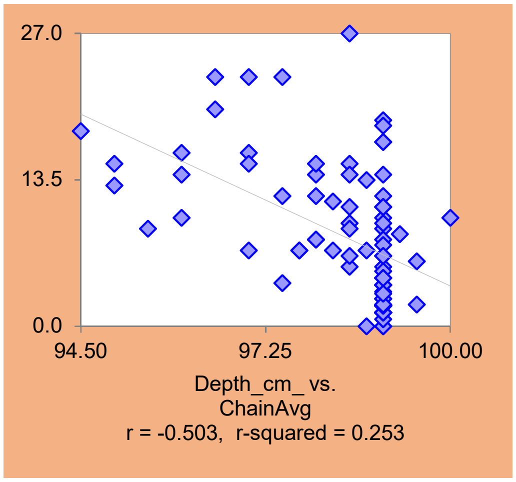


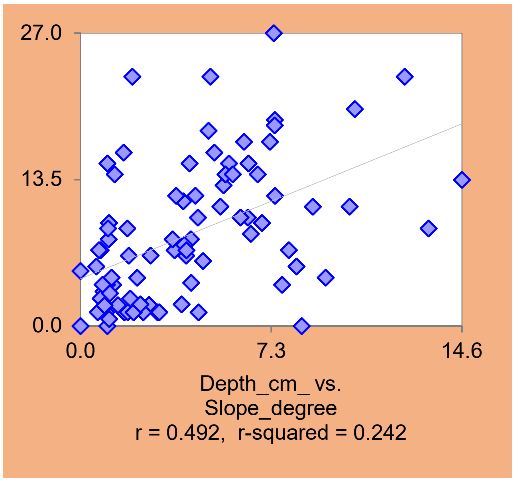
Depth_cm_ vs.
STEPLENGTH
r = -0.453,  r-squared = 0.205

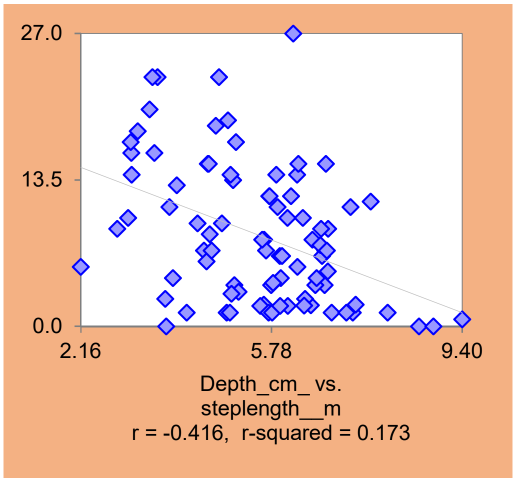


Width_cm_ vs.
STEPLENGTH
r = -0.318,  r-squared = 0.101

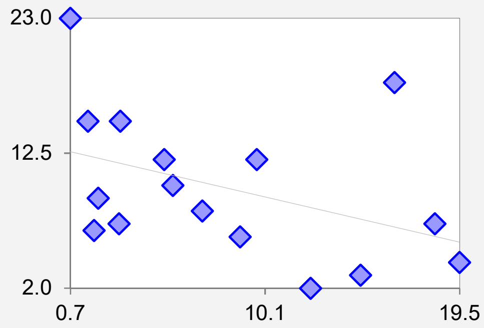
Scatter plots for all trail systems: n=86, with outliers removed.



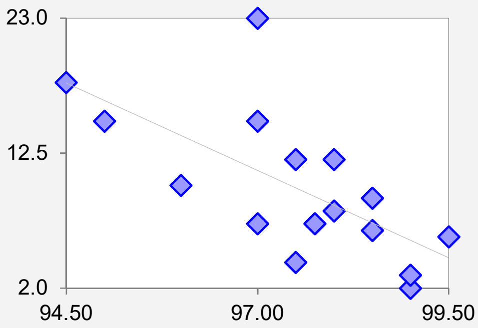




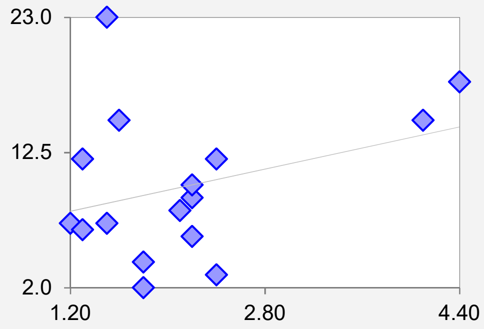
Scatter plots for Slaughter Creek Preserve: n= 16, including all data (outliers not removed)



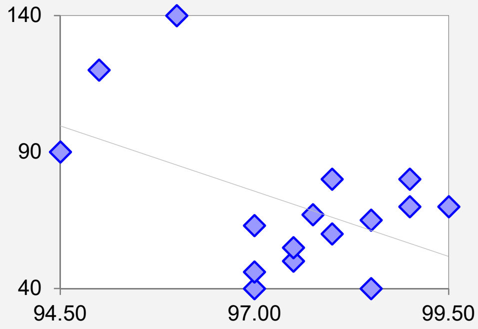
Depth_cm_ vs.
ABS_turnangle
r = -0.416, r-squared = 0.173



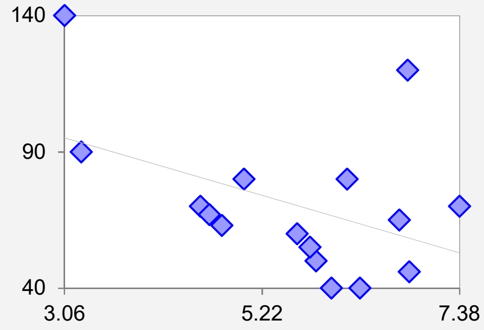
Depth_cm_ vs.
ChainAvg
r = -0.665, r-squared = 0.443



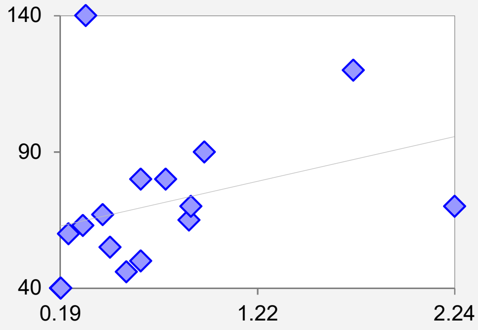
Depth_cm_ vs.
Zabmax
r = 0.330, r-squared = 0.109



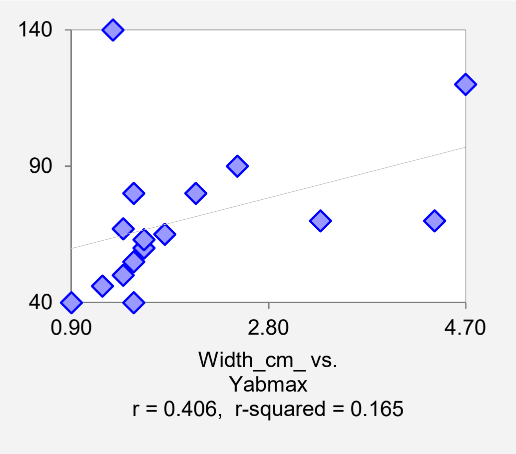
Width_cm_ vs.
ChainAvg
r = -0.489, r-squared = 0.240

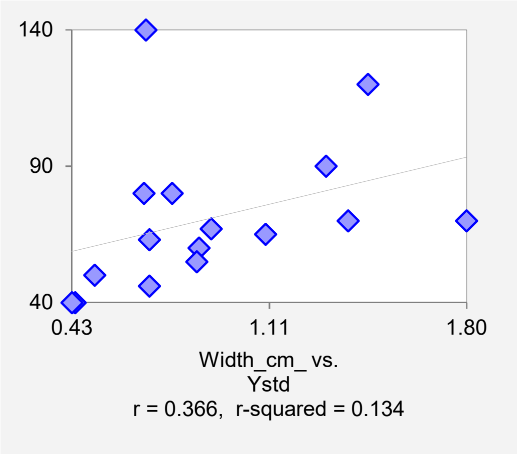


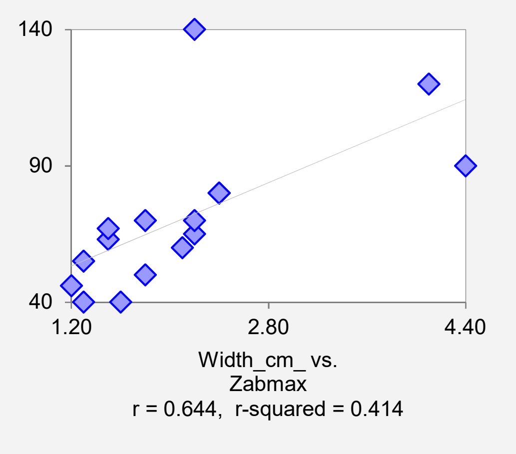
Width_cm_ vs.
steplength__m
r = -0.448, r-squared = 0.200

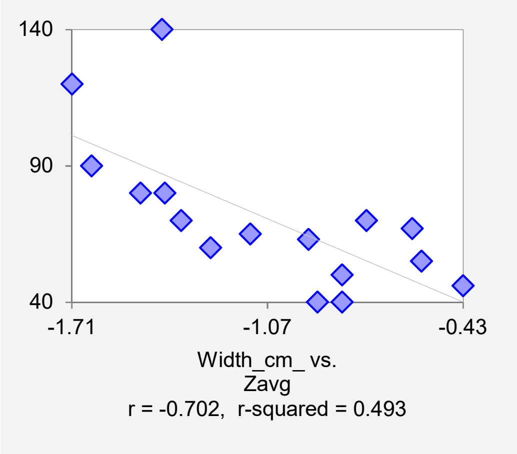


Width_cm_ vs.
Xstd
r = 0.331, r-squared = 0.109

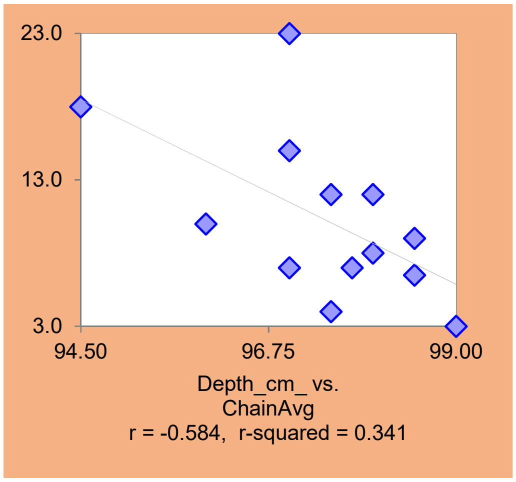


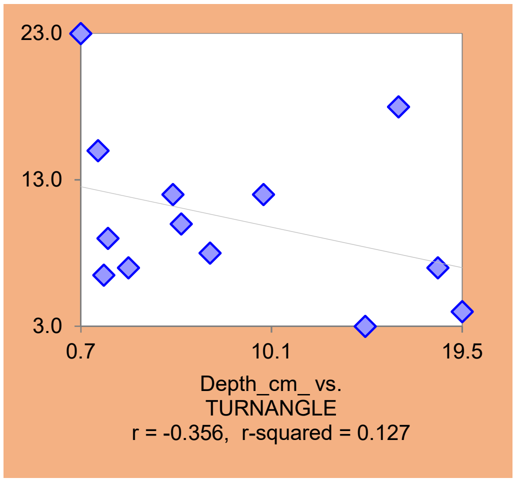


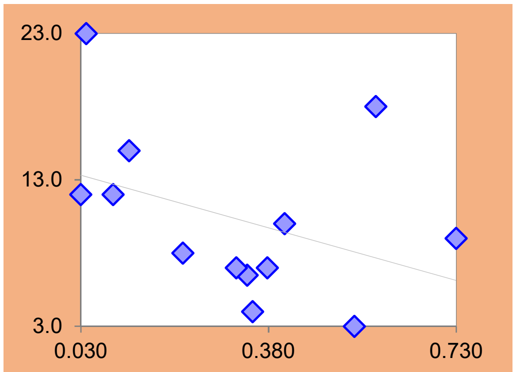




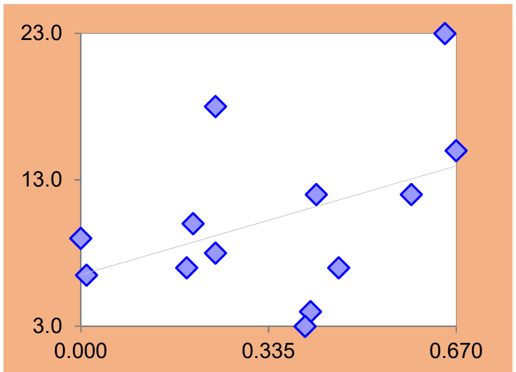
Scatter plots for Slaughter Creek Preserve: n=13, with outliers removed



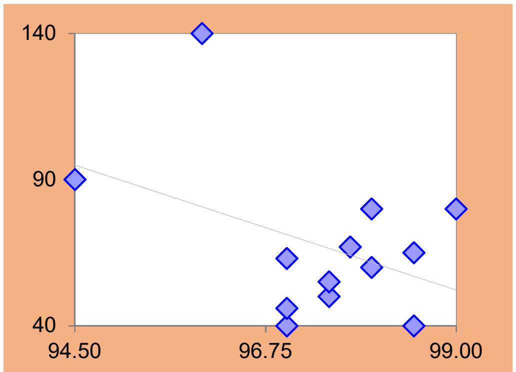




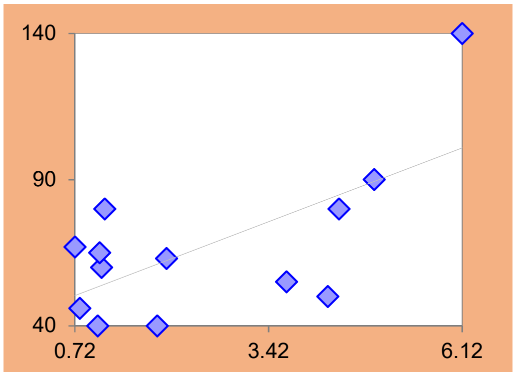
Depth_cm_ vs.
Xavg
r = -0.392,  r-squared = 0.154



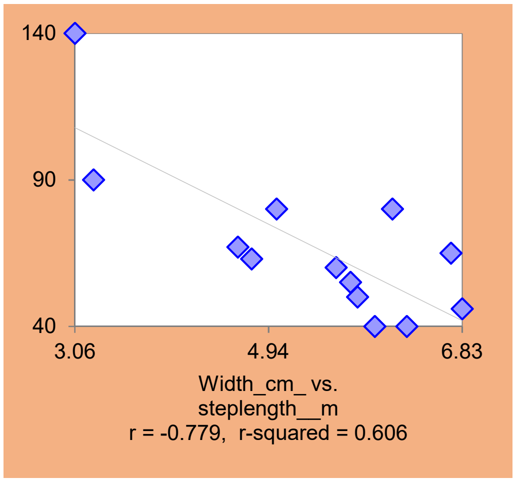
Depth_cm_ vs.
Yavg
r = 0.432,  r-squared = 0.186



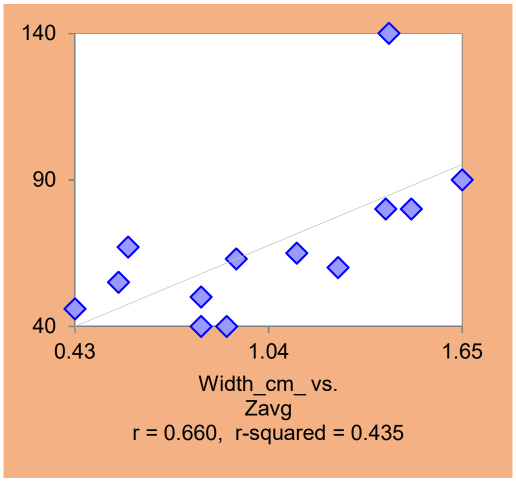
Width_cm_ vs.
ChainAvg
r = -0.419,  r-squared = 0.175



Width_cm_ vs.
Slope_degree
r = 0.651,  r-squared = 0.424

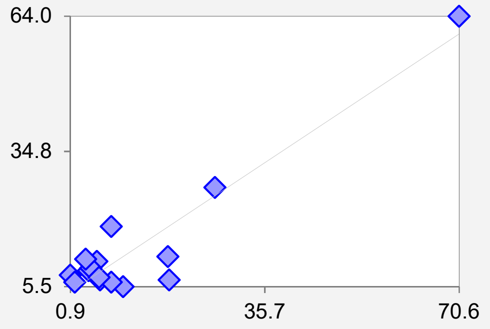


Width_cm_ vs.
steplength__m
r = -0.779,  r-squared = 0.606

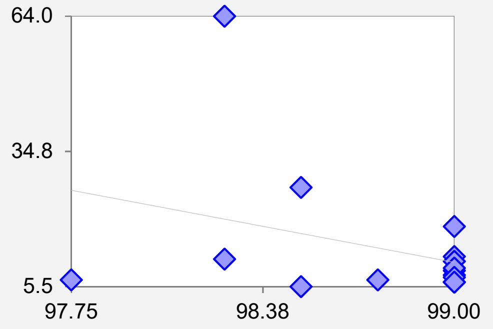


Width_cm_ vs.
Zavg
r = 0.660,  r-squared = 0.435

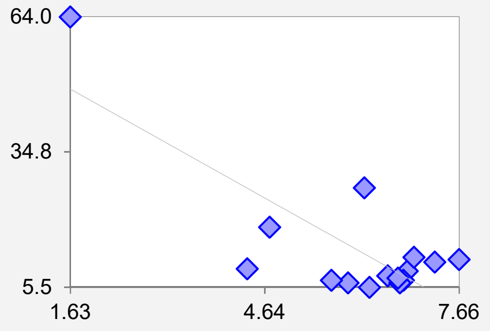
Scatter Plots for Walnut Creek: n=15, including all data (outliers not removed)



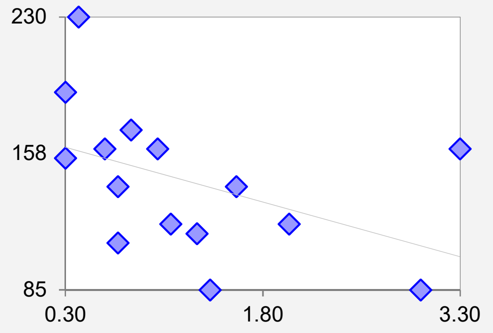
Depth_cm_ vs.
ABS_turnangle
r = 0.937,  r-squared = 0.879



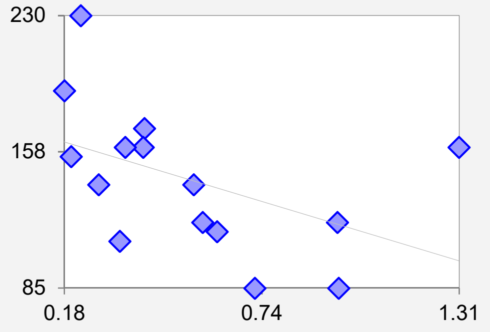
Depth_cm_ vs.
ChainAvg
r = -0.330,  r-squared = 0.109



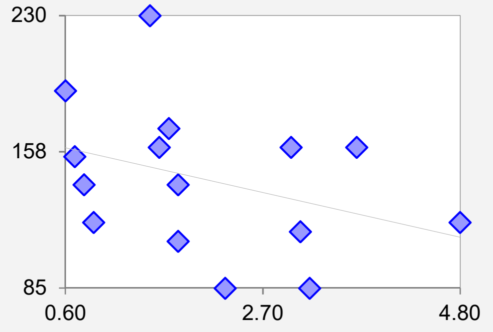
Depth_cm_ vs.
steplength__m
r = -0.788,  r-squared = 0.621



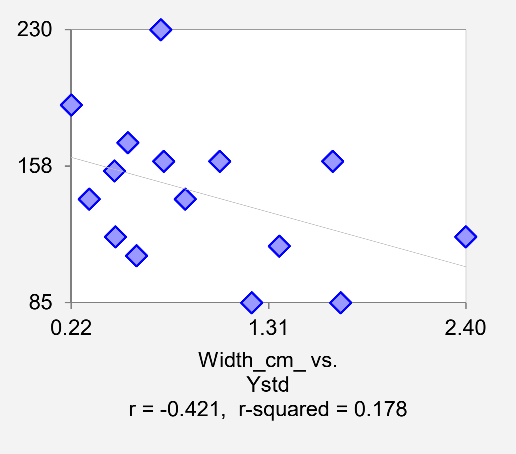
Width_cm_ vs.
Xabmax
r = -0.458,  r-squared = 0.210



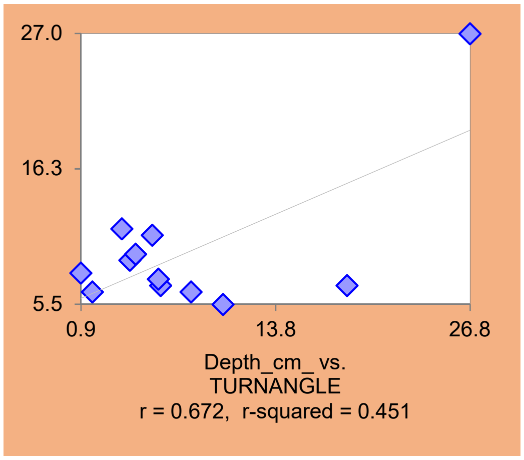
Width_cm_ vs.
Xstd
r = -0.473,  r-squared = 0.224

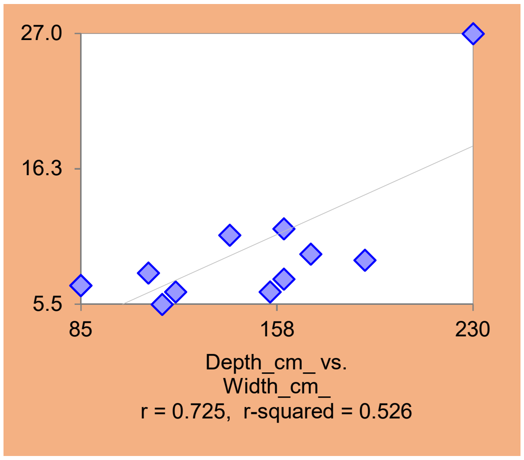


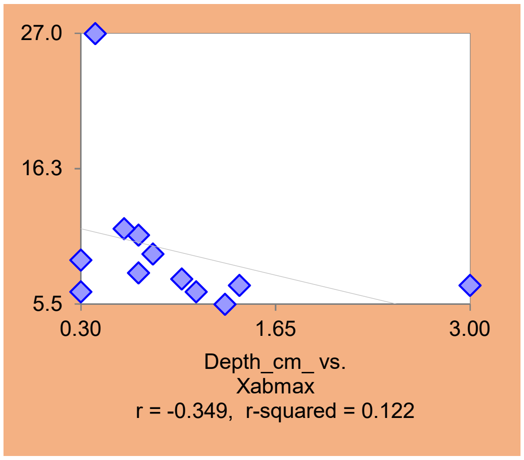
Width_cm_ vs.
Yabmax
r = -0.357,  r-squared = 0.128

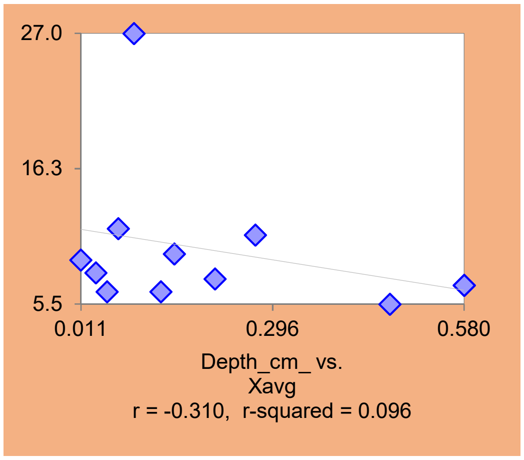


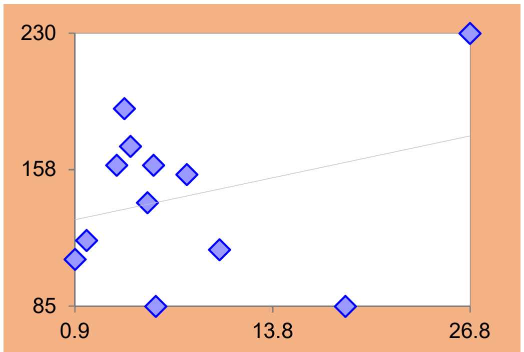
Scatter Plots for Walnut Creek: n=12, with outliers removed



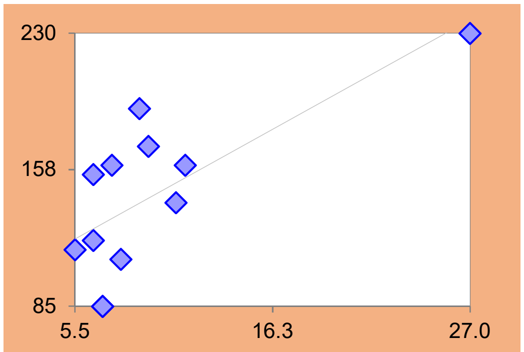




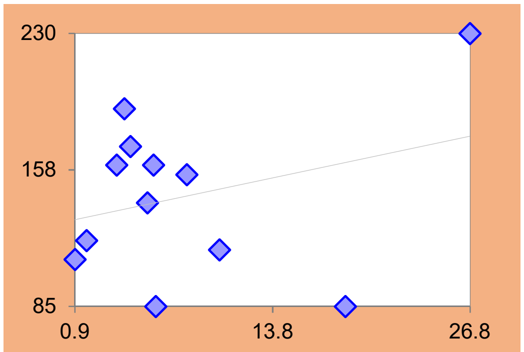




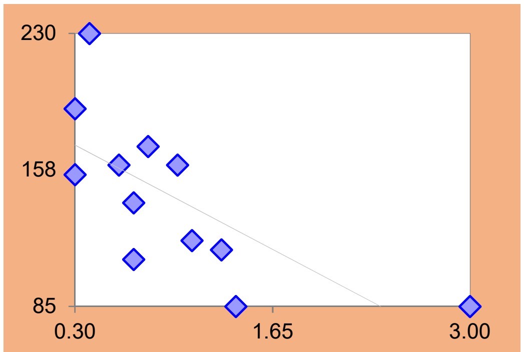
Width_cm_ vs.
ABS_turnangle
r = 0.300, r-squared = 0.090



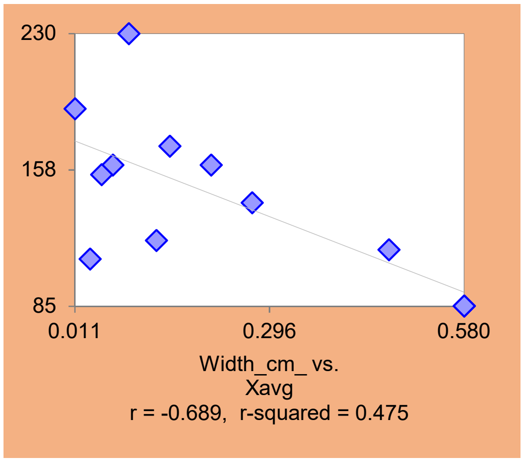
Width_cm_ vs.
Depth_cm_
r = 0.725, r-squared = 0.526



Width_cm_ vs.
TURNANGLE
r = 0.300, r-squared = 0.090

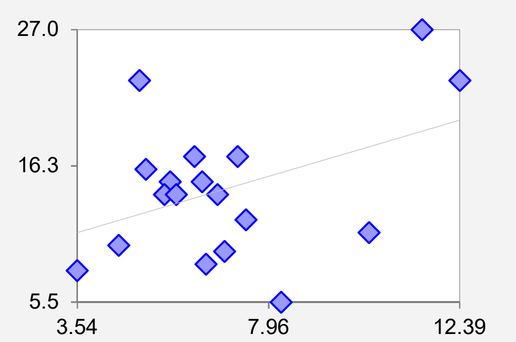


Width_cm_ vs.
Xabmax
r = -0.702, r-squared = 0.493

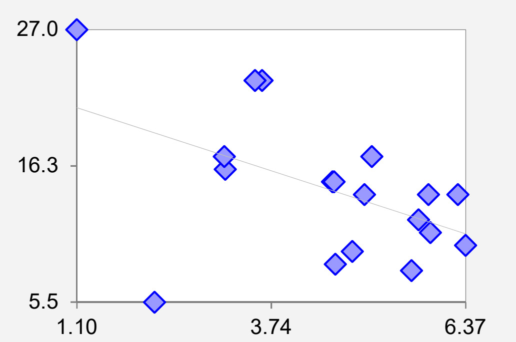


Width_cm_ vs.
Xavg
r = -0.689, r-squared = 0.475

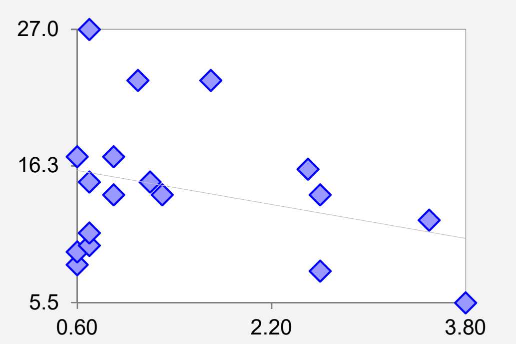
## Scatter plots for Emma Long: n=18, including all data (outliers not removed)



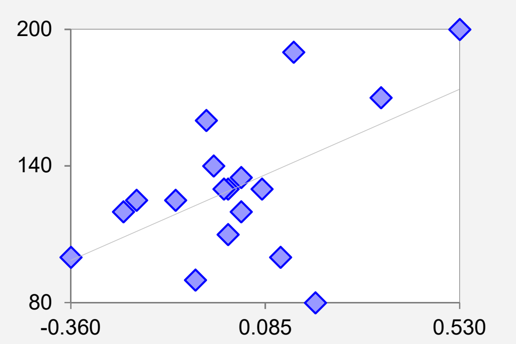
Depth_cm_ vs.
Slope_degree
r = 0.419,  r-squared = 0.175



Depth_cm_ vs.
steplength__m
r = -0.492,  r-squared = 0.242

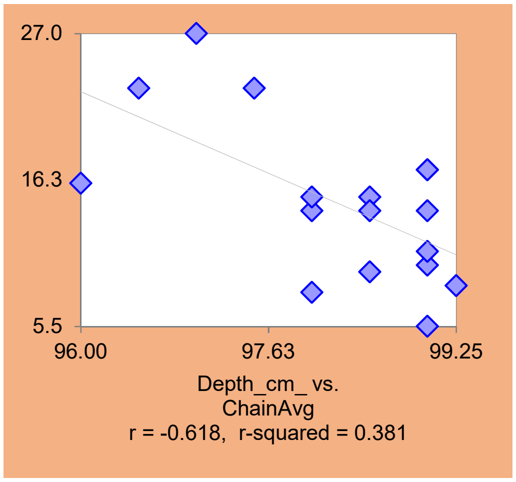


Depth_cm_ vs.
Yabmax
r = -0.310,  r-squared = 0.096

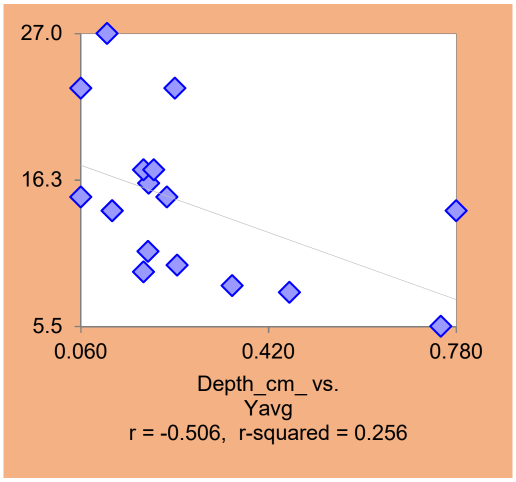


Width_cm_ vs.
Xavg
r = 0.545,  r-squared = 0.297

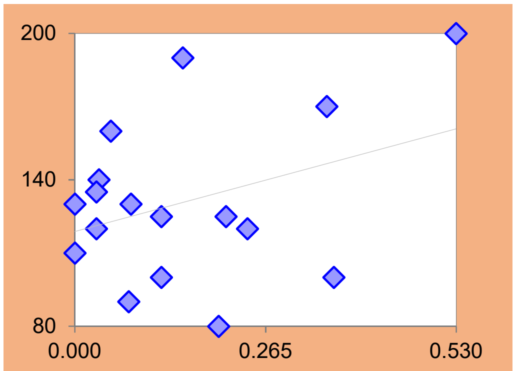
## Scatter plots for Emma Long: n=17, with outliers removed



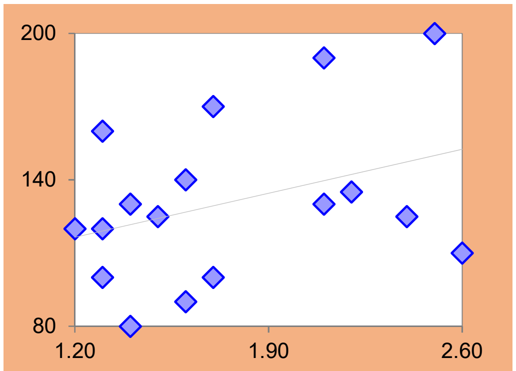
Depth_cm_ vs.
ChainAvg
r = -0.618,  r-squared = 0.381



Depth_cm_ vs.
Yavg
r = -0.506,  r-squared = 0.256

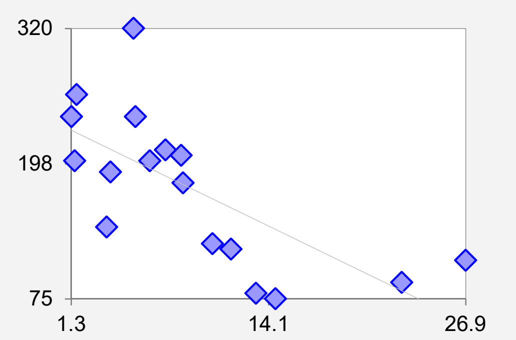


Width_cm_ vs.
Xavg
r = 0.356,  r-squared = 0.126

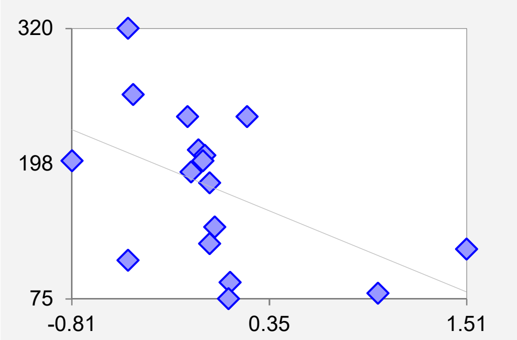


Width_cm_ vs.
Zabmax
r = 0.358,  r-squared = 0.129

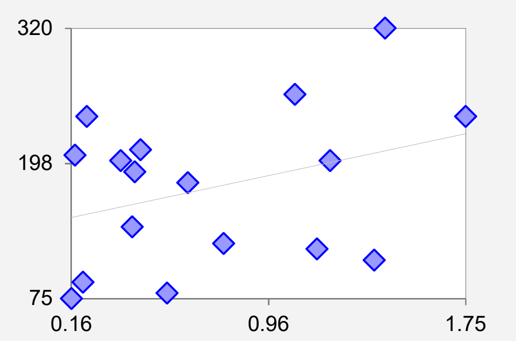
Scatter plots for Barton Creek Greenbelt: n=17, including all data (outliers not removed)



Width_cm_ vs.
Slope_degree
r = -0.701,  r-squared = 0.491

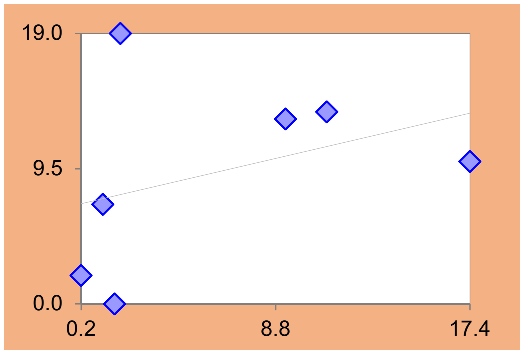


Width_cm_ vs.
Xavg
r = -0.492,  r-squared = 0.242

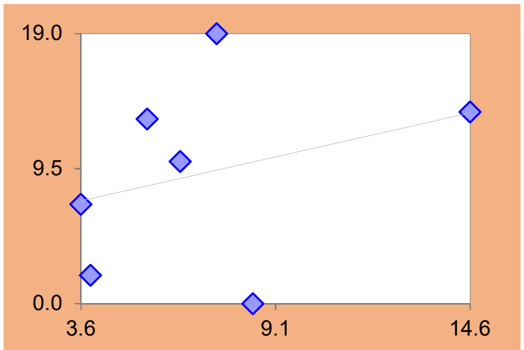


Width_cm_ vs.
Ystd
r = 0.347,  r-squared = 0.120

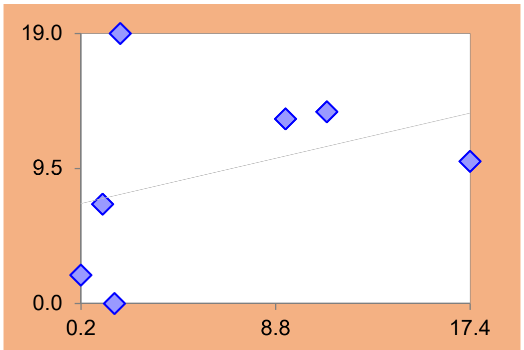
Scatter plots for Barton Creek Greenbelt: n=7, with outliers removed



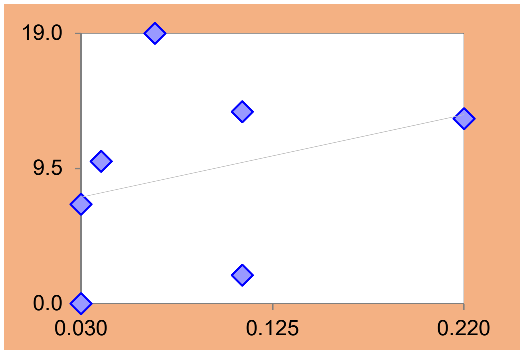
Depth_cm_ vs.
ABS_turnangle
r = 0.361,  r-squared = 0.130



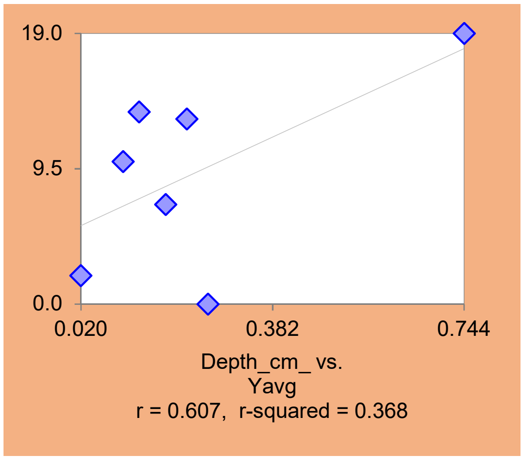
Depth_cm_ vs.
Slope_degree
r = 0.313,  r-squared = 0.098



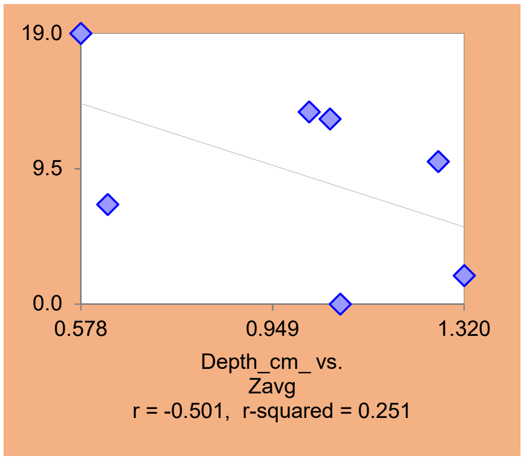
Depth_cm_ vs.
TURNANGLE
r = 0.361,  r-squared = 0.130



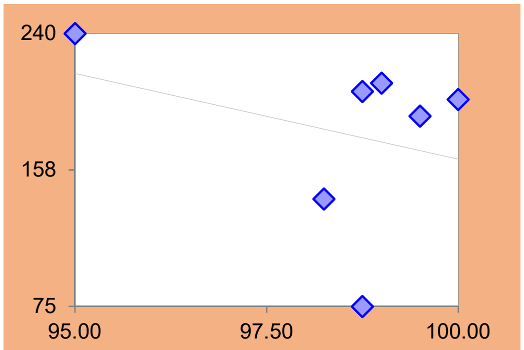
Depth_cm_ vs.
Xavg
r = 0.310,  r-squared = 0.096



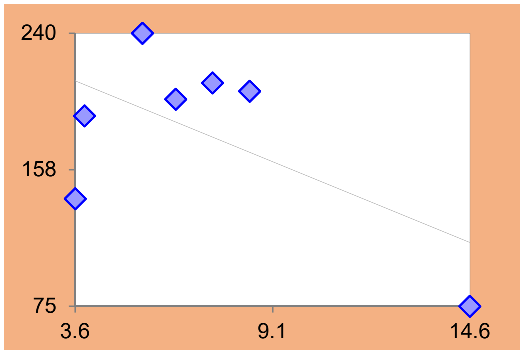
Depth_cm_ vs.
Yavg
r = 0.607,  r-squared = 0.368



Depth_cm_ vs.
Zavg
r = -0.501,  r-squared = 0.251

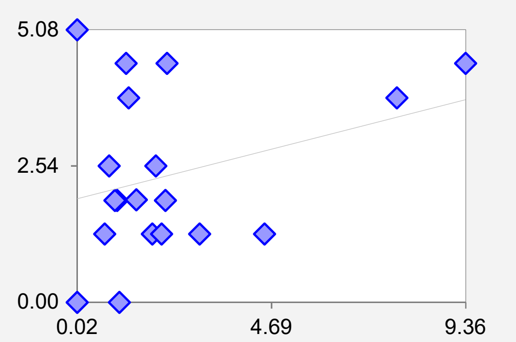


Width_cm_ vs.
ChainAvg
r = -0.306,  r-squared = 0.094

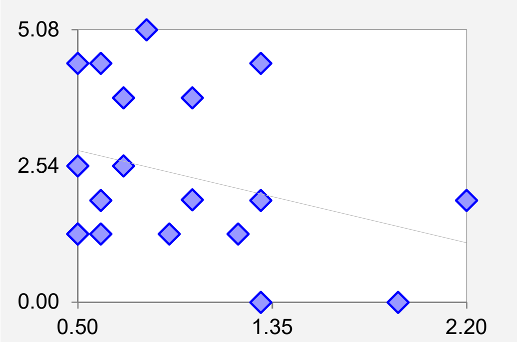


Width_cm_ vs.
Slope_degree
r = -0.603,  r-squared = 0.364

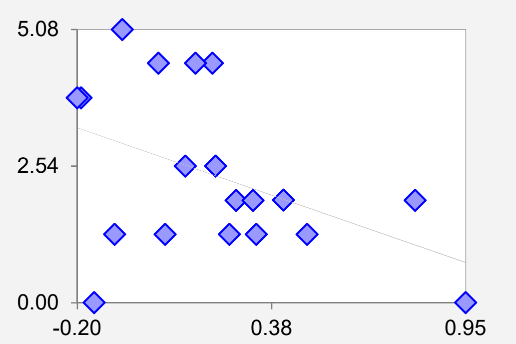
Scatter plots for Quest: n=19, including all data (outliers not removed)



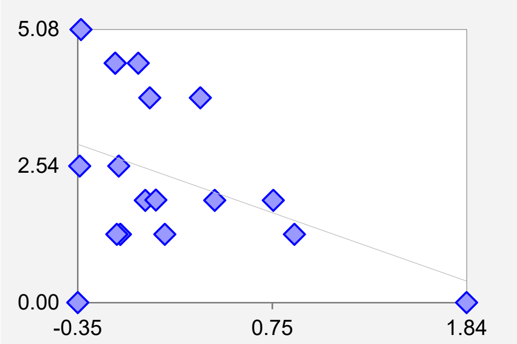
Depth_cm_ vs.
Slope_degree
r = 0.315,  r-squared = 0.100



Depth_cm_ vs.
Xabmax
r = -0.319,  r-squared = 0.102

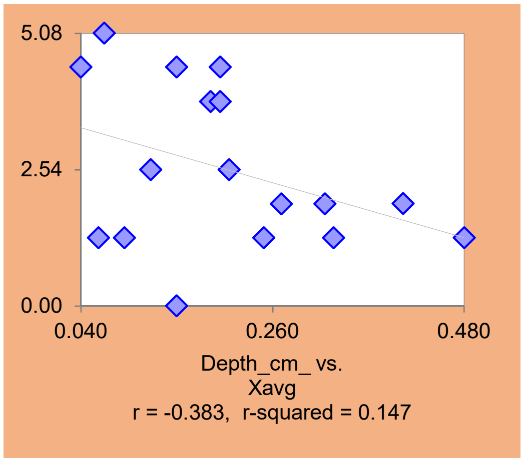


Depth_cm_ vs.
Xavg
r = -0.438,  r-squared = 0.191

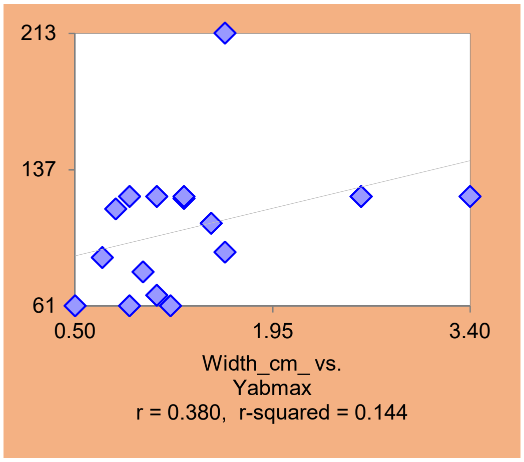


Depth_cm_ vs.
Yavg
r = -0.400,  r-squared = 0.160

Scatter plots for Quest: n=17, with outliers removed



Depth_cm_ vs.
Xavg
r = -0.383, r-squared = 0.147



Width_cm_ vs.
Yabmax
r = 0.380, r-squared = 0.144

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