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VEGETATION STRUCTURE, LIGHT AVAILABILITY, AND SEDIMENT DEPOSITION WITHIN SINKHOLE BUFFERS ASSOCIATED WITH TRACKED AND WHEELED VEHICLE TRAINING AT FORT KNOX, KENTUCKY

Klairoong Pattumma
Southern Illinois University Carbondale, pumapox@yahoo.com

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By
Klairoong Pattumma
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A Thesis
Submitted in Partial Fulfillment of the Requirement for the
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Approved by:

Dr. John Groninger, Chair

Dr. Karl W. J. Williard

Dr. Jon Schoonover

Graduate School
Southern Illinois University Carbondale
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AN ABSTRACT OF THE THESIS OF

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TITLE: Vegetation Structure, Light Availability, and Sediment Deposition within Sinkhole Buffers Associated with Tracked and Wheeled Vehicle Training at Fort Knox, Kentucky

MAJOR PROFESSOR: Dr. John Groninger

Heavy wheeled and tracked vehicle training has been conducted on portions of the landscape of Fort Knox, Kentucky for approximately 60 years. Fort Knox is located on the Kentucky Karst Plain and sinkholes are dominant features of this area. Sinkholes and karst terrain present an atypical problem in combination with this unique land use, potentially impacting downstream and local terrestrial environment. A study of the training area sinkhole complex was conducted as a first step toward mitigating the impact of military activities and reduces potential problems of sedimentation and water quality degradation. A total of 20 sinkholes within Training Areas 9 and 10 at the Fort Knox Military Reservation were randomly selected to represent the study area. The objective of this study was to determine the relationship between stand structural characteristics, understory light availability and understory vegetation in sinkhole riparian buffers and concentrated flow paths and with the amount of sediment entering sinkholes in the study area. Vegetation data were collected during the growing months of May and June in 2009.

All regressions analyses for vegetative structures have r^2 values between 0.000 to 0.308 indicating weak to no correlation among the variables. Light availability and percent herbaceous cover showed moderate and weak relationship in buffers ($r = 0.547$, $p = 0.003$) and flow paths ($r = 0.164$, $p = 0.245$). Sediment gained in splay areas showed no significant relationship to vegetation structure ($r = 0.039$ to -0.335). The relationship between sediment

gained and mean percent herbaceous cover was not significant in flow paths (r = -0.172, p = 0.2341) or buffers (r = 0.130, p = 0.292). While the results of this study suggest the amount of the sediment depositing in the sinkholes was unrelated to observe variation in sinkhole vegetation, the relationship between overstory vegetation and understory vegetation within sinkholes was more noticeable. On site observations strongly suggest that concentrated flow paths were the primary conduits for sedimentation into splay areas. Therefore, management considerations pertaining to training areas should minimize flow paths leading to sinkholes. Best management practices for Fort Knox training areas should integrate these research findings, in addition to current knowledge of riparian buffers and training areas' management requirements.

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CHAPTER 1

INTRODUCTION

Fort Knox Military Installation has been the home of the United States Army Armor Training Center since the 1940s. Heavy wheeled and tracked vehicles have been driven over the landscape for approximately 60 years. Fort Knox is located on the Kentucky Karst Plain with level to steeply rolling hill topography (Baskin et al. 1994). Rolling hills to steep landscapes are ideal topography for tracked vehicle driver training because of the unleveled terrain driving effects. The training areas were designated for heavy use and are exposed to physical and ecological damage. Military activities at Fort Knox are most likely the source of groundwater contaminants such as sediment in basins such as Sycamore Spring Basin and Dry Branch Basin (Connair & Murray 2002). Sinkholes and karst terrain present an atypical problem in contribution to the unique land use, potentially impacting the environment and local residents. Riparian buffers are vegetated areas sometimes retained on the landscape to protect sinkholes and similar low lying areas. At Fort Knox, concerns have been raised that the existing vegetation on riparian buffers may not be effective in reducing sediment into sinkholes.

The conditions of the training areas continue to decline because of improper sinkhole riparian buffer management and a lack of understanding of the relationship between a disturbed karst ecosystem and military activities. A study of sinkhole riparian buffers was essential, to mitigate the impact of military activities and reduce potential problems of sedimentation and degradation of water quality. Sinkholes are susceptible to water runoff, sedimentation and contamination. Groundwater is directly affected by substances entering by seepage through sinkholes. During wet seasons and severe rain events, the splay area within these sinkholes fills with rain and diffuse runoff water. When the water evaporates or percolates through the soil, the fine soil particles remain on the surface. Deposition of these fine soil particles is one of the most extensive threats to surface water and water runoff quality (Petersen & Vandracek 2006). Buffers around sinkholes are a last line of defense in reducing sediment deposition from water runoff from training areas before it enters the groundwater.

Conducting studies within military training areas provides an opportunity to focus on a single anthropogenic disturbance in a relatively small area excluded of farming, logging or grazing (Houser et al. 2006). The collection of the vegetation data and the assessment of its effectiveness in decreasing sedimentation were extensively examined in this study in order to recommend best management practices for the Fort Knox training areas. Training activities continue to deteriorate the sites to bare ground which caused soil erosion and further environmental problems to local areas (Fehmi et al. 2001). This study was designed to determine the relationship between vegetation cover in sinkhole riparian buffers and along concentrated flow paths and the amount of sediment entering sinkholes in Training Areas 9 and 10 at the Fort Knox Military Reservation.

The objectives of this study were: 1) to determine whether variability in stand structural characteristics within sinkhole buffers and concentrated flow paths i.e. overstory, sapling, and herbaceous species composition, density, and basal area, were associated with sediment accumulation in splay areas, 2) to identify relationships between overstory and herbaceous layer cover within sinkholes and sediment accumulation in the sinkhole splay areas, 3) to determine the relationship between estimated understory light availability, understory vegetation density and how the vegetation influence sediment deposition in splay areas, and 4) to recommend additional best management practices to mitigate erosion in training areas.

Hypotheses:

This study predicted that,

- Percent herbaceous cover will be negatively correlated with percentage overstory cover, in the buffers and flow paths
- The presence of herbaceous vegetation within the concentrated flow paths will have a significant impact on the volume of sediment deposited in splay areas
- Light availability will have a significant influence on the percent cover of herbaceous vegetation
- Combined vegetation structure, overstory, understory and herbaceous cover, will have significant influence on sediment accumulation in the sinkhole splay area

CHAPTER 2

LITERATURE REVIEW

This section presents a review of literature on karst landscapes in relation to riparian buffers and management of water quality. Background and history of karst studies are discussed, and the current literature buffers riparian and sedimentation are presented. The review also presents a discussion of research conducted on other military installation training areas and recent studies of Fort Knox, Kentucky.

Karst Landscape and Water Quality

Karst studies can be dated back to 852 BC with a record of karst as the source of springs to the present day with the newest technologies involving all Earth Science disciplines to refine the knowledge of karst (LaMoreaux & LaMoreaux 2007). The study of karst topography has evolved significantly over the years. The first modern karst research was conducted in 1893 by Jovan Cvijic, Vienna in Austria, to gain a better understanding of the overall landscape and karst development. In the United States, karst studies began in the 1930s with cave exploration in relation to water flow. In the 1960s, researchers explored hydrology, chemistry and biology in karst geology. In general, there are two types of karst researchers: professional hydrologists who are using mathematical formulas to understand the formation process, and cavers who explore and map cave networks. At present, scientists are researching and working to create models that can more accurately explain these complex karst systems (White 2007).

Soluble rocks such as limestone are the parent material of karst landscapes. Limestone is highly susceptible to the weathering process. Over time, water erosion weathers the limestone, creates a rolling landscape. As water moves through the landscape and erodes the soluble rocks, caves and its passages are formed (De Waele et al. 2008). Sinkholes are distinct features and easily identified in the Fort Knox area, presenting as circular depressions surrounded by grasses and trees. Strip of grasses and trees separate wheeled and tracked vehicles trails from sinkholes (Petersen & Vondracek 2006). These sinkholes channel surface water to groundwater. Water carries a multitude of pollutants, contaminants, chemicals, debris, and sediment across the land (Conniar & Murray 1994). Without proper sinkhole protection, hazardous substances flow directly into the groundwater without any natural filtering.

Karst landscapes can be found all over the world, from China to South America. Many United States cities such as Chicago and St. Louis are built on karst landscapes (White 2007). Karst terrain is often not recognized by most people because the majority of the landscapes do not appear on satellites images. Sinkholes range from small and unnoticeable to several miles wide covering an entire region. For example, Mammoth Cave region is a well-known karst landscape. Underground passages and cave were created by underground river systems. Water accelerates the weathering process and flow rate in the passages depended on size of the channel and water level (Raeisi et al. 2007).

Another karst characteristic less visible to human eyes is epikarst. Sinkholes are created by the collapse of soluble rocks, whereas, epikarst is formed by fractures found on the upper-most layer of karst landscapes. Water can percolate through these fractures in the same way as through sinkholes. Epikarst is a source of water for aquifers. Water runoff concentrated in the epickarst area can rapidly filter downward into the groundwater system (Klimchouk 2004; Williams 2008). In karst landscapes, protecting groundwater is a challenge.

Influence of Riparian Buffers on Sedimentation and Management Techniques

Few studies have been conducted on the effectiveness of riparian buffers around sinkholes, however many studies in agriculture setting maybe applicable in managing sinkhole riparian. A study of a combination grass and shrub riparian buffer system addressed shallow subsurface flow and pollutant transport (Desbonnet et al. 1994). The results showed that buffer width removed sediment by only 10 percent. The function of grass and shrub buffers was to disperse energy and maintain sheet flow (Mankin et al. 2007). Native grass was useful for trapping sediment from surface runoff. Reduction in total suspended solids from water runoff was studied by simulating runoff on grassy wooded buffer plots (Lee 2000). The grass-shrub buffers studied provided excellent mass reduction of outflow runoff. Results suggested that the experimental design was adequate for reducing sediment (Mankin et al. 2007).

Increased buffer width or the quantity of vegetation around buffers may help improve water quality in an agricultural setting (Perterson & Vondracek 2006). The researchers conducted a study within a karst landscape which consisted of 83 percent agricultural located in southeast Minnesota. Based on a model developed by the researchers, a 30-meter buffer would prevent approximately 10,000 ton yr^{-1} of sediment from entering sinkholes. However, a 15-meter wide buffer was more economical and was found to be just as effective as the wider buffers. The researchers suggested planting herbaceous species such as mixed native grass within the buffers, and any type of vegetated buffers around sinkholes would contribute to sediment reduction and protect the underground water system. The research showed that water runoff was more dispersed around the buffer but that small areas of channelization were present.

Concentrated flow paths or channels pose a significant challenge to water quality protection in karst landscapes. An assessment of concentrated flow paths in agricultural riparian buffers was conducted by a research team in southeastern Nebraska (Dosskey et al. 2002). Researchers observed that the buffer's sediment-trapping ability was significantly reduced when water runoff bypassed the vegetated buffer. They also recognized that dispersed water runoff may improve sediment trapping.

To disperse concentrated flows and benefit from buffers, agroforestry was incorperated as riparain buffers management. Agroforestry is intermix of grass, herbaceous vegetation and trees as riparian buffers and it is a field of increasing study in buffer managemen. Agroforestry as riparian buffer can reduce non point source pollution in grazed pastures (Udawatta et al. 2010). Researchers assessed the effects of agroforestry and grass buffers on the reduction of non point source pollution from grazed pastures into adjacent streams at the Horticulture and Agroforestry Research Center, New Franklin, Missouri. The results revealed that 15-meter buffers efficiently reduced the amount of runoff during large surface flow events. In grazed pastures, the combination of trees and grass in a buffer was more effective in reducing sediment than grass alone due to increased soil porosity and improved soil quality. Sediment was reduced by 25 percent within the agroforestry buffers compared to controlled treatment areas. In addition, most sediment was retained within the first 4 to 7.5 meters (Udawatta et al. 2010). Agroforestry as a riparian buffer was found to be more effective than traditional riparian buffers in reducing sediment in a small watershed (Schultz et al. 2004). Researchers discussed the establishment of the new agroforestry riparian buffers designed at Riparian Buffer National Research and Demonstration Area by the United Stated Department of Agriculture, Bear Creek, Iowa. The focus of their study was the forest riparian buffers in agricultural landscapes. Currently, agroforestry buffers have a positive impact on the function of riparian buffers and are cost effective. More research is needed to better adapt agroforestry management practices to improve water quality.

Grass and shrub riparian buffers are not as well studied as forested and vegetated filter strips. The assessment of the effectiveness of native grass and shrub buffers along Branch Mill Creek in Northeastern Kansas found that the buffers were very effective in reducing sediment (Mankin et al. 2007). Existing grass and shrub buffers with an average width of 9.7 meters removed 99 percent of sediment from simulated runoff before reaching the local streams. Simulated runoff was mixed with known amounts of total suspended solids, phosphorus and nitrogen to accurately calculate removal within the buffer. In this research, total suspended solid exceeded 75 percent for suspended solids and 90 percent for both total phosphorus and total nitrogen (Mankin et al. 2007). The results also demonstrated that combination of vegetative structure, rather than width, was the most important determinant of the amount of nutrients removed. With the right mixture of native grasses and shrubs, the recommended minimum width was 23 meters for trapping sediment and removing nutrients from water runoff.

Grasses and shrubs may be more advantageous and appropriate in removing sediment and nutrients than woody vegetation in different environmental settings such as disturbed landscapes, agricultural fields and urban riparian areas. Many scholarly reviews have suggested that grassy riparian vegetation prevents bank erosion, traps and reduces suspended sediment from entering streams more effectively than areas covered with woody riparian vegetation where banks are lower and less steep (Lyons et al. 2000). In agricultural settings, grass and shrub buffers were found to be more beneficial than woody vegetation for bank stabilization to prevent erosion because of the deep and difficult to dislodge root system (Davies-Colley 1997; Trible 1997). The minimum width of a grassy buffer strip, as narrow as 4 meters, has been shown to effectively remove nutrients and sediment from water runoff (Parsons et al. 1994). Grassy riparian buffers require regular management such as mowing, grazing, burning, and herbicide or they will most likely revert to wooded riparian area (Trimble 1997).

Woody riparian buffers exhibited better water infiltration capabilities and grassy buffer because of the debris and leaf litter that slowed and reduced surface runoff (Frances 1997). Woody vegetative buffers provide shade and decreased water temperature, increased woody debris in stream which increased local flooding (Castelle et al. 1994), and increased organic matter accumulation (Gregory et al. 1991). These reviewers suggested that grassy buffers in agricultural settings may effectively improve water quality. However, grass buffer management is more intensive than woody riparian buffers. The design of riparian buffers largely depends on landowners' objectives and concerns.

The United States Department of Agriculture (USDA) developed standards for forest riparian buffers (Welsch 1991). They recommend three distinct buffer zones: Zone 1: mature trees and native riparian trees and shrubs maintained adjacent from stream banks upslope approximately 15 feet. The primary purpose of this zone is to stabilize stream banks. Concentrated flows will be converted to sheet flow before reaching Zone 1. Zone 2 is upslope from Zone 1 and extends approximately 60 meters. This zone consists of native tree species that are appropriate to the location. The primary function for this zone is nutrient uptake and water infiltration. Management should include maintaining debris and leaf litter to slow water runoff. Concentrated flow should be converted to sheet flow before entering Zone 2. Zone 3 is the outer-most edge of the buffer which extends approximately 20 meters from Zone 2 and is adjacent to agricultural fields. The purpose of this zone is to spread out concentrated flow to a more shallow and uniform flow before it enters Zone 2. Dense native grasses and shrubs are recommended for this zone. Regular maintenance and intensive management are required to prevent natural succession to take place within Zone 3.

The USDA guidelines for forest riparian buffers were implemented to measure the effectiveness of mature riparian buffers to improve water quality on the Coastal Plain of Georgia (Sheridan et al. 1999). The evaluation was performed within Zone 2. Three different treatment sites within Zone 2 were monitored: a clear-cut forest, selective-thinning forest, and a mature forest. Sediment reduction was significant under all three treatment sites; however, the most considerable amount of sediment reduction was in Zone 3 prior to reaching Zone 2. The sediment reduction ranged from 78 to 83 percent reduction for all three treatment sites. Grass and shrub buffers in alone Zone 3 efficiently trapped sediment, reduced runoff and removed pollution regardless of the management of Zone 2. Nonetheless, prior to reaching Zone 3, concentrated flow must be converted to sheet flow to minimize channelization. Less sediment entered sinkholes when water runoff from upland areas dispersed into the form of sheet flow before reaching Zone 2 (Hart & Schurger 2005).

Multiple zones are ideal for riparian design where adequate land is available for to create a proper buffer width. Often times, the suitable mixture of vegetation with shorter buffer width are preferred in certain areas.

<u>Vegetative Compositions of Riparian Buffers and Influential Factors of Buffer Function</u>

In natural riparian settings where zones are not distinctively visible, management can be challenging. Interactions of vegetation composition and structure, understory, herbaceous and light availability become factors in determining the functions of buffers. Anthropogenic disturbances can influence the management of the vegetation and all elements that associated with that particular environment.

Buffers contain a mixture of overstory, midstory, and herbaceous cover. The land cover at Fort Knox region of northern Kentucky was mostly agricultural where most of the natural vegetation had been disturbed (Baskin et al. 1994). Vegetation in this area could be classified as second growth (Smalley 1980). Vegetation in northern Kentucky can be categorized as a mosaic of oak-hickory forest (*Quercus spp.* and *Carya spp.*), which accounts for 53 percent of the overstory and less than 15 percent in the understory, and bluestem prairie (*Poaceae spp.*) (Kuchler 1964; Chester et al. 1995).

The interaction between the vegetation structures of overstory, understory and herbaceous strata may determine the riparian buffer capacity to protect downstream water quality. Measurement of herbaceous production at the San Joaquin Experimental Range, California showed that during the first year of drought, more herbaceous growth occurred in open grasslands than under canopies (Frost & McDougald 1989). However, during the second year, herbaceous production was greater under the oak canopy than in the open grasslands. The availability of sunlight at the ground level positively influenced the abundance of the herbaceous cover. A study conducted in the North Coast Ranges and Sacramento Valley, both low precipitation areas, revealed that under low precipitation (< 50 cm/yr) canopy cover had neither a positive nor negative effect on the production of understory vegetation. However, more precipitation (>50 cm/yr) enhanced the abundance of the understory (Frost et al. 1997). Study sites in boreal forest in Ontario, Canada were selected because of its diversity. The study communities included conifers, mixed-wood and deciduous overstory. Species richness of understory vegetation after fire and logging disturbances was studied and the richness was highest on sites with more available sunlight (Hart & Chen 2008). Also, understory species were more influenced by other species that could tolerate and survive during periods of low precipitation.

Understory diversity is largely influenced by the abundance of overstory cover. An experiment was conducted in northern Wisconsin to determine how site variables affected understory vegetation (Brosofske et al. 2001). It was concluded that canopy cover was the major factor in controlling diversity within the understory. Stand composition was distinctively different under different types of overstory such as coniferous, deciduous, and open canopies. The investigators found that 22 percent of the understory richness was influenced by overstory density alone. This study showed that hardwood stands and open canopy created a greater diversity and richness of understory than coniferous stands. Clear cutting was found to be another factor in plant species diversity. The increased availability of sunlight within disturbed sites explained the greater diversity (Denslow 1985).

The abundance of herbaceous cover may be influenced by the amount of sunlight reaching the forest floor. Several studies have shown that low light availability under a canopy negatively impacts understory establishment. Research was conducted to compare the response of herbaceous vegetation to sunlight and nutrients (Elemans 2004). Light availability was found to affect the ability to change and adapt in biomass production; however, adding nutrients did not affect the growth and production of the plants. Under a dense understory, light was unable to reach the forest floor which impeded the establishment of the seedlings and other perennial groundcover (Messier et al. 1998). Light availability on forest floor was the single environmental factor in control of invasive grass distribution (Cole & Weltzin 2005).

Research in Military Training Areas

The increasing presence of off-road vehicles in natural areas has resulted in more research on military training areas to assess vehicles impact on the environment. Damage resulting from training will occur and is often unavoidable. To mitigate these negative effects, the military designated impact areas for different types of training: foot traffic, artillery, wheeled and tracked vehicles. Due to restricted access for classified training activities and other military constraints, there are gaps in available research that limit the scientific basis for management decisions. Researchers recommended that a more complete spatial coverage throughout the United States be conducted to understand the strategic level of training allocation. A more complete assessment of biota and complex environmental composition is needed to create a meaningful indication of site degradation (Anderson et al. 2005). It is important to understand the site capacity to accommodate a properly designed research model. Knowledge of the broader spatial and temporal areas of military training areas as well as land use history are important in making management decisions. It is essential to be familiar with the capability, capacity and configurations of the sources of the impact such as tracked versus wheeled vehicles.

Tracked vehicle training is a common severe disturbance on military training areas (Guretzky et al. 2006). Researchers reviewed and concluded that military training had tremendous impacts on soil compaction and vegetation structures as vehicles were repeatedly driven over the area (Grantham et al. 2001). An experiment to evaluate vegetation and soil characteristics affected by tracked vehicles in Grafton South State Military Reservation, North Dakota found soil bulk density and bare ground increased under both moderate and heavy use (Prosser et al. 2000). The researchers also discovered that vegetation cover, in this case Kentucky bluestem (*Poa pratensis*), decreased during the first year, but no significant changes occurred in the second year of the observation. A similar study, but in a mixed prairie area, measured disturbance up to intermediate level from tracked vehicles and showed that plants can maintain its species richness and diversity (Leis et al. 2005). In this research, the authors did not specify the type of tracked vehicles or differentiate the levels of disturbances. Therefore, comparing site recovery of different training areas was challenging when the intensity of disturbance varied among sites.

The study of military training impacts to vegetation and soil provides an opportunity to focus on a single factor in the absence of other sources of disturbance such as grazing, farming and logging. A study at Fort Riley, Kansas was conducted to determine training effects on terrestrial and aquatic ecosystems within a watershed (Quist et al. 2003). The authors categorized military training impacts on vegetation cover into five visually distinct locations: none, pass, trail, road and other. Increased intensity training activity caused bare soil to increase. Bare soil covered up to 35 percent of several sites within the training area. The reduction of vegetation was highly connected to training land use and bare soil (Quist et al. 2003). However, in spite of the decreased amount of the vegetation, more introduced species emerged. Similar research examined the effect of military training at Pinon Canyon Maneuver Site in Colorado (Milchunas et al. 1999). Researchers found that there was a decline of vegetative basal cover, woody species seedlings, perennials, and cacti. Conversely, annual and introduced species increased.

Military training activities are not inclusive to vehicles. Dismounted training exercises are also included in military training and cause disturbance to the environment. Research at Jack's Valley Training Area at the United States Air Force Academy in Colorado assessed the impact of foot traffic disturbances on vegetation and soil properties (Whitecotton et al. 2000). The intensity of land use sites was based on the number of days the sites were occupied during summer training. The results indicated that moderate and heavy-use land activities decreased the soil infiltration rate, increased soil's bulk density and compaction and increased soil erosion. Vegetation production and biomass decreased by 68 percent as the intensity of land use increased.

More thorough studies of military training effects on the environment were conducted at Fort Benning Army Installation, Georgia. The understory vegetation under longleaf pine forests was compared and contrasted under four different disturbance intensities; researchers discovered that trees and shrubs were the most common form of vegetation found on sites where light infantry trained (Dale et al. 2002). Understory species abundance was low for the heavily-used training areas due to the frequent removal of vegetation by tank training. Foot traffic resulted in less impact on understory vegetation. The influence of canopy cover had no effect on the abundance and diversity of the understory where little bluestem (*Andropogon scoparius*) was dominant in the understory. A study of fine roots as indicators of erosion was conducted at Fort Benning where military wheeled, tracked and dismounted training caused disturbance and produced a significant amount of sediment (Cavalcanti & Lockaby 2004). The presence of fine root production suggested the intensity of environmental stress. Researchers found that fine roots lessen as the sediment deposition rate increased beyond 0.3 cm yr^{-1}. However, the reasons that fine roots declined remained unidentified (Cavalcanti & Lockaby 2004). A study was conducted at Fort Benning that examined stream chemistry in relation to disturbed soil and vegetation in the upland area. Much of disturbed area was bare of vegetation caused by tracked vehicles. Researchers found that the increase in total suspended solid and inorganic suspended sediment during storms was highly correlated to disturbance. The increase of inorganic suspended sediment may have altered stream chemistry. Upland soil and vegetation disturbances influenced the stream catchment regardless of the condition of the riparian zones (Houser et al. 2006).

Various studies on the effects of military vehicles on twelve U.S. Army installations provided a broad overview of disturbances (Garan et al. 2001). Researchers generally found that plant diversity was significantly reduced at these locations due to the physical contacts of the vehicles. Significant levels of soil compaction and erosion were also found at each installation. At Fort Knox, Kentucky, the researchers reported that severe gully erosion occurred within the training areas and large amounts of sediment were found within sinkholes (Garan et al. 2001). A thorough technical report on the effects of tracked vehicle activity on vegetation at Fort Knox illustrated the removal of vegetation from heavy use of tracked vehicles, which consequently caused severe soil erosion (Severighaus et al. 1979). In undisturbed areas such as sinkholes, sediment deposition was prominent.

Karst landscape presents an additional environmental challenge, especially where the military conducts training. A study to identify buried sinkholes at Fort Campbell Army Airfield (CAAF) in Kentucky found contaminants within small fractures and void systems within rocks (Higuera-Diaz et al. 2007). These contaminants potentially reach the aquifer.

Fuel leakage found at CAAF in 1982 seeped into sinkholes and spread to the aquifer bedrock which threatening local water supplies.

Fort Knox Military Reservation required more research on the relationship of training activities, karst terrain and ground water flow for effective future management. The study included the cantonment area or military camp but excluded the artillery impact areas. The research was conducted by injecting dye into the sinkholes and monitoring the direction and the rate of water flow. The result was that the karst groundwater was controlled by local geologic formation, rock layering and ground water level (Connair & Murray 2002). The majority of the water flowed westward into Otter Creek. In the future, the trace of water from the cantonment area will be monitored, assessed, and evaluated to enable location of the contaminant source for the groundwater at Fort Knox (Connair & Murray 2002).

Existing Management for Fort Knox Military Reservation

Each army installation has an equivalent management plan for training areas with respect to mitigating the environmental damages caused by its training activities. A Resource Inventory and Conservation Plan for Fort Knox was developed for its training areas (Milliken 1996). Milliken discussed each training area's usage, general topography, hydrology, and sedimentation problems. Training Areas 9 and 10 were two of the most active training areas and most subject to severe rill erosion. Roads and tank trails within these areas were essentially bare ground. He suggested that completely closed the areas to any training exercise and re establishing ground cover in the heavily used land was the most effective way. However, this method may not be the most realistic to all damaged areas due to the continued need for training military forces. The plan provided specific management considerations that could be applied to all training areas, including information pertaining to the soil erosion and water runoff problems. Training area 9 consisted of 2,595 acres, and topography is varied from very steep hills to flat bottom land. Otter Creek flows through Training Area 9 and McCracken Spring Lakes is also located within the area. Training area 10 consisted of 3,269 acres and Otter Creek flows through this area. The following suggestions were made for erosion control:

- Land reconstruction should allow on the heavily used training areas for vegetation to be re-established following the construction,
- Site treatment rotation should be scheduled around training exercises,
- Treatment along heavily used areas such as frequently travelled tank trails should be temporary control methods, seeding, hay bale diversion, etc,
- Any complete projects will require annual inspection and regular maintenance to achieve the full potential of the conservation plans.

Water runoffs control suggestions:

- Land grading within training areas should be implemented to maintain sheet flow,
- Conservation practices should provide immediate protection to water sources.

A technical report prepared by Crim et al. (2009), specifically recommended best management practices for Training Areas 9 and 10. The best management practices addressed how to reduce sedimentation, minimize the number of the concentrated flow paths prior to entering the buffers and to fill existing flow paths within the buffers with topsoil. The present study combined with Crim's technical report, will provide a comprehensive knowledge of the vegetation composition of Fort Knox's Training Area in relation to sedimentation problems. Recommendations to mitigate the problems will be based on scientific knowledge which can be practiced and incorporated into the land use objectives of the training areas. She suggested the following management:

- Reduce the number of concentrated flow paths leading to sinkholes
- In forested buffers, thinning is recommended to promote herbaceous species and ground cover. Concentrated flow paths within these areas should be filled with topsoil to establish herbaceous
- Sinkholes with buffers less than 75 meters should have new plantings of grass or widely spaced trees to promote herbaceous species
- Areas that are infrequently used for training should be planted in grass or trees with an emphasis in stream channels draining in these areas to reduce erosion

CHAPTER 3

METHODS

Study Area

Fort Knox is located in north-central Kentucky, approximately 30 miles southwest of Louisville and 18 miles north of Elizabethtown. Fort Knox Military Reservation encompasses an area of over 100,000 acres. Training areas (TA) 9 and 10 combined are approximately 5,864 acres, located in Meade County in the northwestern part of the reservation (Figure 1). Otter Creek flows from south to north through both training areas while State Highway 60 separates the two training areas (Milliken et al. 1996). Sediment from TA's 9 and 10 entered Otter Creek directly through surface runoff and indirectly through an underground drainage system. Sinkholes and small ponds are outlets to the underground drainage system that are filled with sediment as a result of severe erosion caused by heavy military activities. TA's 9 and 10 were selected as study areas because they were subject to severe disturbances (Figure 2 and 3). Types of vehicles that were used included, but were not limited to; M46 Patton tanks (44 tons), M1A1/A2 Abram tanks (67 tons), and Family of Medium Tactical Vehicles (18 tons).

Military training impact areas were concentrated in one area on the reservation to minimize the environmental damage to the rest of the military reservation (Fehmi et al. 2001). In TA's 9 and 10 subsurface soil exposure was clearly visible adjacent to sinkhole buffers (Figure 4 and 5). The impact of wheeled and tracked vehicles was apparent in grass buffers which are in close proximity to frequently used trails.

The area is characterized by relatively level topography, including rolling hills to very steep slopes. Sinkholes are characteristically dominant features, circular depressions and usually surrounded by vegetation. Splay area is a low area in the center of the sinkhole where sediment and runoff from upland area descend and settle (Figure 6). The region has an average annual precipitation of 49 inches (1971-2000), and the average temperature ranges from an annual high of over 87 degrees F to a low of less than 37 degrees F (Arms et al. 1979; Kentucky Unbridle Spirit Cabinet for Economic Development 2009). The geology of the area consists of layered limestone with minor siltstone and shale (Milliken et al. 1996). A-horizon is severely eroded or no longer existed in many intense used areas. Two dominant soil series in training areas area are Baxter and Nicholson soils. Baxter series are severely eroded soils, well drained, and they occur on gently slopes or ridges. Typical profiles of these soils are very gravelly silty clay loam this resulted from weathered limestone (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx retrieved 05/23/2011). Baxter series soils are developed on karstic plain of Mississippi geologic formation (White et al, 1994). Nicholson soil series is another dominant soil within training areas. Nicholson soils have loamy upper subsoil with clayey lower subsoil (White et al. 1994). These soils can be found on ridges and slopes. They are moderately well drained, severely eroded, and brittle fragipan at the depth of 18 to 30 inches (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx retrieved 05/23/2011).   The Ohio River flood plain influences the type and material of Nicholson series (White et al. 1994).

Vegetation in the Fort Knox area includes central hardwood species oak-hickory (*Quercus spp.* and *Cayra spp.*), tall fescue, native warm season forbs and shrubs and grasses. The study areas, excluding areas adjacent to sinkholes, were almost entirely bare soil. Severe sheet and rill erosion and gullies were found in areas adjacent to sinkhole buffers.

Most topsoil was eroded away, leaving subsoil exposed. Military tank trails and roads meandered around sinkholes and followed contour lines and rolling hills. The buffers consisted of strips of grasses and trees extended from bare ground in the edge of the splay area in the sinkhole. The buffer areas between the tank trails and sinkholes were narrow and ranged from a few feet to 30 feet wide.

Sampling Methods

Study Design

Data were collected summer 2009 during a period when no military training exercises or activities were scheduled. Twenty sinkholes (ten each in TA 9 and TA 10) were selected. Sinkholes in the study areas they were randomly chosen and ranged from the 190 feet to 4000 feet in length, smallest to largest in diameter. Vegetation data were collected during the growing months of May and June. The size of sinkholes was measured and the location of flow paths was identified using ArcGIS (Version 9.3) and aerial photos.

V*egetation Sampling and Light Assessment*

Vegetation sampling was conducted in the buffer and major flow paths of the 20 sinkholes with bottles installed. Using an aerial photo and a compass, two random bearing transects were established within the sinkhole buffer and one transect along the primary flow path, from the buffer edge to the splay edge (Figure 6). A quadrat point was placed every 5 meters along each transect, and vegetation was sampled with a 0.5 m^2 frame immediately to the right and left of the quadrat point (Figure 7). All species within the frame were identified and the percent cover of each species estimated. At every third quadrat point, all tree/shrub species from 2.5 to 10 cm diameter at breast height (DBH) and within a 2 meters radius of the quadrat point were identified, a 10 basal area factor (BAF) plot centered on the quadrat point was taken and each “in” tree was tallied. A densiometer reading was taken to estimate percent canopy cover at the third quadrat point. This process was repeated until the edge of the splay area was reached.

Flow path evaluation

The primary flow path was determined by the most obvious gullies that flowed into sinkholes. A quadrat sampling point was established at the center of the flow path starting at the uppermost noticeable point on tank trails of the primary flow path and ending at the edge of the splay area. The same procedures were used to evaluate and assess the entire length of the flow path as was used for vegetation sampling in the buffers.

Sediment collection

Ten 500 mL bottles were installed in the splay area of each sinkhole. The bottles were positioned so the tops were flush with the surface of the splay area (Figure 8). Thus, the bottles captured sediment that settled to the bottom of the splay after rainfall events. Bottles were installed in November of 2008 and collected in June of 2009. Once the bottles were collected, sediment depth was measured. The bottles were then dried in an oven and weighed to estimate total mass (Crim 2009). Comparatively, the dendrogeomorphic method from year 1 estimated an average accumulation rate of 1.27 cm yr^{-1} and sediment loss from the training areas was 46.1 metric ton yr^{-1}. The dendrogeomorphic method used 2 sinkholes from TA 9 and 8 sinkholes from TA 10, assumed an average splay area of 0.3 ha, and used an average bulk density of 1.21 g cm^{-3} to calculate the annual sediment mass (Crim 2009)

Five hundred sampling points for the buffers and 254 sampling points for the flow paths were inventoried from the twenty sinkholes. Two hundred sediment bottles were collected.

Data Analysis

Data were recorded in Microsoft ® Excel 2007, and analyzed using the Statistical Package for the Social Sciences (SPSS) 16. Microsoft ® Excel 2007 was used for any percentages, averages and summation computations. SPSS was used for statistical analysis for correlations, regressions and relationship among the variables. A t-test was used to detect a significant difference between variables. Significance was determined at an alpha level of 0.025 (p-value). One tailed test was used unless otherwise indicated.

Linear regression was used to determine a relationship between each vegetative structure within sinkhole buffers and flow paths. In each sinkhole, average percentage of each vegetative structure was compared to assess significance of differences. The relationship between overstory and herbaceous cover in sinkholes' buffers and flow paths was also analyzed using linear regression. The average sediment gained and lost (metric ton yr^{-1} ha^{-1}) was compared to each vegetation percentage cover. Spearman nonparametric correlation was generated for each pairwise combination.

Coefficients were used to find a correlation between light availability and percent herbaceous covers. Correlations were examined in each sinkhole buffers the percentage open and closed canopy (densiometer reading) and the percentage herbaceous cover for buffers and flow paths. The relationship between means of sediment gained within each sinkhole mean percent vegetation cover was determined by Spearman correlations.

Multiple Regressions were used to determine the relationship between sediment accumulated in sinkholes and combined vegetation composition within buffers and flow paths. Sediment gained in sinkholes was analyzed as a dependent variable, while buffers percent vegetation cover and flow path percentage of vegetation and herbaceous vegetation cover and overstory were predictors' (independent) variables. Analysis of variance (ANOVA) was used to compare the vegetative composition within sinkholes.

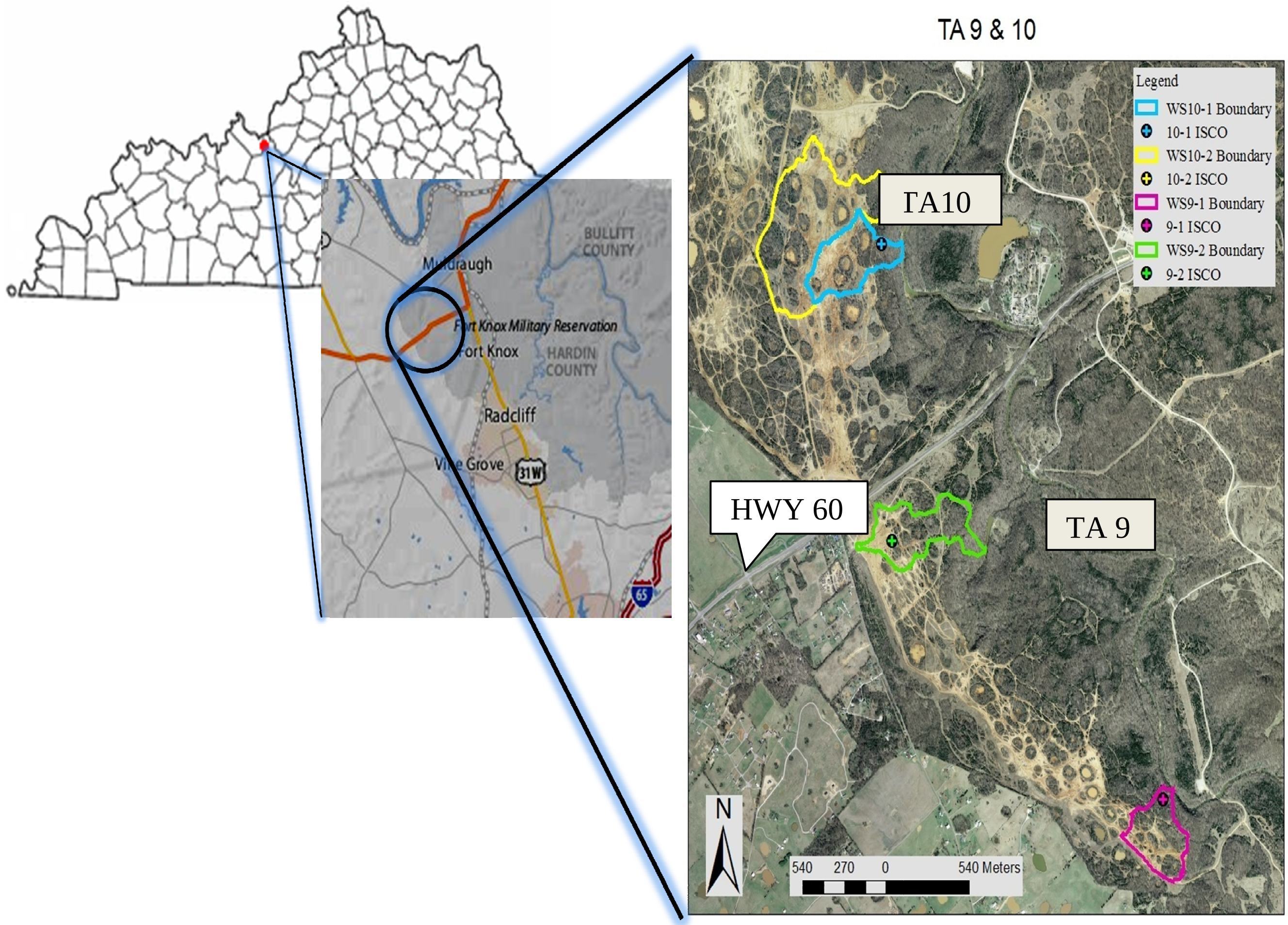

Figure 1. Study Areas: Training Areas 9 and 10, Fort Know, KY

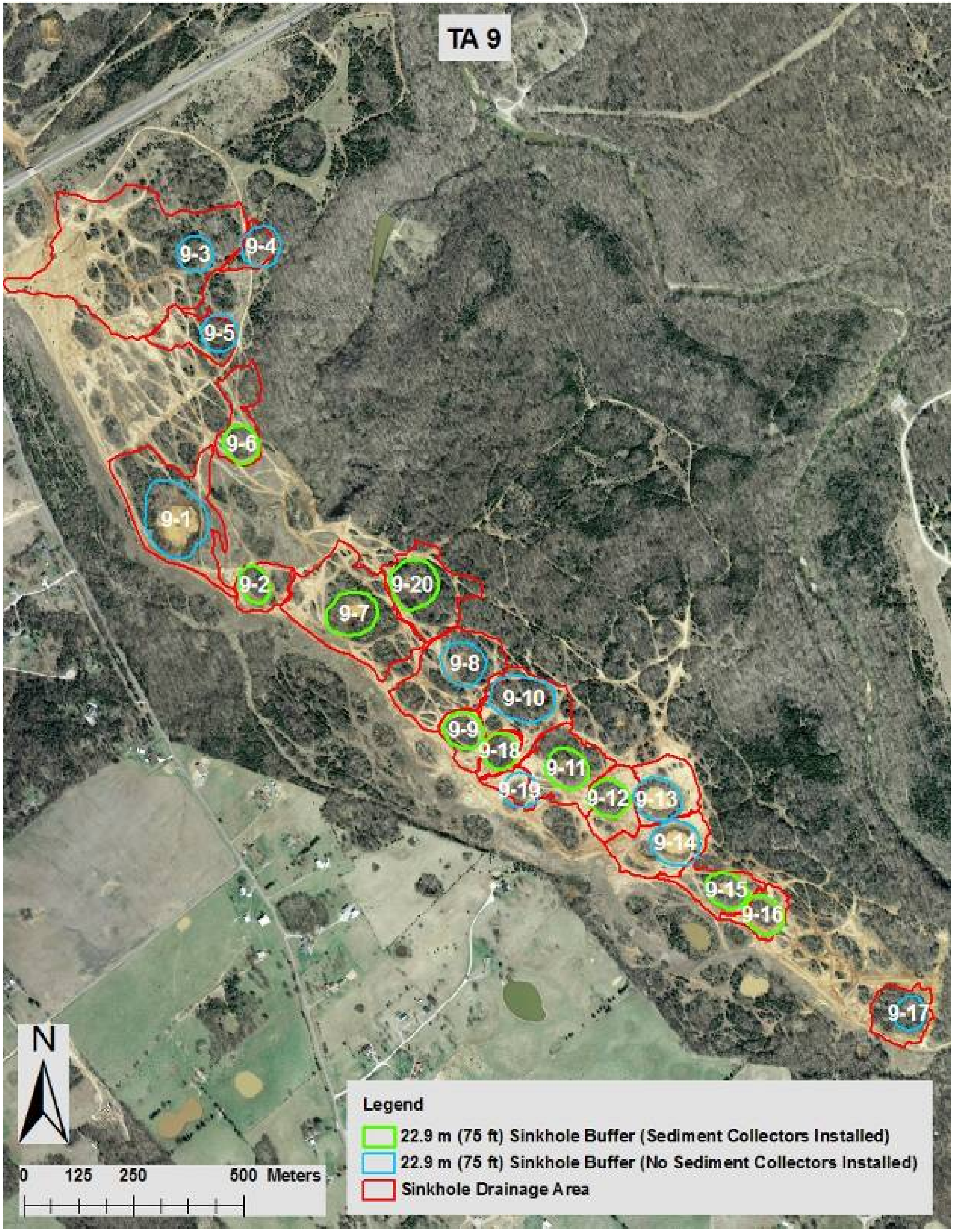

Figure 2. Locations of sinkholes within TA 9. Map by Jackie Crim, Arc GIS ver. 9.3

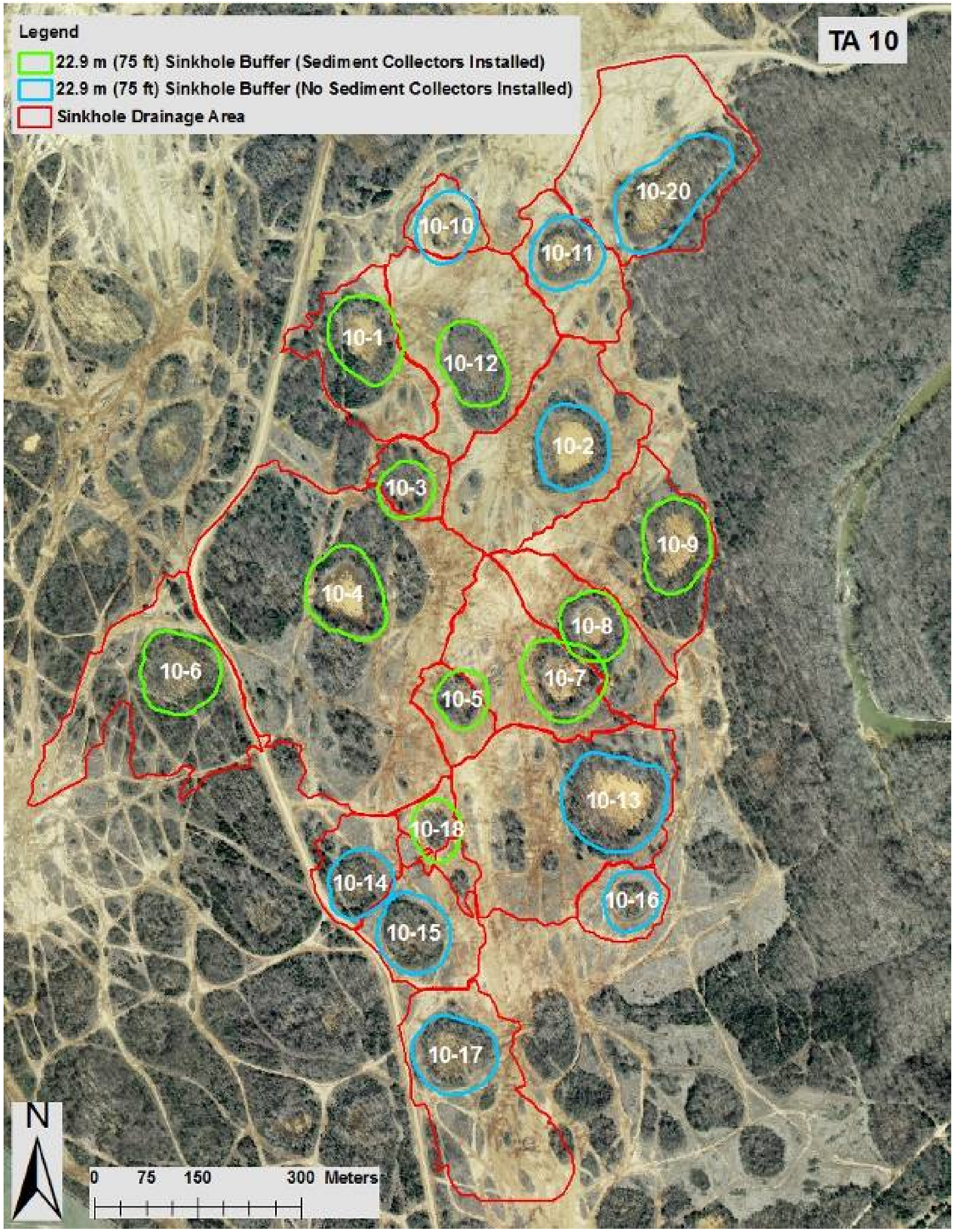

Figure 3. Locations of sinkholes within TA 10. Map by Jackie Crim, Arc GIS ver. 9.3

Figure 4. Training area 9, tank trails condition after rain events in the May 2009. Photo taken by Klairoong Pattumma

Figure 5. Training area 10, tank trails condition in the January 2008. Photo taken by Klairoong Pattumma

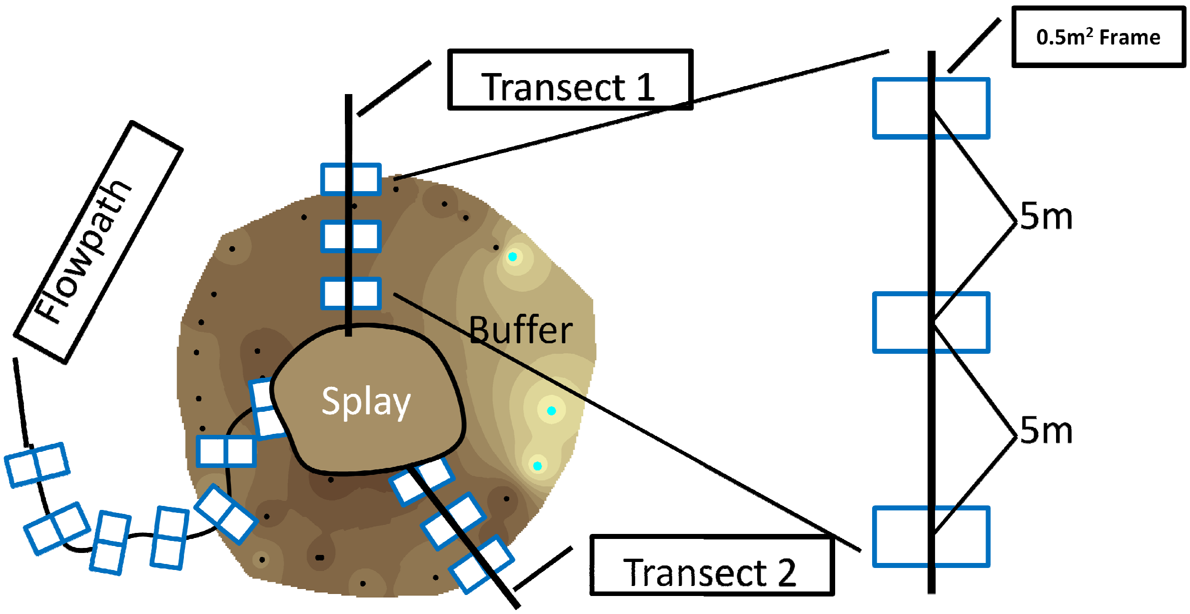

Figure 6. Diagram of Quadrat Sampling point. Vegetation was sampled along two random transects within the buffer and within a major flow path. Sample plots within the transects were 5 meters apart.

Figure 7. Example of vegetation sampling plot in 0.5 m^2 frame.

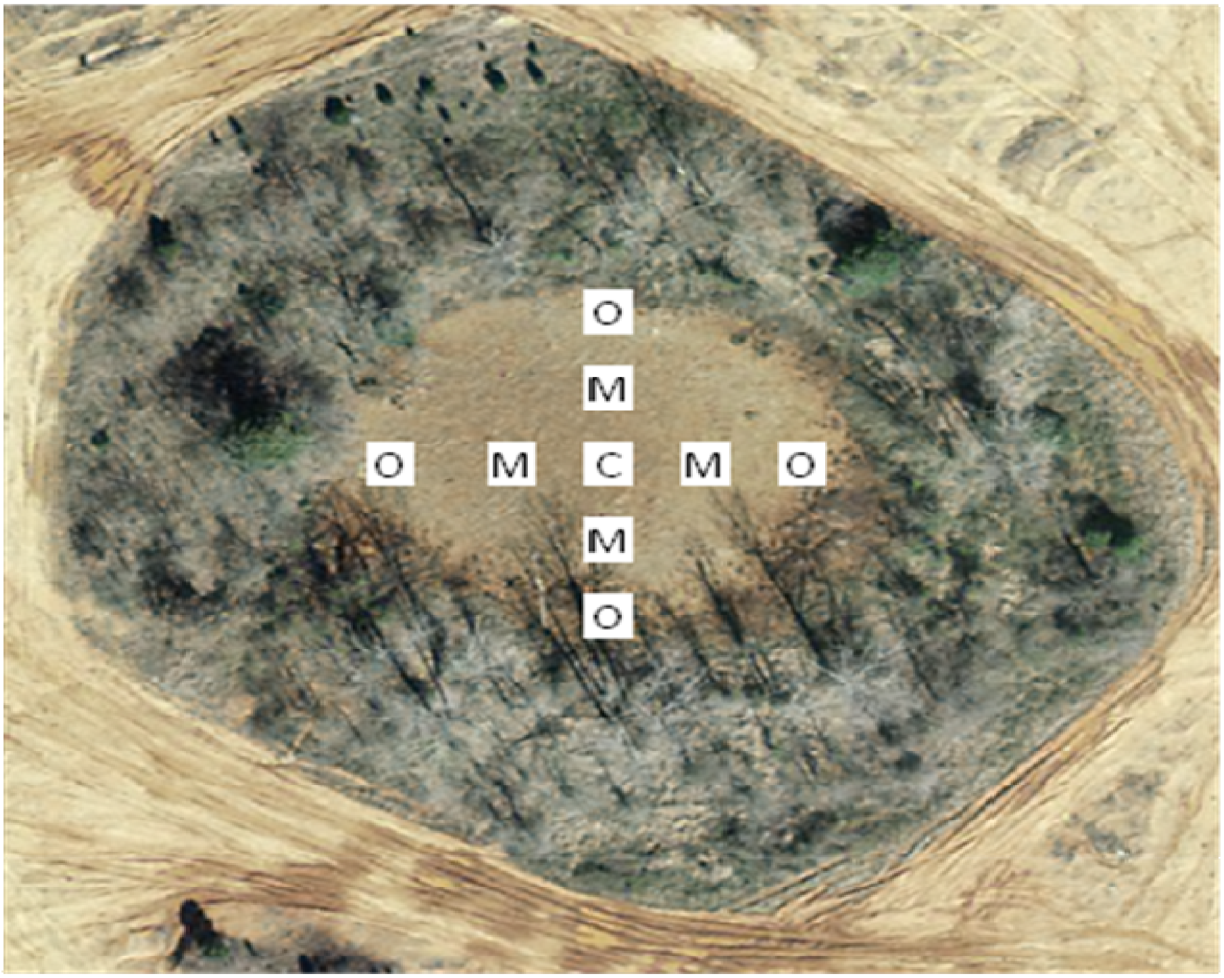

Figure 8. Placement of sediment collectors in splay area. O=outer splay; M=middle splay; C=center splay. Diagram by Jackie Arc GIS ver. 9.3

CHAPTER 4

RESULTS

Vegetation data were collected to determine overstory, midstory, sapling, herbaceous composition and cover within sinkholes. Light penetrating canopy was measured using densiometer reading. Sediment deposition in splay areas was also collected within each sinkhole. A total of 754 sampling points within the buffers and flow paths were inventoried to determine the relationship between vegetation cover in the riparian buffers and concentrated flow paths.

Stand Structural Characteristics

Overstory/Canopy Cover

The average percentage canopy covers were divided into training areas and locations within buffers, flow paths and splays. The average percentage canopy cover within buffers in TA 9 was 78% with a range of 57% to 91%; TA 10 was 79% with a range of 63% to 90%. Mean flow path canopy cover in TA 9 was 69% with a range of 53% to 91%; TA 10 had 66.84% canopy cover with a range of 26% to 91%. Mean splay area canopy cover in TA 9 was 56% with a range of 14% to 80%, and TA 10 was 59% with a range of 16% to 84%. The average canopy cover was higher in buffer than in the flow paths of both TA's. Fifteen out of twenty sinkhole buffers had a higher average percentage canopy cover than the flow paths. A summary of the canopy covers by sinkhole is presented in Table 1.

The most common overstory species found within sinkholes buffers and flow paths in both training areas were: eastern cottonwood (*Populus deltoides*), eastern red cedar (*Juniperus virginiana*) and sassafras (*Sassafras albidum*). Black willow (*Salix nigra*) dominated splay areas. Blackjack oak (*Quercus marilandica*) was observed on the drier upper slopes of the sinkholes. American sycamore (*Platanus occidentalis*) was frequently found near splay areas. Table 2 lists the major tree species found in sinkholes of both TA 9 and TA 10. The overstory species composition was dominated by oak and hickory as well as mesophytic species for both buffers and flow paths.

Saplings

The sinkhole buffers in TA 9 had an average of 2,400 saplings per hectare. Buffers in TA 10 had an average of 3,200 saplings per hectare. TA 9's major flow paths had an average of 2,300 saplings per hectare and TA 10 had an average of 3,900 saplings per hectare. The numbers of saplings in the major flow path ranged from 0.00 to 9,600 per hectare, with the overall average of 3,200 saplings per hectare.

Common species found within buffers within the sapling class were: sassafrass (*Sassafras albidum*), American sycamore (*Platanus occidentalis*), and eastern red cedar (*Juniperus virginiana*). The most common saplings species found within sinkhole flow paths were: flowering dogwood (*Cornus florida*), sassafras (*Sassafras albidum*), and red maple (*Acer rubrum*). Common persimmon (*Diospyros virginiana*) and black willow (*Salix nigra*) were also observed in large quantities. Table 3 and 4 list saplings species that were inventoried within buffers and flow paths.

Herbaceous

The buffers' average percentage groundcover vegetation for TA 9 was 57.05% with a range of 23% to 83%; TA 10 was 55.42% cover with a range of 38% to 70% (Table 1). The most common species were Japanese honeysuckle (*Lonicera japonica*) and periwinkle (*Vinca minor*) both invasive species. Eastern poison-ivy (*Toxicodendron radicans*), Allegheny blackberry (*Rubus allegheniensis*) and coralberry (*Symphoricarpos orbiculatus*) were found in all the sinkholes (Table 5). Herbaceous cover density was greater in the buffers than in the major flow paths for 20% of sinkholes.

Relationship of Stand Structural Characteristics

All of the vegetation structures which included overstory, sapling and herbaceous cover, within sinkholes' buffers and flow paths were positively correlated (Table 6). All regressions for vegetative structures have r^2 values between 0.000 to 0.308 indicating no correlation to positively correlated among the variables.

The relationship between sinkholes' overstory and herbaceous cover was found to be significant in the buffers but insignificant in the flow paths (Table 7 and Figure 9). Buffer mean percentage canopy cover and mean percentage herbaceous cover showed a moderate correlation ($r = -0.555$) and had a significant value ($p = 0.006$).

Stand Structural Characteristics and Sediment Accumulation

The widest and barest gully was typically the primary flow path which brought in more water and deposited the most sediment into the sinkholes. Sediment accumulation in splay areas showed no significant relationship to any vegetation structures (Table 8). Spearman correlations values were between 0.039 to -0.335 which indicated negatively weak to no relationship among the variables. Sediment gained in splay and flow paths mean percent vegetation cover had the strongest relationship ($r = -0.335$) and significant value ($p = 0.075$). Sediment gained and buffers mean percent herbaceous cover showed weak relationship ($r = 0.130$) and no significance ($p = 0.292$).

Sediment gained showed stronger correlation with vegetative structures as each variable added to the multiple regressions (Table 9). Correlation values were between 0.215

to 0.654 and r^2 values were between 0.046 to 0.428. Significant value at 0.025, model 1 ($p = 0.369$) and model 7 ($p = 0.337$) had the smallest significant values.

<u>Light data</u>

Percent of open canopy within sinkhole buffers of TA 9 and TA 10 had an average of 22.31% and 21.59%, respectively and flow paths averaged 27.82% and 30.29% respectively (Table 10). Correlation shows a moderate and positive association ($r = 0.547$) and statistical significance ($p = 0.003$) between percent open canopy in buffer and percent herbaceous cover within buffers (Table 11). There is no statistical significant for the percent herbaceous cover in flow paths ($p = 0.245$), and weak correlation ($r = 0.164$). Percent open canopy in flow paths has a moderate and negative correlation with average sapling cover in flow paths ($r = -0.439$ and $p = 0.026$). ANOVA analysis indicated that there are significant relationship between overstory open canopy and the herbaceous vegetation cover within sinkholes' buffers, $F = 9.447$ and $p = 0.007$.

<u>Sediment data</u>

Sediment deposition rates are shown in Table 12. The training areas are exporting an average of 118.59 metric ton yr^{-1} to the sinkholes, with an average accumulation rate of 4.80 cm yr^{-1}. The training areas are exporting approximately 26 metric ton yr^{-1} ha^{-1} to the 4 streams and approximately 39 metric ton yr^{-1} ha^{-1} to the 20 sinkholes (Crim 2009).

CHAPTER 5

DISCUSSION

Erosion and sedimentation entering into sinkholes are major problems in the army training areas of Fort Knox, Kentucky. Wheeled and tracked vehicles have caused most of the damage that include severe erosion problems. Existing vegetation on the edge of sinkholes, left undisturbed, were supposed to function as riparian buffers to reduce sediment and nutrients entering the sinkholes from water runoff. The relationship between sinkhole vegetation and sedimentation is not well known. This section will discuss: 1) the relationship between vegetation, overstory, understory and groundcover composition within sinkhole buffers, 2) the effectiveness of the overstory vegetation on herbaceous layers in buffers and flow paths, 3) the relationship of light availability influences on vegetation, 4) the effects of vegetation within sinkholes on the sediment deposition in splay areas.

Many studies have shown that riparian buffers were effective in reducing surface runoff and subsurface flow. Chemical and sediment deposition rates were reduced before entering streams and groundwater. The buffers promoted stream restoration which had been degraded by agricultural practices (Lyons et al. 2000). Agroforestry practices were also effective riparian systems which reduced nonpoint source pollution and improved water quality (Udawatta et al. 2010). Planting grass strips interspersed with trees and agricultural crops proved to have ecological and economic benefits.

Overstory

There were no significant relationships between overstory cover and sediment accumulated within sinkholes. The vegetation found within sinkholes was assumed to function as riparian buffers, but species of vegetation inventoried were not efficient in reducing sediment deposition. Much of the runoff entered sinkholes was in a concentrated form. There was evidence of sheet flow on tank trails and more evidence of rill erosion in at buffers edge. Later, runoff became more concentrated and channelized into flow paths. The buffering action of the vegetation was most likely limited due to the channelization of the surface runoff (Dosskey et al. 2002).

Riparian vegetation was well documented as a major influence to maintain water quality by reduction of chemicals movement to water bodies (Dosskey et al. 2010). Flow paths occupied a small area of the sinkholes' buffers but significantly controlled water movement from adjacent upland into the lower area such as sinkhole (Dosskey et al. 2002). This research showed when runoff from agriculture field was evenly distributed riparian buffers could potentially remove up to 99 percent of the sediment. On the contrary, where there was channelized runoff, riparian buffers removed only 49 percent of the sediment. In both TA 9 and 10, a significant amount of storm water runoff and sediment entered sinkholes via channelized flow paths. The species found in the buffer areas may not have the maximum capacity in reducing sediment. These species are associated with the natural succession process and were not planted. Overstory was comprised of eastern hardwood forest species. Major species were American sycamore, eastern cottonwood, and sassafras. Ground cover within flow paths were found to have slight influence in reducing sediment deposited in splay area (Table 11).

According to a survey of Fort Knox endangered species, most of vegetation within the reservation was secondary succession growth (White et al.1994). Timber was cleared for agriculture prior to the area becoming designated as military reservation. Oaks and hickories dominated the uplands and exposed slope. However, the major species found within sinkholes were considered edge species (Goran et al. 1983). The heavily used area impacted the species composition.

Multi-species riparian buffer vegetation research (in the order of silver maple, grass filter, switch grass), conducted in agriculture fields, suggested that silver maple (*Acer saccharinum*) was effective in reducing storm water runoff (Bharati et al. 2002). When woody species were systematically planted with the combination of other grass species, they reduced water runoff and therefore improved water quality. The overstory vegetation within sinkholes on the Karst Plateau (northern Kentucky region) included red maple (*Acer rubrum*), green ash (*Fraxinus pennylvanica*), possumhaw (*Ilex decidua*), sweet gum (*Liquidambar styraciflua*), and tupelo species (*Nyssa spp.*) (Baskin et al. 1997). However, these species were not found to be dominant in the research area. Micro climate and disturbances may result in different forest type with Fort Knox training areas.

Black willow (*Salix nigra*) was the dominant species within splay area because of topographic position and soil moisture. There was not statically significant relationship between vegetation in the splay and the reduction of sediment lost within sinkholes ($p = 0.075$). The correlation between total vegetation and sedimentation was weak ($r = 0.039$, $p= 0.435$). The only outlets from sinkholes were through the fractures and percolation between the rock layers and entering the ground water system. Vegetation in the splay areas may not have been effective in reducing sediment because water bypassed the vegetation and entered the groundwater through cracks and fissure (Raeisi et al. 2007; Vondracek 2006). Willow oak (*Quercus phellos*) was the most abundant species in sinkholes on the Kentucky Karst Plain region (Baskin et al.1997). The significant quantity of willow oak may due to the specie is associated with bottomland hardwood and relatively tolerant to flooding (Young et al. 1995).

Buffer Overstory and Herbaceous

The result of this study showed the negative relationship between overstory and herbaceous cover. The relationship of the canopy cover to the herbaceous was evident in the buffers but not flow paths. The higher the canopy cover, the less groundcover was on the sinkhole buffers. Canopy covers also influenced light penetration. The fewer canopy covers, the more sunlight reaches the ground layer and the more photosynthesis occurs for plants, thereby influencing the abundance of herbaceous. Light reaching the ground was directly affected by canopy cover (North et al. 2005). When photosynthesis occurred, more energy and water was needed to produce energy; this process had potential for moisture stress (Pausas & Austin 2001). Herbaceous cover required more water uptake and abundance of stems and roots slow down the water flow velocity and therefore more water percolates to the ground. As a result, storm water runoff was reduced prior to entry into sinkholes. Herbaceous vegetation also competed with woody vegetation for water in the summer months (Davis et al. 1998). The flow path might be excessively disturbed by the amount of the runoffs and sediment for the herbaceous vegetation to take the advantage of the sunlight.

There was no significant relationship between buffer mean percentage herbaceous cover and sediment in the sinkhole ($p = 0.292$). Herbaceous vegetation within the sinkholes was not effective in reducing sediment. Concentrated flow paths influenced the effectiveness of herbaceous cover in reducing sedimentation. Grass-shrub vegetation as stream riparian buffers significantly reduced sedimentation into streams and was positively accepted by farmers as management practices (Barden et al. 2003).

This study also measured light penetration in the sinkhole buffers and flow paths. Light may have influenced the abundance of herbaceous cover. The relationship between sunlight and the response of herbaceous richness was studied and found that the herbaceous response to sunlight, higher cover and richness associated with direct and more sunlight reaching the ground. Most herbaceous cover under a closed canopy in semi arid ecosystem was influenced by soil moisture (North et al. 2005). In this study, no moisture data was obtainable from the buffers or flow paths. The relationship between light availability and herbaceous cover was significant in the sinkhole buffers ($p = 0.003$) but not flow paths ($p = 0.304$). Light was reliable in predict the abundance of herbaceous cover in buffers but not in flow paths. In flow paths, the disturbance from water runoff and channelization may have limited herbaceous vegetation to benefit from sunlight availability on the forest floor.

Flow path Overstory and Saplings

The relationship between flow paths overstory percent cover and quantity of sapling was significant with positive correlation ($r^2 = 0.439$, $p = 0.026$). In the flow path, increasing canopy cover resulted in increasing saplings. The results were unanticipated; the correlation between overstory and saplings was expected to have negative relationship. As canopy cover increases, less saplings or understory vegetation presence because of the less available light for photosynthesis. The amount of sunlight that reached the understory depended on the opening of the canopy, location of the opening and structure of the forest (Battaglia 2000). The canopy shade is likely to benefit understory under dry conditions by reducing drought stress. Because of the effects of light and water availability under canopy cover may contribute to the positive correlation of the flow path overstory and saplings (Callaway et al.1991).

Woody vegetation is commonly used in stream bank stability to minimize erosion. Woody debris and forest floor duff also slow down the flow of storm runoff. Wooded riparian soils have generally good infiltration capacity because of the root systems. The abundance of the saplings in the flow path under canopy cover may be due to lower competition from herbaceous cover. Herbaceous vegetation can substantially reduce soil water under the canopy shade, therefore the survival of the tree seedling could be lower (Davis et al. 1999). There was no significant difference between flow path canopy cover and herbaceous cover ($p = 0.345$). Herbaceous cover was considerably less abundant; this may be a factor to the positive correlation of the overstory and sapling in the flow path. In this study saplings found within buffers had a moderate to weak relationship ($r = 0.439$, $p = 0.026$). The abundance of saplings in buffers may contribute to soil stability and therefore less channelization and fewer flow paths.

Herbaceous layers

In sinkhole buffer areas, herbaceous vegetation covers was most abundant where sunlight was the most available ($p = 0.003$). This research hypothesized that the abundance of the overstory would affect the abundance of the herbaceous percentage cover. The relationship between overstory and herbaceous cover would be negative, the greater the overstory canopy cover, the lesser the herbaceous cover.

Buffers

Within sinkhole's buffers, there was a significant relationship between the canopy and herbaceous cover ($p = 0.006$). Herbaceous vegetation was most abundant where sunlight was most available. This finding corresponded with Cole and Weltzin (2005) who also found most understory species were most abundant where canopy covers were partially enclosed. In areas within sinkhole buffers that were without any overstory cover, herbaceous vegetation covered up to 100% of the research plot. Small numbers of woody seedlings were found amid herbaceous cover. Herbaceous vegetation competed vigorously for water with other vegetation and water became a limited resource (Davis et al. 1998). This may have caused the minimal growth of small seedlings within sinkhole buffers where herbaceous was plentiful.

The most frequently found herbaceous species within sinkhole buffers were: periwinkle, coralberry, and Japanese honeysuckle. The percentage ground cover of the species was unevenly distributed throughout both training areas, due to the overstory cover and the disturbance intensity. The more diverse the overstory species, the greater the diversity of understory vegetation in oak stands (Simmons & Buckley 1992). However, there was not a pattern occurrence of herbaceous species under certain overstory species. The influence of overstory composition and stand structure on herbaceous mixed aspen forest of northern Minnesota was examined and found that the diversity of the understory composition was moderately explained by overstory structure (Berger & Puettmann 2000). The disturbances within training areas could have been a factor in the distribution and diversity of the herbaceous plants. The understory vegetation within training areas with different training intensities at Fort Benning, Georgia, found diversity of species among understory vegetation (Dale et al. 2002).

Flow paths

Within the sinkholes' concentrated flow paths, there was no correlation between overstory vegetation and herbaceous cover (r = 0.007). Concentrated flow paths were observed to limit the potential of riparian buffers because sediment trapping ability was reduced when runoff was channelized into sinkholes (Dosskey et al. 2002). There was little research found in the relationship between herbaceous cover in the concentrated flow paths to the overstory cover. The abundance of herbaceous plants within flow paths may not be influenced by canopy cover or light availability. Concentrated flow paths contributed to the weak relationship between herbaceous cover and sediment due to the irregular and inconsistent flow to water. The dynamic of periwinkle and Japanese honeysuckle were most likely a function of the soil and water because they found the most abundance within flow paths and near splay area. Without the knowledge of soil and water, and measurement of these elements, ability to make inferences is limited.

Vegetation buffers were more effective when runoff was dispersed through existing buffers. Herbaceous vegetation competed for water and therefore took up more water from soil surface due to a relatively shallow root system (Wynn & Mostaghimi 2006). Vegetation was widely accepted as bank stabilization and restoration. Herbaceous cover was also a good indicator of soil erosion. Stream banks with less than 10 percent herbaceous cover experienced the highest percentage of soil erosion (Heartsill-Scalley & Aide 2003). Herbaceous covers slowed down storm runoff and trapped sediment from entering sinkholes when the flow of water was more spread out. However in training areas at Fort Knox, concentrated flow paths channelized runoff into sinkholes, and the buffering function of the vegetation was greatly reduced.

<u>Light</u>

Light availability on the forest floor was greatly dependent on overstory canopy cover. In Training Areas 9 and 10, vegetation on the forest floor was negatively correlated with closed canopy overstory and positively correlated with open canopy overstory. There was less vegetation production where less sunlight reached the forest floor. The result of this study was consistent with the study of light availability in northern hardwood forest research which found that light was negatively correlated with the abundance of midstory vegetation (Miller et al. 2002; Messier et al. 1998). In this study light influenced the abundance of the quantity of sapling within flow paths ($p = 0.026$). Within sinkholes' buffers light also affect the abundance of the herbaceous cover ($p = 0.003$).

Light both directly and indirectly influences understory vegetation composition. Light reduction from dense overstory cover contributed to the establishment of herbaceous in the buffers and sapling around the flow path. The reduction of light influenced the dispersal of introduced grass species in eastern deciduous forests in the United States (Cole & Weltzin 2005). In contrast, in this study light did not have any significant role in influencing the establishment of herbaceous cover within flow paths ($p = 0.245$). The amount of sediment and water might have caused these unanticipated results.

<u>Sedimentation</u>

Sediment accumulation or eroded within sinkholes in both training areas did not significantly correlate to vegetation composition or structure. R squared values were close to zero for all the variables related to sediment. This demonstrates that vegetation within sinkholes did not have an impact on sedimentation ($p = 0.435$). Flow paths were the major contributor of sediment in sinkholes, which affected the role of vegetation as buffers. Water runoff was channelized to the sinkholes and bypassed the vegetated portions of the buffers so that the vegetation did not intercept sediment prior to reaching splay areas. Bottles placed in the center of the splay and those between the center and outer edge experienced significantly greater sediment accumulation than the bottles placed on the outer portion of the splay. Therefore, it is likely that the sinkholes are experiencing some sediment loss to the underground drainage network. A mound is not forming towards the center of the splay, i.e. the plug is likely sinking (Crim 2009).

Few studies were found regarding concentrated flow of sediment into streams. However, many researchers observed that vegetation buffers became ineffective when there was a break in buffers and sediment bypassed buffers through concentrated flow (Dosskey et al. 2002). Otter Creek flows north through TA 9 and TA 10. Water quality downstream of the training areas was found to be significantly degraded because of the training activities occurring in these areas. Crim's (2009) study revealed that a total suspended solid (TSS) was higher in Otter Creek where it exiting TA 10 than where the creek entered TA 9 (Figure 19 and Table 13). Concentrated flow paths may have greatly restricted the buffers ability to trap sediment (Dosskey et al. 2002). In training areas, the evidence of the land grading to reduce concentrated flow paths and disperse the runoff before reaching buffers was along the main trails. Land grading must be maintained regularly otherwise additional sediment will enter sinkhole. The efficiency of the buffers was also based on the distribution of runoff area. However in military training areas, the activities and the intensity of the training also contributed to the overall area surface erosion.

A widely accepted management guideline was published by USDA (Walsch 1996). The functions of the different buffer zones (grass and forbs, scrubs, and trees) depended upon the size of watershed and agricultural activity. Recommendations made for site preparation and maintenance were extensive before establishment of the buffers. Based on the study, forest riparian buffers could be applied to a variety of ecosystem and land use activities. Different agroforestry buffer designs could be more effective in reducing the nonpoint source (NPS) pollutants in streams and ground water and meeting management objectives (Schultz et al. 2004)

A future opportunity for this type of study is the design of inventories in training areas on different army installations. In addition an inventory resources where karst topography exists or irregular runoff patterns could use this research a baseline. The results could be unexpected. Anthropogenic disturbances such as wheeled and tracked vehicles can alter the results. Furthermore, additional soil and water information from sinkholes is recommended was subject of future research to link vegetation composition and structure. However, recommendations to improve the training areas for restoration can be applied to most riparian buffers.

Study Limitations

Time was the most limiting factor for this study because the summer of 2009 was the only season for data collection. The dates and times for the data collection were also limited because of the military training exercises and consequently limited access to the training areas. The location of the study area was also a challenge. Military training areas are often remote, and the fact combined with restrictions caused many unpredictable incidents. These variables caused data collection procedures to slow down or cease. Some sinkholes were inaccessible after rain events, and mud and clay immobilized the All Terrain Vehicle (ATV). Therefore data collection was completed only during dry, summer days. Due to time and other factors, the original 40 sinkholes that were planned to sample; only data from 20 sinkholes were collected. Four transects for each sinkhole were pre-designated to assess the buffer's vegetation was reduce to two systematic transects during data collection due to limited time and personnel.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This study has shown that riparian buffers in sinkholes were not as effective in reducing sediment entering catchment areas in military training areas on karst terrain at Fort Knox, Kentucky.   This was due to the concentrated flow paths that channelized runoff from bare tank trails into sinkholes and bypassed the vegetated buffers. However, weak and negative relationships between sediment gained and the total area of vegetation may indicate that the overall vegetation contributed to reducing sediment.

The relationship among the vegetation composition and structure within sinkholes was more obvious. The results suggest that sediment entered Otter Creek increases as the creek flows through training areas (Table 13). Concentrated flow paths contributed to sedimentation in splay areas. Flow paths that are directly connected to splay area can negate any positive effect of the vegetated buffer. The width of the buffers around sinkholes was inadequate due to tank trails being so close to the buffer edge. However, more bare ground around sinkholes can be a factor in the amount of sedimentation.

Based on this study and published literature, concentrated flow paths should be dispersed prior to reaching the buffers. The relationship between herbaceous covers in the flow paths and the amount of sediment gained in sinkholes was moderate, and might be more effective than longer buffer width in reducing sediment around sinkhole buffers.

Perhaps, the scientific research on the effects of military activities can be implemented in other army training areas where types of impacts match those found in this study. In the long run, it is feasible to convert the vegetative species to improve the riparian buffers in such heavily exploited areas, if limit use of military vehicles. The opportunity for this type of research on military installation is substantial because it is necessity to minimize the impact from military activities.

Recommendations for best management practices are an integration of this research finding, current knowledge on riparian buffers and training areas management requirements for Fort Knox.   Riparian buffer zoning guidelines from USDA and Crim's recommendations should be implemented throughout training areas. Fort Knox training areas required that all sinkholes should have at least 75 meters of vegetated buffers which extend from the edge of the splay area to the tank trail. In addition, based on this research's findings the following management practices are recommended:

- Zone 3, adjacent to tank trails and roads, maintain native shrubs, herbaceous and grass to disperse water runoff prior reaching the buffers,
- Newly planted areas must be clearly marked and protected from training activities,
- To reduce the number of flow paths, native grasses and herbaceous covers should be planted to stabilize the ground and increase soil quality,
- Harvesting of overstory to allow more light to reach forest floor to promote herbaceous cover.

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APPENDICES

Table 1. Summary of sinkhole and vegetation data collected in Training Area 9 and 10

Sinkholes	Catch Area (m^2)	Splay Area (m^2)	Veg Area (m^2)	%Veg Area	Basal Area ($ft^2\,ac^{-1}$)	Buffer # of Saplings	Buffer Saplings per m^2	FP # of Saplings	FP Saplings per m^2	Average % Herb Buffer	Average % Herb Flow path	Average % CC Buffer	Average % CC FP	Average % CC Splay
9-2	11759	567.31	6245.23	53.11	56.0	3.2	0.25	1.0	0.08	54	31	82	55	80
9-6	16535	957.32	9864.44	59.66	90.0	4.0	0.32	6.0	0.48	23	28	87	82	67
9-7	50522	2866.98	28282.13	55.98	80.0	2.3	0.18	1.0	0.08	45	52	91	88	31
9-9	10194	1235.38	3869.09	37.95	100.0	1.0	0.08	2.0	0.16	50	32	68	74	77
9-11	24676	1749.41	13545.86	54.89	36.7	3.0	0.24	2.5	0.20	79	45	67	60	73
9-12	15784	1307.70	6577.07	41.67	43.3	3.7	0.29	4.7	0.37	54	34	84	54	19
9-15	14976	1124.65	7718.39	51.54	40.0	4.0	0.32	0.0	0.00	72	73	71	53	14
9-16	9773	1198.04	3347.82	34.26	50.0	1.0	0.08	1.0	0.08	83	68	57	54	62
9-18	6846	926.16	3695.34	53.98	55.0	5.0	0.40	8.0	0.64	67	61	86	91	71
9-20	28437	3240.18	17095.08	60.12	80.0	3.4	0.27	3.3	0.27	44	63	85	84	63
10-1	29916	3634.30	16061.24	53.69	62.9	2.9	0.23	5.5	0.44	63	63	63	67	55
10-2	52616	3668.27	15068.46	28.64	47.5	2.3	0.18	6.0	0.48	65	55	79	58	72
10-3	10006	929.49	4886.11	48.83	74.3	5.0	0.40	12.0	0.96	38	25	88	91	84
10-4	138802	4310.19	84071.63	60.57	81.4	3.0	0.24	5.0	0.40	60	23	86	70	74
10-5	10572	815.01	3449.95	32.63	37.5	2.8	0.22	4.7	0.37	49	47	66	80	69
10-6	54469	3961.44	31842.48	58.46	56.0	3.4	0.27	0.3	0.03	70	40	71	57	64
10-7	35151	4020.63	8864.99	25.22	49.6	5.7	0.45	1.8	0.14	48	25	76	58	44
10-8	25981	2168.93	12075.55	46.48	32.7	7.0	0.56	7.5	0.60	58	66	90	82	16
10-9	42477	3694.35	19918.11	46.89	40.9	4.0	0.32	5.0	0.40	45	15	85	80	31
10-18	6372	836.97	1856.92	29.14	70.0	4.0	0.32	1.0	0.08	59	38	81	26	80

Table 2. Number of observed stems, average diameter at breast height and names of overstory species found within sinkhole buffers and flow paths

Common Name	**Scientific Name**	**Ave DBH**	**# Observed**
Sassafras	*Sassafras albidum*	4.75	66
Eastern cottonwood	*Populus deltoides*	14.21	60
Eastern red cedar	*Juniperus virginiana*	6.45	35
Blackjack oak	*Quercus marilandica*	14.14	31
American sycamore	*Platanus occidentalis*	10.66	29
Black willow	*Salix nigra*	6.2	26
Red hickory	*Carya ovalis*	11.305	20
American elm	*Ulmus americana*	8.64	19
Flowering dogwood	*Cornus florida*	3.85	18
Shingle oak	*Quercus imbricaria*	9.27	18
Common persimmon	*Diospyros virginiana*	5.19	17
Kentucky coffee tree	*Gymnocladus dioicus*	8.87	16
Pin oak	*Quercus palustris*	17.58	16
Red maple	*Acer rubrum*	7.85	13
Box elder	*Acer negundo*	6.55	10
Post oak	*Quercus stellata*	16.49	9
Swamp white oak	*Quercus bicolor*	7.9	9
Black cherry	*Prunus serotina*	5.3	8
Black locust	*Robinia pseudoacacia*	6.5	8
Chinkapin Oak	*Quercus muehlenbergii*	11	6
Black walnut	*Juglans nigra*	9.12	5
Yellow-poplar	*Liriodendron tulipifera*	11.82	5
Alternate-leaf dogwood	*Cornus alternifolia*	3.225	4
Green ash	*Fraxinus pennsylvanica*	5.83	4
Black hickory	*Carya texana*	13.5	3
Indistinguishable	Indistinguishable	8.33	3
Red mulberry	*Morus rubra*	2.5	3
Shagbark hickory	*Carya ovata*	11.3	3
American basswood	*Tilia americana*	7.85	2
Chestnut oak	*Quercus prinus*	9	2
Northern red oak	*Quercus rubra*	14.6	2
Pawpaw	*Asimina triloba*	5.75	2
Cherrybark oak	*Quercus pagoda*	30.5	1
Eastern redbud	*Cercis canadensis*	3.7	1
Honey locust	*Gleditsia triacanthos*	8.5	1
Roughleaf dogwood	*Cornus drummondii*	5	1
Southern red oak	*Quercus falcata*	20	1
White oak	*Quercus alba*	29	1
Winged sumac	*Rhus copallina*	4.2	1

Table 3. Major sapling species found within sinkhole buffers of Training Areas 9 and 10

Common Name	**Scientific Name**
American Elm	*Ulmus americana*
*American Sycamore	*Platanus occidentalis*
Black Cherry	*Prunus serotina*
Black Locust	*Robinia pseudoacacia*
Black Willow	*Salix nigra*
Blackjack Oak	*Quercus marilandica*
Boxelder	*Acer negundo*
Common Persimmon	*Diospyros virginiana*
*Eastern Cottonwood	*Populus deltoides*
Eastern red cedar	*Juniperus virginiana*
Flowering Dogwood	*Cornus florida*
Kentucky Coffee tree	*Gymnocladus dioicus*
Pin Oak	*Quercus palustris*
Red Hickory	*Carya ovalis*
Red Maple	*Acer rubrum*
*Sassafras	*Sassafras albidum*
Shingle Oak	*Quercus imbricaria*
Swamp White Oak	*Quercus bicolor*

Table 4. Major sapling species found within sinkhole flow paths of Training Areas 9and 10

Common Name	**Scientific Name**
*FloweringDogwood	*Cornus florida*
*Sassafras	*Sassafras albidum*
*Red Maple	*Acer rubrum*
Common Persimmon	*Diospyros virginiana*
Black Willow	*Salix nigra*
American Sycamore	*Platanus occidentalis*
Devil's Walkingstick	*Aralia spinosa*
American Elm	*Ulmus americana*
Red Hickory	*Carya ovalis*
Black Locust	*Robinia pseudoacacia*
Eastern Cottonwood	*Populus deltoides*
Eastern Redcedar	*Juniperus virginiana*
Boxelder	*Acer negundo*

*3 most common species

Table 5. Herbaceous species found within buffers and flow paths within sinkholes of Training Areas 9 and 10

Buffers		Flow paths	
Common Name	**Scientific Name**	**Common Name**	**Scientific Name**
American elm	*Ulmus americana*	American. elm	*Ulmus americana*
American sycamore	*Platanus occidentalis*	Annual ragweed	*Ambrosia artemisiifolia*
Annual ragweed	*Ambrosia artemisiifolia*	Black medic	*Medicago lupulina*
Black medic	*Medicago lupulina*	Black willow	*Salix nigra*
Black willow	*Salix nigra*	Blackberry	*Rubus allegheniensis*
Blackberry	*Rubus allegheniensis*	Blue-stemmed goldenrod	*Solidago caesia*
Blackjack oak	*Quercus marilandica*	Buttonbush	*Cephalanthus occidentalis*
Blue phlox	*Phlox divaricata*	Cattail sedge	*Carex typhina*
Blue-stemmed goldenrod	*Solidago caesia*	Common blue violet	*Viola sororia*
Boxelder	*Ace negundo*	Common cinquefoil	*Potentilla simplex*
Bull thistle	*Cirsium vulgare*	Common persimmon	*Diospyros virginiana*
Buttonbush	*Cephalanthus occidentalis*	Common plantain	*Plantago major*
Chestnut oak	*Quercus prinus*	Common sunflower	*Helianthus annuus*
Chinkapin oak	*Quercus muehlenbergii*	Coralberry	*Symphoricarpos orbiculatus*
Cleavers	*Galium aparine*	Crabgrass	*Digitaria spp.*
Common blue violet	*Viola sororia*	Crownvetch	*Securigera varia*
Common cinquefoil	*Potentilla simplex*	Daisy fleabane	*Erigeron annuus*
Common persimmon	*Diospyros virginiana*	Dandelion	*Taraxacum officinale*
Common plantain	*Plantago major*	Devil's walkingstick	*Aralia spinosa*
Common sunflower	*Helianthus annuus*	Downy skullcap	*Scutellaria incana*
Common yarrow	*Achillea millefolium*	Dutchman's breeches	*Dicentra cucullaria*
Coralberry	*Symphoricarpos orbiculatus*	Eastern poison ivy	*Toxicodendron radicans*
Crabgrass	*Digitaria spp.*	Fall panicgrass	*Panicum dichotomiflorum*
Daisy fleabane	*Erigeron annuus*	Flowering dogwood	*Cornus florida*
Dalligrass	*Paspalum dilatatum*	Giant foxtail	*Setaria faberi*
Devil's walkingstick	*Aralia spinosa*	Green briar	*Smilax spp.*
Downy skullcap	*Scutellaria incana*	Hoary ticktrefoil	*Desmodium canescens*
Dutchman's breeches	*Dicentra cucullaria*	Hop clover	*Trifolium agrarium*
Early spurge	*Euphorbia commutata*	Japanese honeysuckle	*Lonicera japonica*
Eastern poison ivy	*Toxicodendron radicans*	Jerusalem artichoke	*Helianthus tuberosus*
Eastern red cedar	*Juniperus virginiana*	Johnson grass	*Sorghum halepense*
Fall panicgrass	*Panicum dichotomiflorum*	Kentucky bluegrass	*Poa pratensis*
Flowering dogwood	*Cornus florida*	Kudzu	*Pueraria lobota*
Fragrant bedstraw	*Galium triflorum*	Oxeye daisy	*Chrysanthemum leucanthemum*

Buffers

Common Name	Scientific Name
Garlic mustard	*Trifolium agrarium*
Jerusalem artichoke	*Helianthus tuberosus*
Johnson grass	*Sorghum halepense*
Kudzu	*Pueraria lobota*
Lovegrass	*Eragrostis Spp.*
Mayapple	*Podophyllum peltatum*
Narrowleaf mountainmint	*Pycnanthemum tenuifolium*
Oxeye daisy	*Chrysanthemum leucanthemum*
Partridgepea	*Cassia fasciculata*
Periwinkle	*Vinca minor*
Post oak	*Quercus stellata*
Queen Anne's lace	*Daucus carota*
Red clover	*Trifolium pratense*
Red hickory	*Carya ovalis*
Red maple	*Acer rubrum*
Red mulberry	*Morus rubra*
Rush	*Juncus spp.*
Sassafras	*Sassafras albidum*
Sedge	*Carex spp.*
Sericea lespedeza	*Lespedeza cuneata*
Shining bedstraw	*Galium concinnum*
Spangle grass	*Chasmanthium Latifolium*
Swamp milkweed	*Asclepias spp.*
Swamp white oak	*Quercus bicolor*
Violet woodsorrel	*Oxalis violacea*
Virginia creeper	*Parthenocissus quinquefolia*
White heath aster	*Symphyotrichum ericoides*
White oak	*Quercus alba*
White snakeroot	*Ageratina altissima*
White sweet clover	*Melilotus alba*
White wild licorice	*Galium circaezans*
Wild rose	*Rosa spp.*
Wild yam	*Dioscorea villosa*
Winged sumac	*Rhus copallina*
Yellow sweet clover	*Melilotus officinalis*
Yellow-poplar	*Liriodendron tulipifera*

Flow paths

Common Name	Scientific Name
Red maple	*Acer rubrum*
Rush	*Juncus spp.*
Sassafras	*Sassafras albidum*
Sedge	*Carex spp.*
Virginia creeper	*Parthenocissus quinquefolia*
White sweet clover	*Melilotus alba*
Wild rose	*Rosa spp.*
Yellow sweet clover	*Melilotus officinalis*

Table 6. Summary of linear regression results for vegetative structures to test for significance between variables

Independent Variables Dependent Variables	Correlation		t-Value	*p-Value	Standardized Coefficient Beta
	R	R^2			
Total vegetation area Buffers mean % canopy cover	0.369	0.136	1.404	0.055	0.314
Total vegetation area Flow paths mean % canopy cover	0.393	0.154	2.07	0.043	0.438
Total vegetation area Splay area mean % veg cover	0.021	.0004	-0.087	0.465	-0.02
Buffer mean % canopy cover Buffer mean % herb cover	-0.555	0.308	-3.082	0.006	-0.588
Buffer mean % canopy cover Mean sapling per M^2	0.439	0.193	2.042	0.026	0.434
Buffer mean % canopy cover Buffer basal area (ft^2 ac^{-1})	0.270	0.073	1.012	0.124	0.232
Flow paths mean % canopy cover Flow paths mean % herb cover	-0.095	.009	-0.029	0.345	-0.007

* Sig. (1-tailed)

Table 7. Summary of table of linear regression of overstory cover and herbaceous layers within sinkholes buffers and flow paths

	DF	R Square	Unstandardized Coefficeints	Standardized Coefficient	Std. Error	ANOVA F-Value	ANOVA *P-Value
Buffers mean percent canopy cover Buffers mean percent herbaceous cover	1,18	0.345	-0.843	-0.588	0.274	9.496	0.006
Flow paths mean percent canopy cover Flow paths mean percent herbaceous cover	1,18	0.000	-0.007	-0.007	0.246	0.001	0.977

* sig. (2-tailed)

Table 8. Summary of linear regression results of sediment gained within sinkholes to individual dependent variables

	Spearman's rho Correlation	p-value*	ANOVA	
			F-value	Sig
Sediment gained (Ton/Yr) Buffer basal area (ft^2 ac^{-1})	-0.160	0.251	0.421	0.525
Sediment gained (Ton/Yr) Total vegetation area	0.039	0.435	0.869	0.364
Sediment gained (Ton/Yr) Buffer mean percent canopy cover	-0.198	0.201	0.219	0.645
Sediment gained (Ton/Yr) Buffer mean percent herbaceous cover	0.130	0.292	0.000	0.992
Sediment gained (Ton/Yr) Flow paths mean percent canopy cover	-0.108	0.324	0.151	0.702
Sediment gained (Ton/Yr) Flow paths mean percent herbaceous cover	-0.172	0.234	2.121	0.162
Sediment gained (Ton/Yr) Splay area mean percent vegetation cover	-0.335	0.075	0.618	0.442
Sediment gained (Ton/Yr) Average sapling per M^2	-0.222	0.173	1.715	0.207

*Sig. (1-tailed)

Table 9. Summary of multiple regression and ANOVA results of sediment gained in sinkholes and stand structural characteristic

	R	R^2	Adjusted R^2	DF	ANOVA F-value	ANOVA P-value
Model 1	0.215	0.046	-0.007	1, 18	0.089	0.369
Model 2	0.219	0.048	-0.064	2, 17	0.429	0.658
Model 3	0.22	0.048	-0.13	3, 16	0.271	0.845
Model 4	0.417	0.174	-0.046	4, 15	0.79	0.549
Model 5	0.446	0.199	-0.087	5, 14	0.696	0.635
Model 6	0.569	0.323	0.011	6, 13	1.035	0.446
Model 7	0.654	0.428	0.094	7, 12	1.281	0.337

Dependent: Sediment gained

Model 1: Percentage total vegetation areas

Model 2: Model 1 + Buffer mean % canopy cover

Model 3: Model 2 + Flow paths mean % canopy cover

Model 4: Model 3 + Flow paths mean % herbaceous cover

Model 5: Model 4 + Buffers mean % herbaceous cover

Model 6: Model 5 + Splay area mean vegetation

Model 7: Model 6 + Average sapling per M^2

Table 10. Summary of average percent open canopy (OC) and closed canopy (CC) within sinkholes buffers, flow paths, and splays areas

Sinkhole	Ave % OC in Buffer	Ave % CC in Buffer	Ave % OC in Flow path	Ave % CC in Flow path	Ave % OC in Splay	Ave % CC in Splay
9-2	18.15	81.85	17.2	82.8	20.50	79.50
9-6	13.40	86.60	18.20	81.80	33.00	67.00
9-7	9.23	90.78	12.50	87.50	69.20	30.80
9-9	32.10	67.90	26.30	73.70	23.10	76.90
9-11	33.33	66.67	39.93	60.07	27.00	73.00
9-12	16.03	83.97	45.67	54.33	81.10	18.90
9-15	28.60	71.40	46.80	53.20	86.30	13.70
9-16	42.90	57.10	45.80	54.20	38.20	61.80
9-18	14.30	85.70	9.40	90.60	29.10	70.90
9-20	15.07	84.93	16.38	83.62	37.20	62.80
10-1	37.03	62.97	32.65	67.35	45.20	54.80
10-2	20.93	78.25	41.60	58.40	27.60	72.40
10-3	11.80	88.20	9.40	90.60	16.10	83.90
10-4	14.36	85.64	30.40	69.60	26.00	74.00
10-5	33.65	66.35	19.93	80.07	30.90	69.10
10-6	28.66	71.34	43.10	56.90	35.60	64.40
10-7	24.27	75.73	42.25	57.75	55.90	44.10
10-8	10.03	89.97	18.35	81.65	84.50	15.50
10-9	15.40	84.60	20.15	79.85	69.20	30.80
10-18	19.10	80.90	47.50	52.40	20.50	79.50

Table 11. Summary of linear regression results of open canopy (light penetration) and understory vegetation

	Spearman's rho Correlation	p-value*	ANOVA F-value	ANOVA Sig
Percent open canopy in flow paths (Light) Percent herbaceous cover in flow paths	0.164	0.245	0.274	0.607
Percent open canopy in buffer (Light) Percent herbaceous cover in buffer	0.547	0.003**	9.447	0.007
Percent open canopy in flow paths (Light) Flow paths mean sapling cover	-0.439	0.026	7.489	0.014

*Sig. (1-tailed)
** Significant at the .025 level

Table 12. Sediment deposition rates in sinkholes (Crim 2009)

Sinkhole	Sediment Depth (cm yr^{-1})	Mass Export from TA (metric ton yr^{-1})	Mass Export from TA (metric ton yr^{-1} ha^{-1})	Drainage Area (ha)
10-7*	16.64	682.19	194.16	3.51
9-11*	10.52	296.78	120.32	2.47
9-9*	7.52	116.07	113.90	1.02
10-9*	7.92	273.06	64.31	4.25
10-6*	6.07	263.76	48.44	5.44
9-7*	9.41	244.16	48.35	5.05
10-1	4.78	109.73	36.69	2.99
10-2	6.06	137.44	26.13	5.26
9-15	4.28	38.93	26.01	1.50
9-6	3.69	31.93	19.32	1.65
9-16	2.64	15.11	15.47	0.98
10-8	3.63	32.30	12.44	2.60
9-2	2.28	9.57	8.14	1.18
9-12	1.85	10.78	6.83	1.58
10-5	2.36	6.95	6.57	1.06
10-4	3.26	83.01	5.98	13.87
9-18	1.22	3.82	5.59	0.68
10-3	1.82	4.53	4.53	1.00
10-18	1.37	2.25	3.54	0.64
9-20	1.17	9.43	3.32	2.84
TA 9 Average	4.42	76.81	36.72	4.54
TA 10 Average	5.20	150.01	40.28	1.42
Overall Average	4.80	118.59	38.50	2.98

*Priority Sinkholes (Top 3 Sinkholes in Each TA with Highest Sedimentation Rates)

Table 13: Mean to TSS entering Otter Creek at TA 9 and exiting Otter Creek at TA 10. TSS increased as Otter Creek flows through training areas.

	Mean Entering mg/L (TA 9)	Mean Exiting mg/L (TA 10)	SE Entering mg/L	SE Exiting mg/L
Baseflow	4.24	7.23	0.55	1.17
Stormflow	9.9	32.68	2.89	4.07
Combined Flows	5.83	14.33	0.96	2.24

Figure 9. Comparison of linear regressions between percent herbaceous vegetation cover and percent overstory open canopy within sinkholes' buffers and flow paths

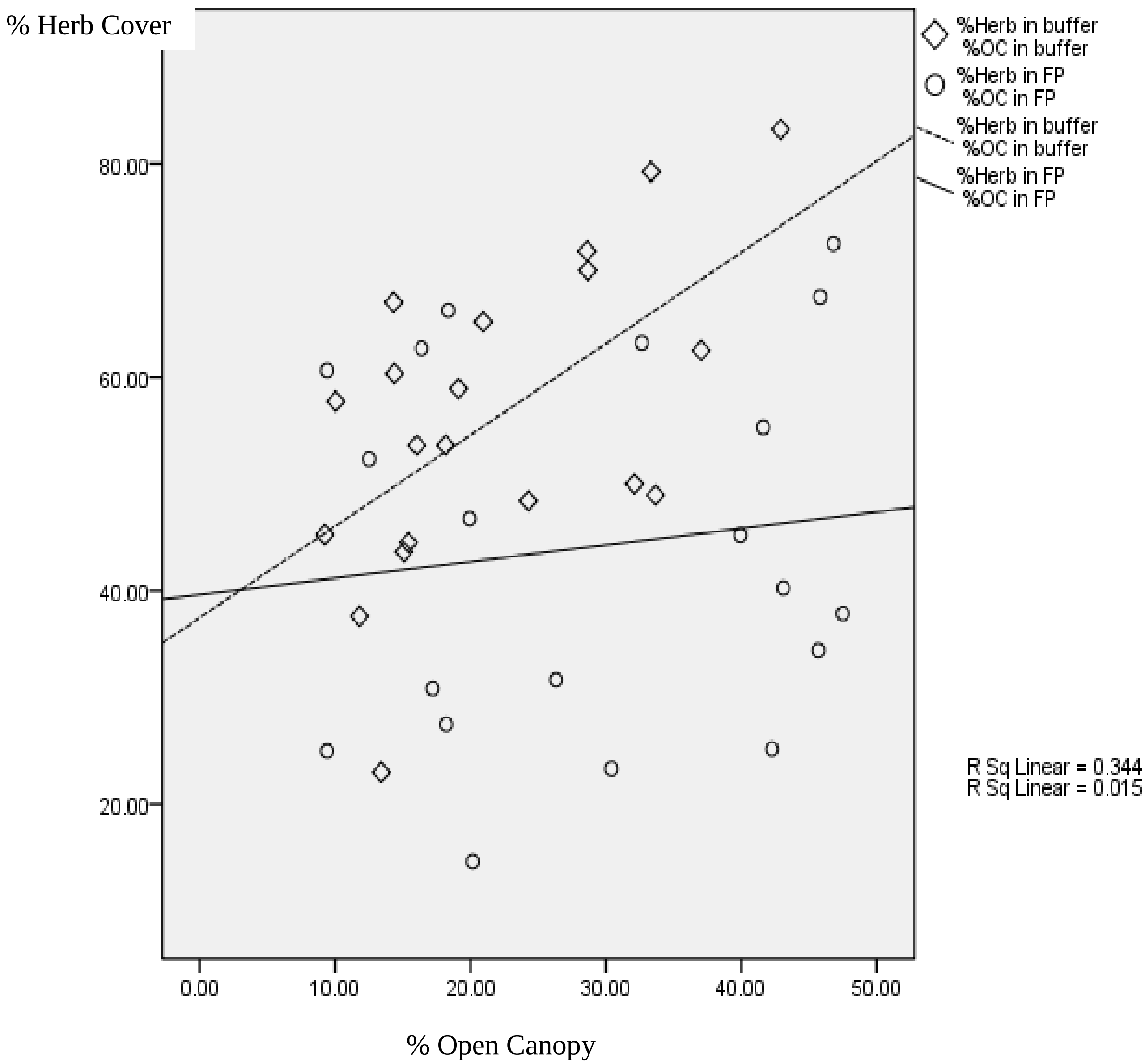


Figure 10. Comparison of the means of the percent herbaceous vegetation cover and percent open canopy (densiometer reading) within buffers

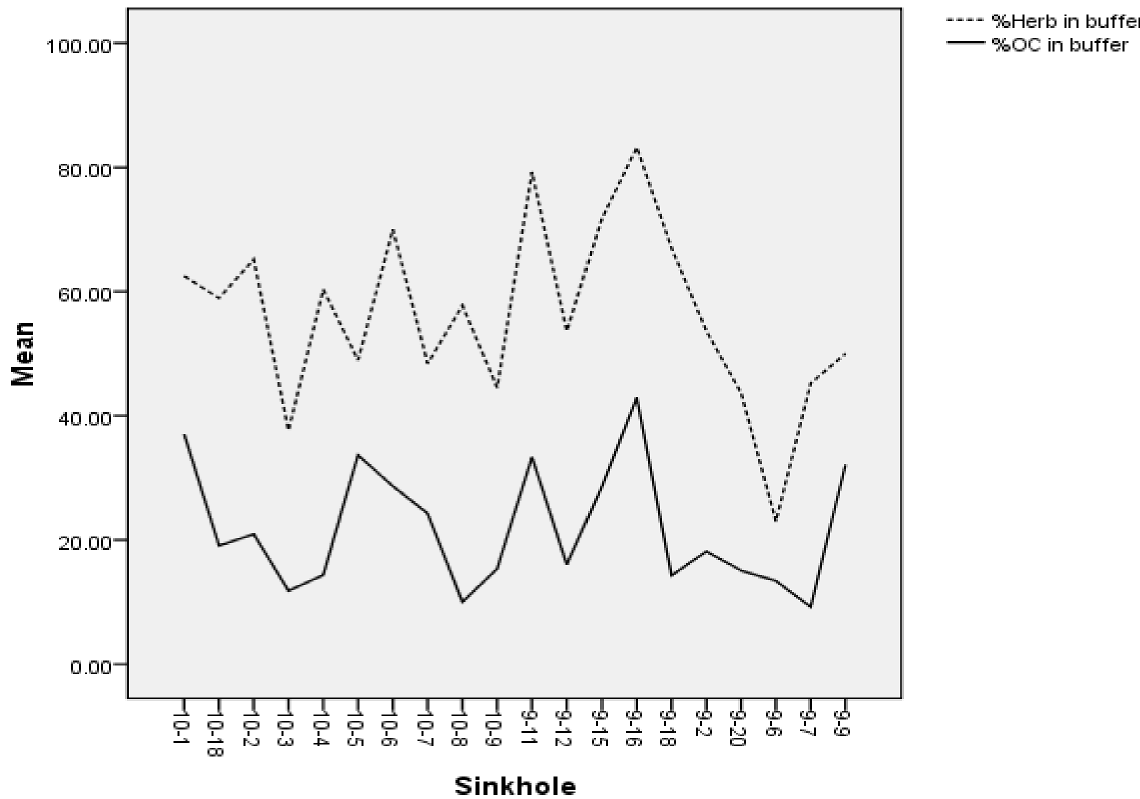


Figure 11. Correlation of percent herbaceous vegetation cover and overstory open canopy within buffers, p-value = 0.003 (significant level at 0.025)

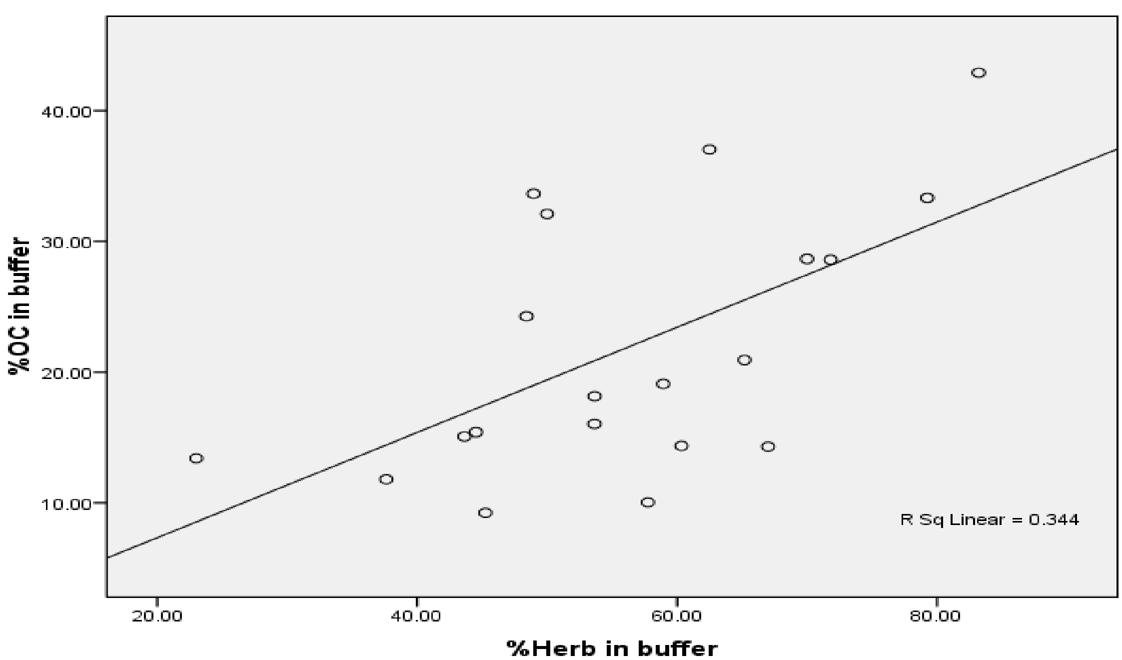


Figure 12. Comparing the means of the percent herbaceous vegetation cover and percent overstory open canopy within sinkholes' flow paths

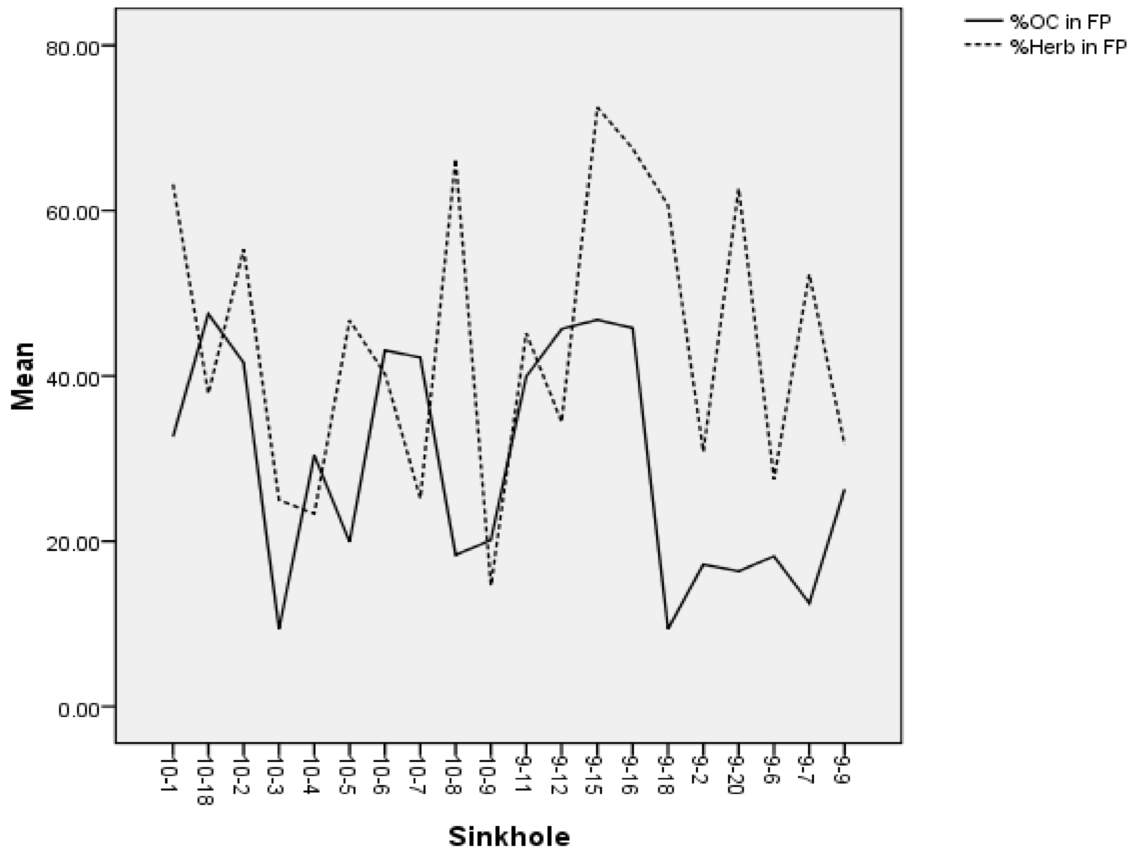


Figure 13. Correlation of percent herbaceous vegetation cover and overstory open canopy within sinkholes' flow paths, p-value = 0.304 (significant level at 0.025)

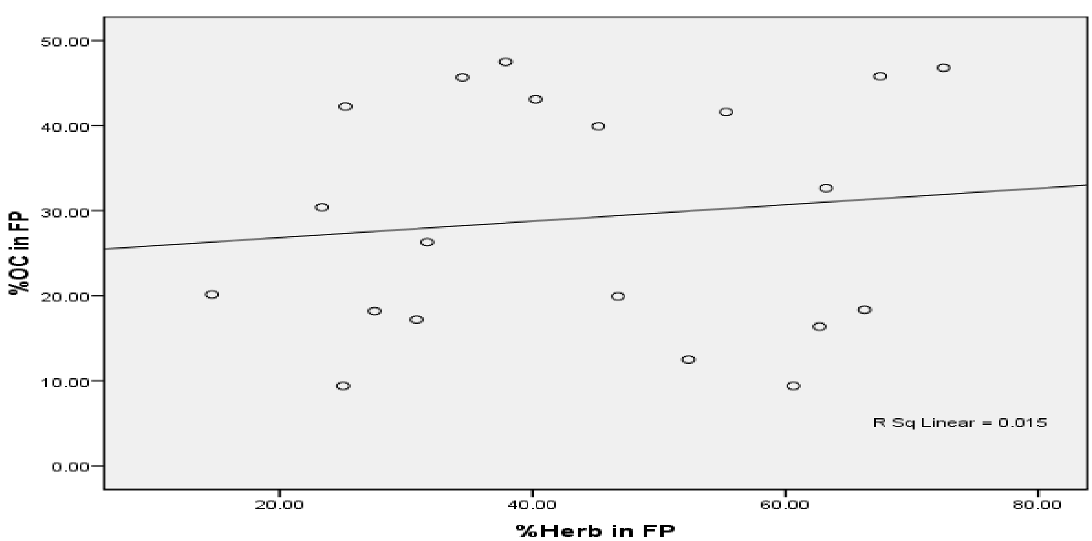


Figure 14. Comparison between mean percent overstory canopy cover and mean herbaceous vegetation cover within sinkhole buffers

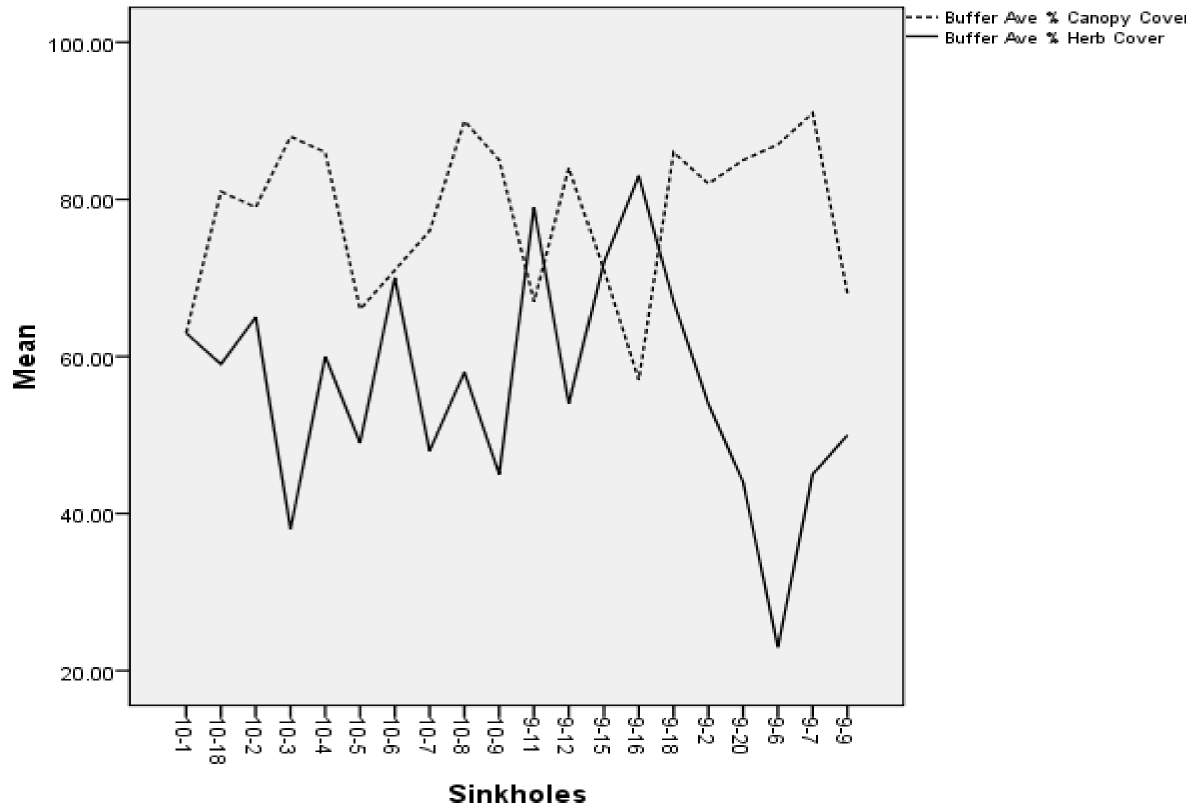


Figure 15. Correlation of percent herbaceous vegetation cover and mean overstory canopy cover within buffer, p-value = 0.003 (significant level at 0.025)

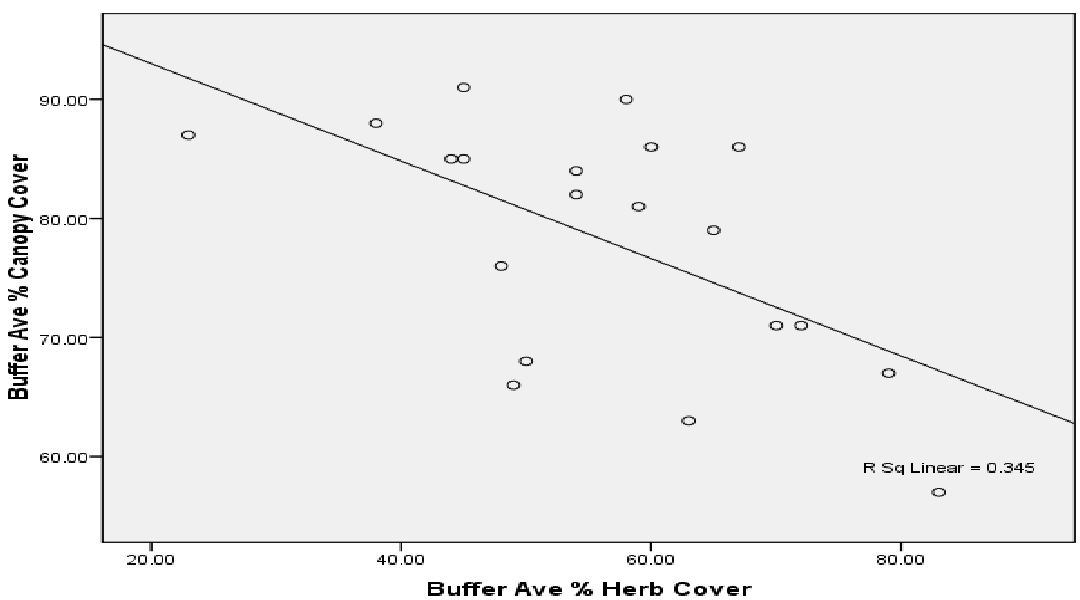


Figure 16. Comparison between mean percent overstory canopy cover and mean percent herbaceous vegetation cover within flow paths

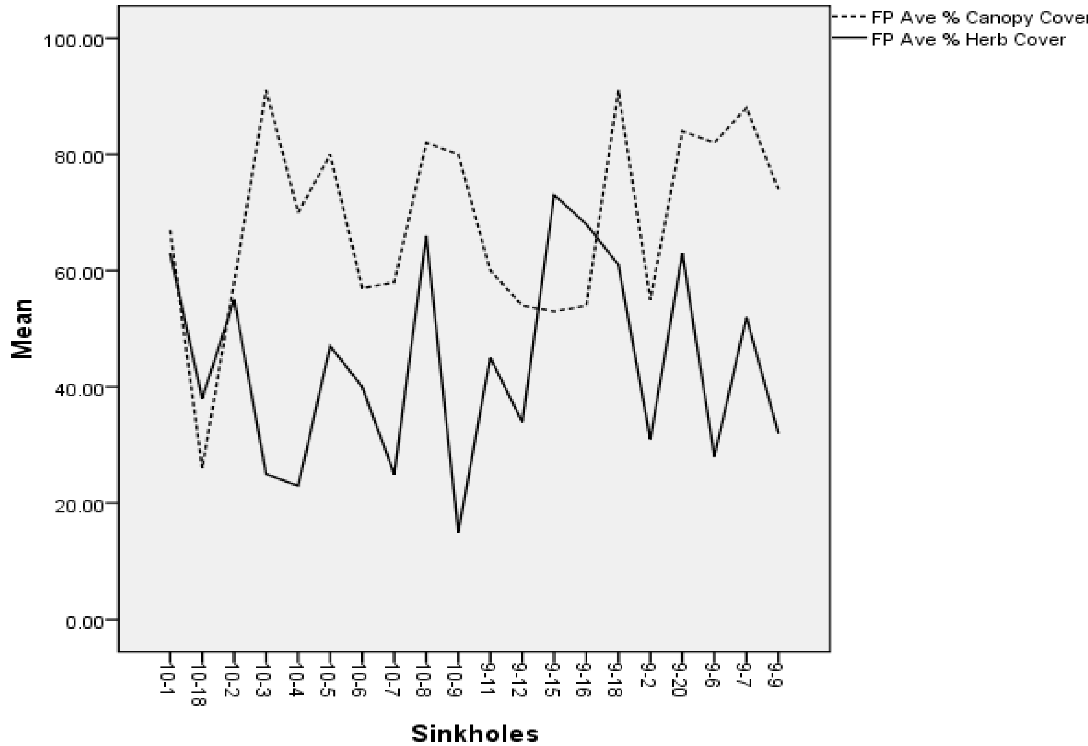


Figure 17. Correlation of percent herbaceous vegetation cover and canopy cover within flow paths, p-value = 0.489 (significant level at 0.025)

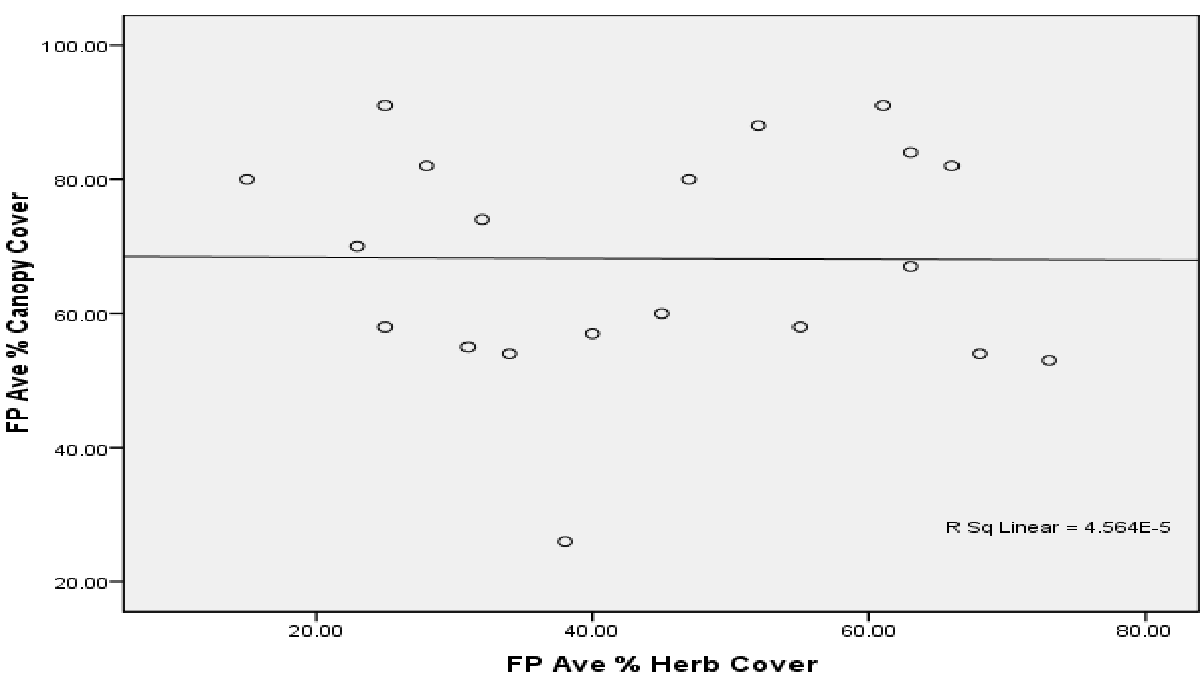
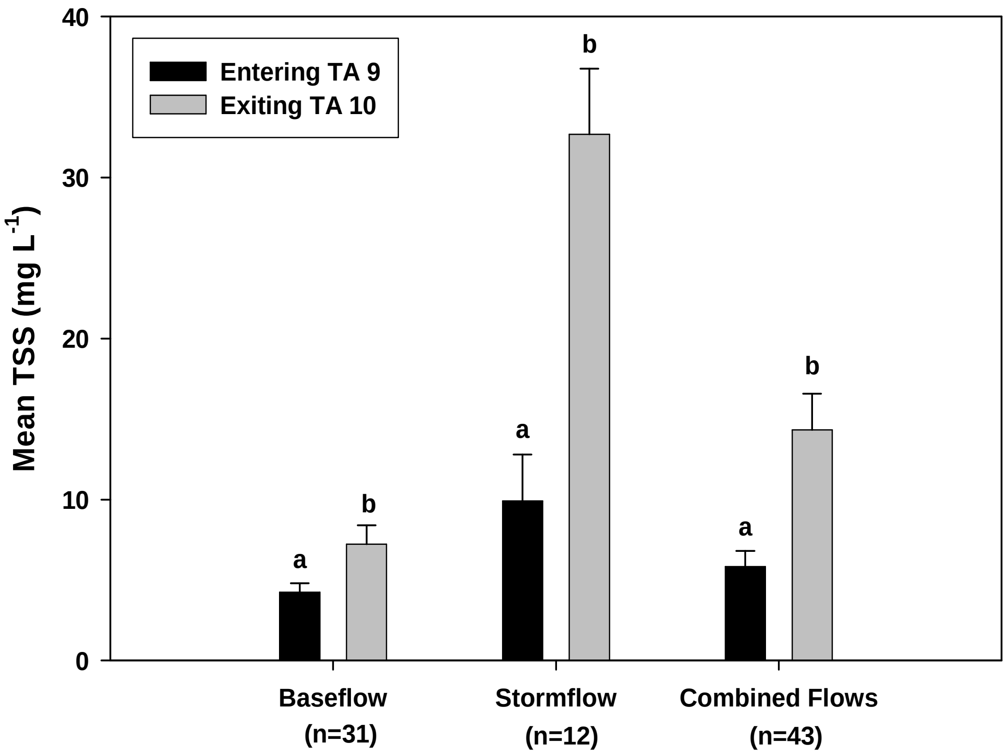


Figure 18: Otter Creek TSS concentration data. Different letters indicates a significant difference (a=0.05) in TSS within flow categories. Crim (2009)



VITA

Graduate School
Southern Illinois University

Klairoong Pattumma

pumapox@yahoo.com

Southern Illinois University Carbondale
Bachelor of Science, Forestry, Outdoor Recreation Resource Management, May 2004

Special Honors and Awards:

- Dean's List 1999-2004
- Xi Sigma Pi National Forestry Honor Society, 2004
- National Heritage Interpreter, 2003-2004
- Golden Key National Honor Society, 2004
- Magma Cum Laude, 2004

Thesis Title:
Vegetation Structure, Light Availability, and Sediment Deposition within Sinkhole Buffers Associated with Tracked and Wheeled Vehicle Training at Fort Knox, Kentucky

Major Professor: Dr. John W. Groninger, Department of Forestry