Soil Erosion and Modeling Following Closure Best Management Practices for Bladed Skid Trails in the Ridge and Valley Region

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ABSTRACT

Sediment is a prevalent non-point source pollutant associated with forest operations. Roads and skid trail surfaces have erosion rates that are greater than the harvest area. Forestry best management practices (BMPs) have been developed to minimize erosion on skid trails, but few projects have compared the effectiveness of different BMPs for bladed skid trails in the mountains. This project evaluated soil erosion rates from bladed skid trails in the Ridge and Valley physiographic region of Virginia following an operational timber harvest. Skid trails were assigned into six blocks where each block had similar slopes and soils. All BMP treatments had waterbars, which are considered the minimum acceptable BMP closure treatment. Each block contained four different skid trail closure BMP treatments (waterbar only (Control), slash-covered (Slash), seeded (Seed), and seeded with fertilizer and mulch (Mulch)). The 24 treatment units were isolated with waterbars and installed following the Virginia Department of Forestry (VDOF) BMP guidelines. The randomized complete block design had three slope class ranges: gentle (0%-10%), moderate (11%-20%), and steep (21%-30%). Stormwater runoff from skid trails was directed at downslope waterbars and eroded material was trapped in silt fences at each treatment area. Depth and area of eroded soil collected in silt fences was measured monthly to quantify total erosion volume for the skid trail area and converted to a per acre basis. Volumes were converted to mass using soil bulk density within the trapped sediment. Control treatments had an average erosion rate of 6.8 tons ac^{-1} yr^{-1}, with rates up to 73.5 tons ac^{-1} yr^{-1} following installation and during extreme rainfall events. Seed treatments recorded an average erosion rate of 2.6 tons ac^{-1} yr^{-1}, with rates reaching 27.2 tons ac^{-1} yr^{-1}. Adding grass seed provided ground cover, but not consistently over time. Due to high rates of ground cover, the Mulch treatments averaged 0.5 tons ac^{-1} yr^{-1} with an extreme of 3.8 tons ac^{-1} yr^{-1}. Slash treatments were found to reduce erosion rates to an average of 0.4 tons ac^{-1} yr^{-1}, with the highest rate being 1.8 tons ac^{-1} yr^{-1}. Site characteristics on experimental units were collected quarterly in order to model erosion rates with commonly used erosion models for forestland (USLE-Forest, RUSLE2, WEPP:Road).

Direct erosion estimates were compared to erosion model predictions produced by USLE-Forest, RUSLE2, and WEPP:Road in order to partially confirm the relationship between sediment trap data and the models. Using multiple analyses it was determined that USLE-Forest and RUSLE2 predicted mean values that are more similar to the actual measured rates, RUSLE2 and WEPP:Road have better linear relationships to the measured rates than does USLE-Forest, and USLE-Forest was the most statistically similar to the measured data using a nonparametric Steel-Dwass Multiple Comparisons Test. All models performed inadequately when attempting to predict Control or Slash treatments; while all models performed the best at predicting Mulch treatments.

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1.0 INTRODUCTION

Water quality is important to the health and economic stability of the United States, therefore, both federal and state legislation, regulations, and policy have been developed in order to protect watersheds and water quality. The largest sources of pollution to the nation's streams are considered non-point source pollutants or NPS's that are primarily attributable to land uses such as agriculture, mining, urbanization, atmospheric deposition, and forestry (USEPA, 2003). Sediment is the NPS most often associated with forest operations. Forest roads and skid trails account for disproportionately large quantities of sediment (Grace, 2005; Sun et al., 2004; Yoho, 1981), particularly when forest roads are poorly designed, constructed, or have inadequate forestry best management practices (BMPs) applied. Problems such as inadequate road or trail closures, poorly implemented stream crossings, or excessive amounts of bare soil can lead to sedimentation (Aust and Blinn, 2004).

Forestry best management practices (BMPs) include guidelines developed to minimize erosion and subsequent sedimentation into streams. Multiple literature reviews have been conducted to evaluate the effectiveness of BMPs across the southeast (Anderson and Lockaby, 2011; Aust and Blinn, 2004; Cristan et al., 2016; Ice, 2005; Shepard et al., 2004). These studies clearly indicate that BMPs can effectively reduce erosion and improve water quality. Aust and Blinn (2004) reviewed the effects of various harvest and site preparation operations with BMPs on water quality. Forest operations were found to have potentially negative effects on soil erosion, and sediment and nutrient delivery to streams; however, the use of adequate and appropriate BMPs were found to have a substantial role in reducing both erosion rates and recovery times following harvest operations. Arthur et al. (1998) conducted a study more specific to the mountainous regions of the southeast by comparing timber harvests with and without BMPs. It was determined that by implementing proper planning and the use of BMPs, soil loss was greatly reduced in the years following harvesting operations. BMP implementation has also been shown to significantly reduce predicted erosion from firelines in the Appalachian region using waterbars, grass seed, and mulch (Christie et al., 2013). Overall, research indicates that forest operations such as the use of bladed skid trails can influence water quality, but forestry BMPs can be effective in protecting water quality. However, little research has directly compared the effectiveness and costs of alternative BMPs for skid trail closure in mountainous terrain.

Skid trail closure BMPs are important because skid trails often have erosion rates several time greater than from mature forests (Sawyers et al., 2012; Wade et al., 2012a). Similar studies have been conducted in the past; however, they examined the effects of BMP implementation on overland and bladed skid trails in the Piedmont physiographic region (Sawyers et al., 2012; Wade et al., 2012a). Both studies found that having ground cover present on skid trails in the form of slash, grass, or grass and mulch significantly reduces erosion rates. Harvests in mountainous areas are on steeper terrain and often require use of bladed skid trails rather than overland skidding (Swift, 1985). Morris et al. (2012) modeled the amount of sediment loss from steep and poorly covered bladed skid trails in the Allegheny Mountains of West Virginia and estimated erosion rates approximately 50x greater than for bladed skid without good BMPs. This study aims to expand on previous research and provide both actual and predicted erosion rates for bladed skid trails in the Ridge and Valley Physiographic province of Virginia.

1.1 Literature Review

1.1.1 Erosion Processes

The erosion process contains three distinct parts: detachment, transportation, and deposition (VDEQ, 1992). The impact of rain upon bare soil causes detachment of particles from the soil. The shear stress needed to detach soil from its natural soil matrix is dependent upon the soil texture and structure as well as the average overland flow depth and the slope steepness (Foster et al, 1997). It is then transported downhill and collects more eroded soil as it continues (Zhang et al, 2009). The velocity of water flow subsides upon entering lower gradient or more tortuous pathway as might be caused by a low point, slow-moving stream, SMZ, or water control feature; causing the eroded soil particles to settle out and be deposited in that location (Lakel et al., 2006a). Erosion occurs in three different types: interrill (sheet), rill, and gully erosions. Interrill erosion occurs as a sheet of water flows over the soil surface. Rill erosion is a result of concentrated water flow in a specific channel. Gully erosion, like rill erosion, occurs in concentrated channels; however the capacity and velocity of water is increased, leading to larger, deeper channels with further accelerated soil detachment (Laflen et al., 1991). If litter layer and ground vegetation are removed, interception rates are much lower and unimpeded pathways are longer, which then directly impacts the soil surface and increases erosion rates (Grace, 2002; Larson et al., 1997; Reid and Dunne, 1984).

1.1.2 Sediment Concerns

Once the eroded soil enters a stream, it is considered sediment (Yoho, 1980). The two main processes by which soil particulate matter reduces water quality are sedimentation and turbidity (Henley et al., 2000). Sedimentation is defined as the process by which sediment is deposited on streambed substrata. Sedimentation occurs when sediment in flowing water loses velocity and larger particles settle out. The larger silt and sand particles are typically involved in this process, while smaller clay particles and fines increase turbidity. Turbidity is the amount of small solid particles and dissolved solids that are suspended in water which directly affect the water color (Henley et al., 2000). As turbidity increases, less light can penetrate the water, leading to reduced photosynthesis rates in aquatic plants and phytoplankton (Douglass and Swank, 1972; Kirk, 1985). This decreased rate of energy production can make its way up the food chain to larger fauna. The combined effects of sediment and turbidity have potentially drastic negative effects on the macro- and microfauna of stream systems (Henley, et al., 2000). Another type of NPS associated with forest operations are nutrients (Fox et al., 1983; Neary et al., 2009). Occurring naturally or added by fertilization, nutrients attached to sediment have been found to impact stream water quality by changing the overall chemistry of a stream; leading to changes in the aquatic ecosystem through eutrophication (Grace, 2005; Sun et al., 2004). Stream ecosystems and watershed health are dependent upon water quality, and as such, protecting water quality by reducing sediment production is imperative.

1.1.3 Forest Roads and Water Quality Impacts

Forest roads and skid trails are major components of the forest access system that is needed in nearly all forest operations, but are particularly critical for conventional ground-based harvesting operations in the eastern US. Kochenderfer (1977) quantified the typical area occupied by forest roads and skid trails in the central Appalachians and concluded that 5-11% of the total harvest area is comprised of roads and skid trails for a traditional wheeled-skidder harvesting system, specifically, 84% of exposed mineral soil following a harvest occurred in skid trails. Kochenderfer also found that steeper slopes require additional skid trails in order access felled stems.

The litter and vegetation in an undisturbed forest intercept rainfall and minimize raindrop erosive forces on the soil surface (VDEQ, 1992). As skid trail areas increase, the potential for bare soil increases. For overland skidding, the traffic and removal of trees removes both litter layer and vegetation. Bladed skid trails, which are in reality a low-standard road, actually remove litter, vegetation and surface mineral soils (Pierzchała, 2014).

Harvesting practices can increase a site's water yield (Hibbert, 1965; Stednick, 1996). In the removal of trees, evapotranspiration is reduced, especially for the first year after harvesting (Brown, et al., 2005). In the following years, water yield gradually decreases again as vegetation becomes established and evapotranspiration rates increase (Bosch and Hewlett, 1982; Douglass and Swank, 1972; Douglass and Goodwin, 1980; Kuraś, 2012). Roads can potentially increase runoff production by intercepting subsurface flow from cutbanks during storm events; this runoff is then channeled to streams by roadside ditches if present (Wemple, 2003; Dymond et al., 2013). Roads may also serve to increase the drainage density within a watershed and speed the runoff to streams (Eisenbies et al., 2007). The increased runoff produced from subsurface storm flow interception by roads has been shown to have varying degrees of impact upon water quality; however road effects were determined to have a larger impact upon water quality than the actual clear-cutting of trees (Croke et al., 2006).

Road templates (including skid trails) can have a large effect on erosion. Cut and fill slopes are potentially major erosion sources (Swift, 1984b). In some cases in the mountains, cut and filled areas can become substantial in size and height due to the steeper terrain being traversed. Without vegetative cover, fillslopes and cutslopes can develop loose soils due to freeze and thaw cycles in the winter (Swift, 1985). This can lead to slumping of soil and washouts from storm runoff from the road and culverts. Erosion from cutslopes becomes significantly greater if the cut bank exceeds 4 feet in height (Kochenderfer, 1987). Cut and fillslopes should be sloped properly and seeded to minimize the amount of slumping and erosion (Grace, 2005).

Stream crossings are an important component of forest roads and skid trails. Stream crossings directly connect runoff with streams and poorly closed stream crossings can accelerate stream sedimentation rates (Wear et al., 2013). Stream crossings compromise the streamside management zones (SMZs) and can channel water directly into the stream itself. Proper SMZ implementation is a critical method used to maintain stream quality, thus activities such as stream crossings which can potentially compromise the SMZ integrity should be minimized (Lang et al., 2015). The VDOF BMP guidelines (2011) recommend a minimum SMZ width of 50 feet for normal situations. Lakel et al. (2010) found that SMZ width has little impact on its effectiveness, as long as the SMZ is not breached by channelized flow from roads or other highly disturbed sites. SMZs have been found to be one of the most important best management practices, due to their simplicity in implementation and their ability to greatly reduce the amount of sediment entering streams from forest roads (Sun et al., 2004).

1.1.4 BMPs

1.1.4.1 BMP Implementation

Forestry best management practices (BMPs) are guidelines established by most states that are designed to reduce the effects of forest operations on water quality (Virginia Dept. of Forestry, 2011). The BMPs are designed to reduce impacts from nutrients, chemicals, thermal, and organic pollutants, but sediment is the primary focus (Wang et al., 2004). The Clean Water Act tasked each state with implementing and monitoring BMPs (Ice, 1997). The National Association of State Foresters (NASF) reported that by 2001, all states had developed forestry BMPs, and the average rate of BMP implementation is 86% (Sun et al., 2004). Cristan (2015) recently reported that the southeastern states have an overall BMP compliance rate of 92%. BMPs are specialized for pre-harvest, harvest, and post-harvest conditions. Perhaps the most important component of BMPs is related to pre-harvest planning. Pre-harvest planning permits better control of road grades, soil stabilization BMPs, water control BMPs, and location of logging decks, roads, skid trails, and stream crossings (Swift, 1985; Swift et al., 1999). Pre-harvest planning is particularly important for sites having adverse terrain that may require more time, effort and expense for installation of BMPs, such as those found in mountain regions (Aust et al., 1996). Arthur et al. conducted a study comparing three watersheds. One watershed was left unharvested as a control and the other two were clearcut. One of these harvested watershed featured BMPs while the other was harvested without regard to BMP guidelines. While both harvested areas experienced reduced water quality compared to the control site, the non-BMP site had significantly increased water quality issues (Arthur et al. 1998). Another similar study compared the effects of harvest and site preparation with and without the use of BMPs. The first watershed was clearcut with BMPs and site preparation, the second was clearcut without BMPs and with site preparation, and the third watershed was left as a control. This research also concluded that the use of BMPs significantly increase water quality (Wynn et al., 2000).

Recent trends show that BMP implementation is being included in an increasing number of harvests (Cristan et al., 2015). Additionally, BMP effectiveness is increasing, partially due to the states raising BMP standards by increasing sophistication and detail (Ice et al., 2010). There are also trends suggesting that as BMP compliance increases, water quality also increases proportionally (Sun et al., 2004).

1.1.4.2 Forest Road BMPs

Soil stabilization methods are used to reduce erosion by rainfall. For forestlands, vegetation is an important soil stabilization technique. For harvested areas, residual soil litter, slash, and re-growing vegetation provide erosion control. Areas having exposed bare soil may require additional measures. Grass seeding is a very common method on temporary roads, decks, and skid trails due to its ease of planting and growth abilities (Grace, 2002; Swift 1984a). The grass roots function to anchor soil particles in place and the above-ground portion of the plants serve to act as a ground cover, increasing rainfall interception and slowing water velocities (Swift, 1984a). To be most effective, grass should be seeded immediately after skid trail closure and germination and establishment results are usually more reliable in spring and fall. Popular grass species include ryegrasses and fescues; however there is an effort to utilize more native grasses (Maynard and Hill, 1992). The primary grasses recommended for the mountains of Virginia are KY-31 Fescue and Perennial Ryegrass (Virginia Department of Forestry, 2011). Prior to seeding, ground compaction due to machinery should be ameliorated by scarification, and fertilizer and lime may be necessary in order to resolve soil pH and nutrient deficiencies. Straw mulch can also be added to shelter seeds pre-germination, as well as increase soil moisture (Maynard and Hill, 1992). Mulch is also useful in dissipating the amount of rainfall impact upon bare soil (Wade et al., 2012a).

Other methods of reducing erosion on bare soils include using gravel (decks and roads) and slash (skid trails) as ground cover. These are beneficial in that they begin providing cover immediately, whereas grass requires time to germinate and grow (Wade et al., 2012a). Gravel has been found to be an adequate ground cover, being effective enough to reduce sediment production by 7.5 times as compared to a bare road (Brown et al., 2013; Kochenderfer and

Helvey, 1987). Brown et al., (2014) also demonstrated that gravel can be a very effective ground cover for stream crossing approaches. In this study, rainfall was simulated on stream approaches which had been surfaced with gravel of varying depths and lengths. It was found that as more gravel was added to the surface of an unsealed road, total suspended solids (TSS) in runoff decreased significantly. However, it is generally not feasible to surface temporary roads such as bladed skid trails with gravel due to the expense.

Temporary roads and skid trails can be closed to ameliorate runoff issues. Closure can be achieved by placing water control structures such as waterbars at regular intervals as well as planting or mulching for soil stability (Aust and Blinn, 2004). More intensive, less common road removal techniques exist, including tillage, cross-drain removal, excavating road fill from stream channels, and re-shaping hillslope contours by modifying the road template (Madej, 2000).

Mulch is commonly utilized to stabilize areas of bare soil and is usually less expensive than using gravel (Lyons and Day, 2009). Mulch types include chipped harvest residuals, mulched wood, and straw. Mulching with any of these materials significantly reduces erosion rates by 42-76% (Foltz, 2012). Slash, or residual tops and limbs from felled trees can also be used to reduce erosion by increasing rainfall interception and slowing runoff. By applying slash and compacting or "tracking it in" with a piece of machinery, slash provides ground cover that can hold soil in place, even as harvesting equipment continues to use the road or trail (Grace et al., 1998). Logging slash has been found to be both economical and effective in reducing road and trail erosion (Sawyers et al., 2012; Wade et al., 2012a). Manmade materials such as mats or geotextile fabrics can also be used for erosion reduction on roads and skid trails (Grushecky et al., 2009). Mats (of either natural or manmade materials) are also useful in lining roadside ditches, where increased water velocity has the increased capability to detach soil and transport it to streams (Burroughs and King, 1989, Lang et al. 2015).

Water control structures divert or reduce water movement from bare soil surfaces on roads to more stable undisturbed areas where water can be slowly filtered through the litter layer (Luce and Black, 1999). Waterbars are the most commonly used water control structure for closing skid trails, due to their low cost, simplicity and effectiveness. Waterbars are mounds of soil pushed to a height of 2-3 feet and at a 30-45 degree angle to the centerline of the trail (VDOF 2011). A bulldozer can efficiently install and compact waterbars. These specifications will ensure that the water is effectively diverted from the trail and that the waterbar is not overtopped by flow. Waterbar compaction is also important to ensure that the waterbar does not wash out over time. Waterbars are intended for permanent closure of temporary roads and skid trails. Road use should be restricted following installation of waterbars, as continued trafficking can degrade the waterbars to a point that they are no longer effective. Christopher and Visser (2007) found that post closure traffic was a significant cause of waterbar failure. Road or skid trail slope determines appropriate waterbar spacing. As slope increases waterbars should be placed closer together in order to be effective (VDOF, 2011; WV Division of Forestry, 2009). Haupt (1959) determined that as road slopes increase the potential for erosion increases exponentially; as such, slope lengths must be broken up into shorter distances by water control features in order to reduce erosion potential.

1.1.4.3 Bladed Skid Trails

Skid trails are temporary roads installed to access timber by harvesting equipment (Stuart and Carr, 1991). Bladed skid trails are distinguishable from overland skid trails in that a bulldozer is used to construct the trail in areas with steep adverse grades or off-camber slopes that may complicate skidding. Therefore, bladed skid trails are very common in mountainous regions with operations using rubber tired skidders. These trails should be closed out after harvest completion because of their steep nature and lower standards, which can result in higher erosion rates (Wade et al., 2012). The Virginia Department of Forestry has BMP guidelines specifically for bladed skid trails, due to the bare soil conditions that they create (Virginia Dept. of Forestry, 2011). VDOF (2011) guidelines include constructing trails with grades less than 25%, providing for frequent grade breaks to minimize slope lengths, and use of both drainage structures (e.g., waterbars) and stabilization (e.g., cover practices) to reduce erosion.

Furthermore, bladed skid trails should be located outside of the SMZ. The “drainage structures” mentioned above include culverts, water turnouts, water bars, rolling dips, and broad based dips. Soil stabilization practices can include slash, mulch, or rock. After use, skid trails should be closed with water bars to control water runoff, and may be either seeded, slashed, mulched, or a combination of those to stabilize the soil surface (Virginia Dept. of Forestry, 2011; WV Division of Forestry, 2009; North Carolina Division of Forest Resources, 2006; Georgia Forestry Commission, 2009). Typical trail closure BMPs include waterbar installation and seeding, however, straw or mulching is recommended but not always included in trail closeout (Aust and Blinn, 2004; Croke and Hairsine, 2006).

1.1.5 Soil Erosion Modelling

On-site measurement of erosion is both costly and time consuming, thus erosion models are commonly used to estimate erosion potentials (Fu et al. 2010, Wade et al. 2012b). Several models are available to assist agricultural land managers to best evaluate possible erosion issues, and have been adapted to forest use over time (Dissmeyer and Foster 1980). Erosion models can be used by forest managers to make silvicultural, management, or even forest engineering decisions (Elliot, 2004). They are frequently modified to maintain and increase their accuracy and dependability (Fu et al, 2010). The Universal Soil Loss Equation (USLE) is a common method used to determine potential soil loss for sheet and rill erosion. Developed by the USDA in 1954 and adapted to forest land use in 1980 (Dissmeyer and Foster 1980), it is one of the most common soil loss models. Being relatively simple to use, it also provides the most basic version of soil loss modelling. The USLE model is:

$$A=RKLSCP$$

Whereas, A is the annual soil loss per unit area, R is the rainfall and runoff factor, K is the soil erodibility factor, L represents the slope-length factor, S is the slope-steepness factor, C is the cover and management factor, and P represents the support practices factor (Dissmeyer and Foster, 1980). The rainfall and runoff factor is determined based upon the average weather conditions at the location of interest. The soil erodibility factor (K) is a function of multiple soil characteristics: soil texture, organic matter content, structure, and permeability. A soil's erodibility factor can usually be found in a soil survey or soil description (USDA NRCS, 2009). However, for more precise erodibility factor estimation, each of the characteristics can be determined and input into the soil erodibility nomograph. Slope-length factor (L) is "the ratio of soil loss from the field slope length to that from a 72.6-foot length under identical conditions" (Dissmeyer and Foster, 1980). Likewise, slope-steepness factor (S) is defined as "the ratio of soil loss from the field slope gradient to that from a 9-percent slope under otherwise identical conditions" (Dissmeyer and Foster, 1980). These two variables can be determined from a table found in "*A Guide to Predicting Sheet and Rill Erosion on Forest Land,*" written by Dissmeyer and Foster. Cover and management (CP) factors are based upon the amount of bare soil, presence of canopy, soil reconsolidation, organic matter content, fine roots, residual binding effects, onsite storage, and steps.

The USLE was revised and converted to a computerized format, labeled the Revised Universal Soil Loss Equation or RUSLE. This model was first produced in the early 1990's, and RUSLE1.06 and RUSLE2 were both released in 2003. Although the algorithm from the USLE was kept, it was modified for improved accuracy by deriving soil loss factors with alternative approaches. This revision included changes to make the model more suited for use with forest lands. Other improvements included updated rainfall coefficients, after changing some of the R factors in the eastern US based on weather data collected from more than 1,200 weather stations. Soil erodibility (K) was varied seasonally for increased accuracy. The LS factor was improved in that it takes into account the "susceptibility of the soil to rill erosion relative to interrill erosion," and the Cover factor used a new algorithm for determining cover based on prior land use, canopy cover, soil cover, and soil surface roughness (Renard et al., 1999). In Renard's study, the USLE and RUSLE were both compared on rangeland and cropland. It was found that at times, RUSLE tended to produce either lower or higher values than the USLE model on the same site, depending on what specific factors were changed. RUSLE2 has no specific data files for forest roads, however there are "highly disturbed land" files that can be modified to suit different forest road treatments (Wade et al., 2012b).

The Water Erosion Prediction Project (WEPP) is a model produced by the USDA NRCS and USFS to replace the USLE formula. This "models soil erosion as a process of rill and interrill detachment and transport" (Laflen et al., 1991). The WEPP model is potentially more attractive to users in that it estimates daily conditions that affect erosion, over the course of a year. In WEPP, senescence, plant growth, residue accumulation and decomposition, as well as daily temperatures and soil water availability are taken into account to provide a very detailed estimate of soil loss over time. An additional benefit is the ability to model complex slopes and forest road profiles, with features such as cutslopes and fillslopes, ditches, and road surfaces (Fu et al., 2010). Four types of data files are required to run WEPP: 1) a climate file, to include data on daily precipitation and temperature, 2) a hillslope file, which can contain multiple points to describe a slope's shape, 3) a soils file, which can include multiple soil types across the hillslope, and 4) a management file containing information on soil disturbances, and vegetative conditions present (Elliot, 2004). Weather data is obtained through Cligen, the USDA's weather resource. The weather file models weather data on a daily basis for more than 1,000 climates (Cligen Overview, 2015). Using the hillslope file, WEPP determines the erosion or deposition rates for at least 100 points of the hillslope if there is any runoff predicted that day (Elliot et al., 1999). Because WEPP, like other models, was originally intended for cropland or rangelands, there have been many efforts to adapt it for forest uses (Dun et al., 2009; Elliot et al., 1995; Elliot et al., 1997; Elliot et al., 2001; Morfin et al., 1996; and Tysdal et al., 1997). One of these efforts is the WEPP:Road model interface. This program allows the user to determine the amount of sediment delivered to the stream through the forest buffer and amount of sediment eroded from each portion of the road, as well as the distribution of erosion and the presence of a sediment plume in the forest (Elliot et al., 2000). At this time, the selections for cover and land use scenarios appear to limit WEPPs utility for estimation of erosion for many eastern forest management regimes (Brown et al., 2015).

There have been several attempts to compare modeled erosion estimates to sediment trap data. Wade et al. (2012b) compared sediment trap data to predictions by all three models. Erosion rates were estimated from different sections of bladed skid trail in the Piedmont of Virginia using sediment traps, and were then compared to erosion rates predicted by USLE-Forest, RUSLE2, and WEPP:Road models. It was found that overall, all three models performed satisfactorily for identifying erosion hazards and making management decisions. When comparing the modeled data, it was determined that USLE-Forest ranged from 0.9x to 2.2x the actual erosion rates from data collected from the sediment traps. RUSLE2 ranged from 0.4x to 2x the actual erosion, and WEPP:Road ranged from 2.3x to 7.5x (Wade et al., 2012b). These data indicated that the USLE and RUSLE2 can be useful at approximating erosion rates, but WEPP:Road values should only be used for ranking purposes at this time. WEPP modelling efforts can be improved with laborious programming, but are time consuming and require many measurements to modify the working files. Foster, et al., (2003) found similar results when comparing USLE, RUSLE1.06, and RUSLE2.

1.1.6 Sediment Traps

Most sediment traps use some type of geofabric. Silt fences have been used in construction and development situations to trap erosion and reduce sediment. They have also been found to be an effective means by which sediment can be measured for research purposes (Fox, 1983; Robichaud and Brown, 2002). Being effective in both cost and in collecting sediment, silt fences are a synthetic cloth material with small openings that allow water to flow through but captures most soil particles. Robichaud and Brown compiled what is considered to be an extensive guide for the use of silt fences in capturing and measuring sediment. Through their research, it was found that silt fences can be used on slopes of 3-70%, and are effective even under heavy snow conditions. In flume studies, silt fences have been found to capture between 68% and 98% of sediment, depending upon the weave of the material and sediment particle sizes. Silt fences must be properly installed to ensure that they are effective in collecting sediment. Additional stakes and sandbags may be used to increase strength of the fence, or if necessary, multiple fences may be used (Robichaud and Brown, 2002). Because of variability of soil erosion, it may be necessary to measure sediment deposits in silt fences for an extended period of time, especially if the amount of erosion is predicted to be minimal. As the length of time over which data is collected increases, the variance decreases as sediment accumulates in traps (Nearing et al., 1999). For this reason, it is necessary to carry out soil loss experiments over an adequate amount of time to reduce variation in collected data.

1.2 Research Objectives

The literature clearly indicates that BMPs can be used to reduce erosion from bladed skid trails and that models might be a useful approach for estimating erosion from such areas. However, there are no studies that have compared BMPs and erosion from bladed skid trails in the Ridge and Valley physiographic region with direct measurements and models. Thus, this project was developed to address three primary objectives.

1.) Measure erosion rates from operational bladed skid trails closed with different BMPs. BMP treatments were:

- a) waterbars only (bare soil between waterbars as a control);
- b) waterbars and planted with grass seed;
- c) waterbars, fertilized, planted with grass seed and mulched with straw; and
- d) waterbars with slash from logging operations in between.

2.) Compare the measured erosion rates with those produced by current road and hillslope erosion models in order to partially confirm them. These models are:

a.) the Universal Soil Loss Equation-Forest (USLE-Forest),

b.) the Revised Universal Soil Loss Equation, version 2 (RUSLE2), and

c.) the Water Erosion Prediction Project-Road (WEPP:Road).

3.) The final objective is to estimate the costs of closure using the various treatments.

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2.0 ASSESSING THE EFFECTIVENESS OF BLADED SKID TRAIL CLOSURE BEST MANAGEMENT PRACTICES IN THE RIDGE AND VALLEY REGION

2.1 Abstract

Access roads and skid trail surfaces with inadequate best management practices can produce the majority of erosion produced from forest harvesting operations. We evaluated soil erosion rates from operational bladed skid trails in the mountains of Virginia following a timber harvest. The randomized complete block design included six blocks; each block containing four different skid trail closure BMP treatments (waterbar only (Control), slash-covered (Slash), seeded (Seed), and seeded with fertilizer and mulch (Mulch)). Each of the 24 treatment units were isolated with waterbars, installed following the Virginia Department of Forestry (VDOF) BMP guidelines. The area and depth of deposited sediment collected in silt fences were measured monthly to quantify erosion rates on a per acre basis. Control treatments resulted in an average erosion rate of 6.8 tons ac^{-1} yr^{-1} (15.1 tonnes ha^{-1} yr^{-1}), with rates up to 73.5 tons ac^{-1} yr^{-1} (164.6 tonnes ha^{-1} yr^{-1}) following installation and during extreme rainfall events. Seed treatments resulted in an average erosion rate of 2.6 tons ac^{-1} yr^{-1} (5.9 tonnes ha^{-1} yr^{-1}), with rates reaching 27.2 tons ac^{-1} yr^{-1} (61.0 tonnes ha^{-1} yr^{-1}). Adding grass seed added ground cover, but not consistently over time. Due to high rates of ground cover, Mulch treatments averaged 0.5 tons ac^{-1} yr^{-1} (1.1 tonnes ha^{-1} yr^{-1}) with an extreme of 3.8 tons ac^{-1} yr^{-1} (8.4 tonnes ha^{-1} yr^{-1}). Slash treatments were found to reduce erosion rates to an average of 0.4 tons ac^{-1} yr^{-1} (0.8 tonnes ha^{-1} yr^{-1}), with the highest rate being 1.8 tons ac^{-1} yr^{-1} (3.9 tonnes ha^{-1} yr^{-1}). All additional BMP treatments significantly reduced soil erosion rates over the Control treatments, with Mulch and Slash being the most effective.

Keywords: soil erosion, BMPs, skid trails

2.2 Introduction

Sediment is the most common non-point source (NPS) pollutants from forest operations (US EPA, 2003; Yoho, 1980). The forest operations generally creating the most sediment are haul roads, logging decks, skid trails, and stream crossings (Lakel et al., 2010). Cristopher and

Visser (2007) determined that haul roads and skid trails remained the primary source of sediment pollution from forest harvests, even 2 to 8 years after their closure. Bladed skid trails are often used in steep terrain to facilitate operator safety and skidding productivity. It was recently estimated that approximately 7.7% of a forest harvest on steep terrain in the Appalachian Mountains consists of bladed skid trails (Worrell et al., 2011). Worrell et al. (2011) estimated that erosion rates on bladed skid trails in the mountains can average 17.2 t ac^{-1} yr^{-1} (38.6 tonnes ha^{-1} yr^{-1}). Wade et al. (2013) measured erosion from bladed skid trails in the Piedmont that produced 1.3 to 61.2 tons ac^{-1} yr^{-1} (3.0 to 137.1 tonnes ha^{-1} yr^{-1}). Such skid trails are highly erosive due to bare soil exposure, terrain slope steepness, and low road drainage standards (Anderson and Lockaby, 2011; Grace, 2002). These problems are compounded by continued use or heavy traffic (Lang et al., 2015). The combination of these factors are known to increase erosion; therefore increasing the possibility of stream sedimentation and degradation (Grace, 2005; Swift, 1985).

Forestry BMP guidelines recommend that forest managers close out skid trails following harvesting operations. Eroded soil from skid trails can be delivered to streams, thus reducing stream water quality. Increased sediment in streams reduces water quality by increasing water temperatures, abrading the gills of fish, altering the stream channel morphology to reduce habitat for aquatic wildlife, and affecting the feeding habits of aquatic wildlife (Croke and Hairsine, 2006; Douglass and Swank, 1972; Henley et al., 2000). As soil erodes from skid trails, it also reduces the site quality by removing nutrients and decreasing soil depth; thus further reducing site productivity of the skid trails (Aust and Blinn, 2004).

Erosion problems can be minimized with appropriate skid trail planning and design prior to harvesting (Arthur et al., 1998). However, erosion control practices are recommended following construction and/or harvest operations. Waterbars and wing ditches channel the flow of water away from trails and into the harvest area, where slash or leaf litter dissipate the concentrated flow (VDEQ, 1992). Logging residues from the harvest, often referred to as slash, can be used to provide ground cover for skid trails. McGreer (1981) examined bladed skid trails on volcanic soils and found that slash can reduce soil erosion by up to 99%. The Virginia Department of Forestry and other state forestry agencies across the southeast recommend the use of slash to close out skid trails (Georgia Forestry Commission, 2009; North Carolina Division of

Forest Resources, 2006; Virginia Department of Forestry, 2011a; West Virginia Division of Forestry, 2009). The use of slash has the potential benefit of improving the chemical and physical properties of soil as it decays (Wade et al., 2013). Slash is also beneficial on steep slopes, fill slopes, or stream crossing approaches where immediate ground cover is needed. Slash may also reduce undesirable ATV traffic on such sites. Seeding exposed soil with grass seed is another common method of reducing soil erosion (Grace, 2002; Maynard and Hill, 1992). However, grass seed requires time to germinate after being applied to the skid trail, and there can be issues with grass survival. These issues can be mitigated through the use of lime, fertilizer, or mulch to improve soil chemical and physical properties and to reduce removal or movement of seeds (Foltz, 2012; Lyons and Day, 2009). Current literature indicates that there are research gaps regarding the effectiveness of specific skid trail BMPs and their associated costs. The objectives of this study were designed to eliminate that gap in regards to steep mountain terrain in the Ridge and Valley physiographic province.

2.2.1 Study Objectives

The primary objective of this study was to evaluate the effectiveness of different bladed skid trail closure BMPs by quantifying soil erosion from bladed skid trails following closure with different BMP practices. The secondary objective was to assess the costs of each closure BMP treatment relative to erosion reduction efficacy of the treatment.

2.3 Methods

2.3.1 Study Area

The study site was located in the Ridge and Valley physiographic province; on Virginia Tech's Fishburn Forest, located in Montgomery County, Virginia (Figure 2.1). The site was logged in late 2014-early 2015 in a shelterwood overstory removal of upland hardwoods and mixed pine-hardwood. The average high and low temperatures for this location in January are 41.5°F (5.3°C) and 21.4°F (-5.9°C). The average high and low temperatures in July are 82.2°F (27.9°C) and 60.1°F (15.6°C). Average yearly precipitation is 40.89in (103.86cm) (NOAA, 2010). The soils are typically very shallow, well drained silt loams, being derived mostly from shale, siltstone, and sandstone residuum and dominated by Berks-Weikert complex soil series (USDA NRCS, 2015). The erodibility factor for these soils is estimated to be 0.43 (USDA NRCS, 2015). Site species primarily consisted of Chestnut Oak, Northern Red Oak, Scarlet Oak, Eastern White Pine, White Oak, Black Oak, Yellow-Poplar, Pignut Hickory, and Virginia Pine. Skid trails were laid out in a method of logger's preference and featured slopes from 0-35%, with side-slopes up to 45%.

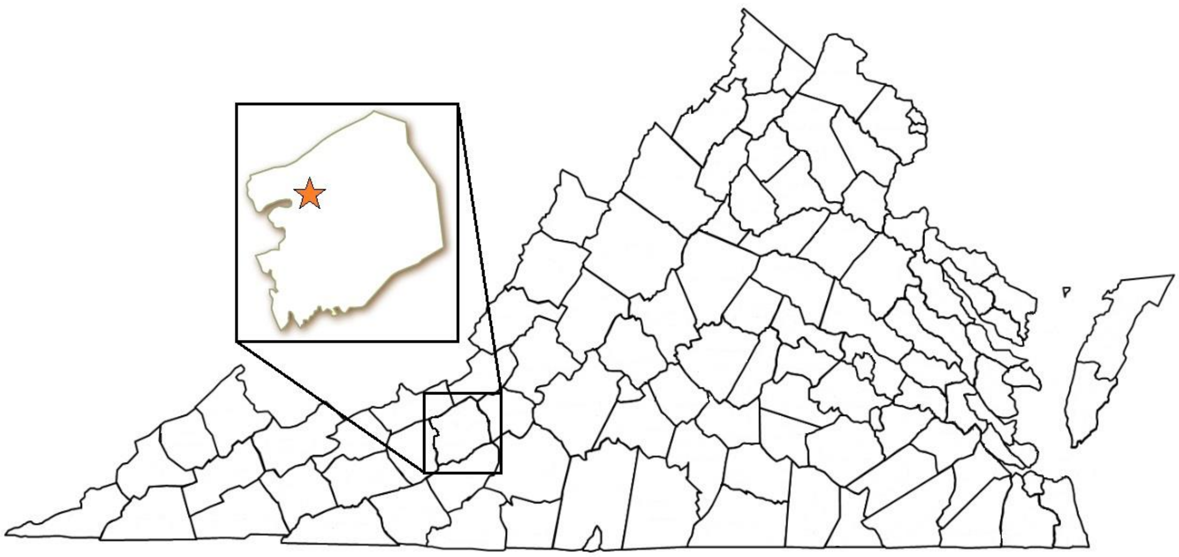

Figure 2.1: Location map of harvest site within Montgomery County, Virginia.

2.3.2 Treatments

This study was arranged as a randomized complete block design with repeated measures. Blocks were assigned based on slope class: Gentle (0-10% slope), Moderate (11-20% slope), and Steep (>20% slope). Six blocks (two in each slope class) each contained four treatments: 1) waterbars with bare soil in between (Control), 2) waterbars and planted with grass seed, (Seed) 3) waterbars, fertilized, planted with grass seed and mulched with straw (Mulch), and 4) waterbars with slash from logging operations utilized as ground cover (Slash). The four treatments were randomly assigned within each block using a random number generator, thus providing 24 experimental units. Waterbars and closure treatments were installed on the operational bladed skid trails using a John Deere 450 bulldozer in April, 2015. Treatment sections were approximately 50ft (15.2m) long, and +-10ft (2m) wide. On steeper slopes (>20%), treatments lengths were reduced to 40ft (12.2m) in length in order to comply with BMP guidelines (VDOF, 2011a). Earthen berms were constructed on either side of the skid trail to restrict overland flow and sediment from lateral movement from the trail and funnel sediments toward sediment traps. The uphill section of each treatment contained a waterbar to channel flow from uphill areas away from the treatment, thus isolating treatments and defining contributing areas. The lower end of each treatment was similarly defined with another waterbar that channeled water flow off of the trail and into a sediment trapping area encircled by a silt fence (Figure 2.2). Each waterbar was constructed at a 30-45 degree angle to the centerline of the road, and to a height of 2-3ft (0.6-0.9m) to ensure effectiveness in channeling water flow. A total station was used to measure the total contributing area of each treatment, as well as exact length, slope, and slope profile.

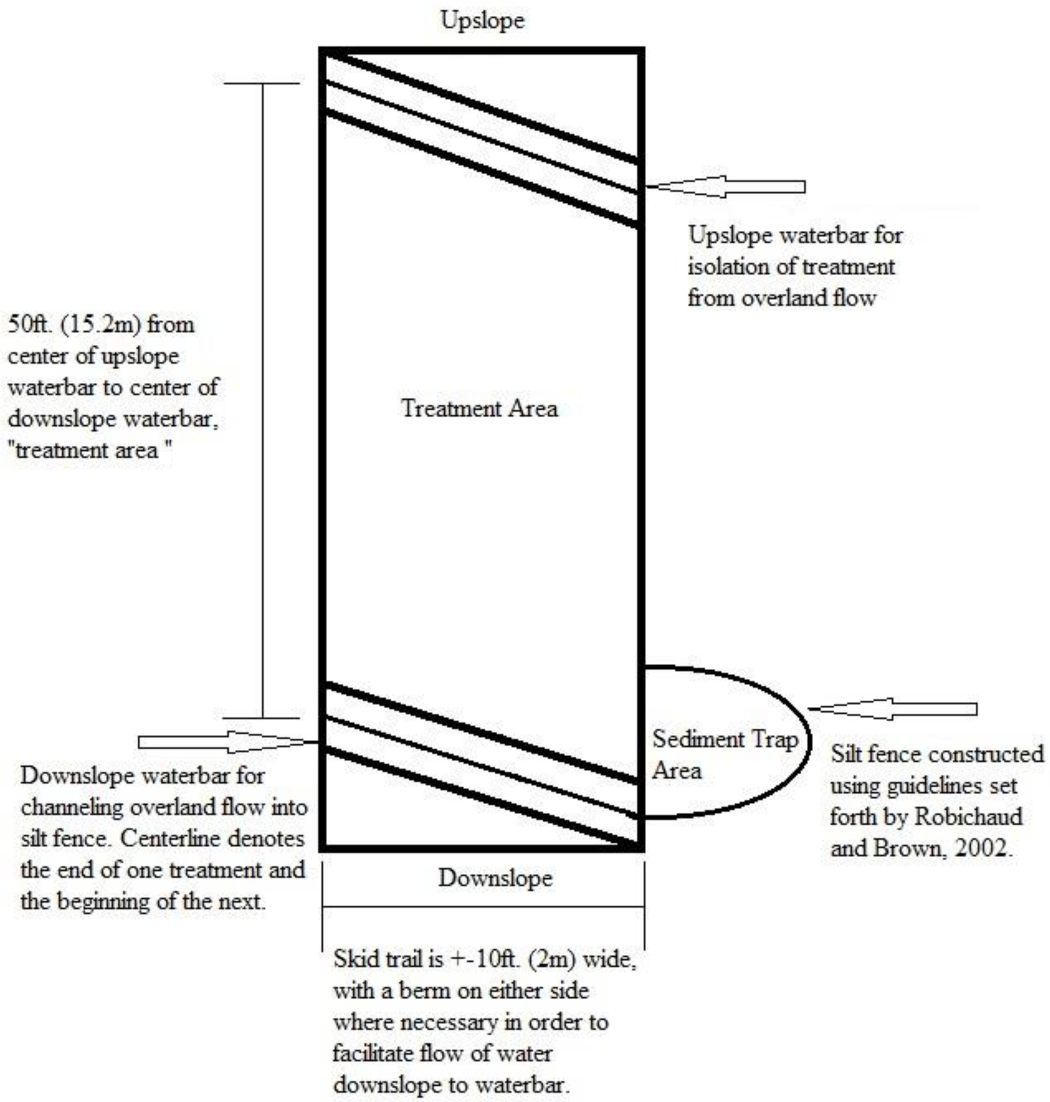

Figure 2.2: Layout of each 50ft (15.2m) experimental unit.

The Control treatment contained waterbars with no ground cover to represent the minimum acceptable BMPs. Seed, mulch, and fertilizer applications were based on recommended rates from the VDOF BMP manual (VDOF, 2011a). For the Seed treatment, grass seed was applied at the time of skid trail closeout (April 2015) using a mix of 50% perennial ryegrass (*Lolium perenne*) and 50% KY-31 fescue (*Festuca arundinacea*). Seed was applied at a rate of approximately 150 lbs per acre (33.6 kg/ha). For the Mulch treatment, the same grass seed mixture was applied, along with fertilizer and straw mulch. Straw mulch was spread by hand at a rate of approximately 80 bales/acre to ensure 100% coverage. Fertilizer was applied at a rate of approximately 300 lbs per acre (336 kg/ha) of 10-10-10. Slash treatments were hand applied onto skid trails to ensure uniform coverage and then compacted with the bulldozer to make contact with the ground. After compaction, slash was at a depth of approximately 1-2ft (0.3-0.6m) (Figure 2.3).

Figure 2.3: Comparison photographs of each BMP treatment following project installation. Note the downslope waterbar with sediment trap in each photo.

2.3.3 Sediment Trap Efficiency

Sediment trapping efficiency was calculated to determine the amount of eroded material that was captured by the silt fences. This was determined by conducting a soil particle size analysis on both the collected sediment and the trail surface to make a comparison between the two. Analysis was performed using the hydrometer method (Gee et al., 1986). It was assumed that smaller, clay particles can more easily pass through the silt fence material. It was determined that sand and silt percentages increased, while the percentage of clay particles decreased when comparing the soil from the trail surface to the eroded material (Table 2.1). This supports the assumption that the silt fences are not 100% efficient at trapping clay particles (Robichaud and

Brown, 2002). Since 8% of the soil clay content was lost, we assumed a trapping efficiency of 92%, and all collected data was corrected by 8%.

Table 2.1: Results of soil particle size analysis in terms of percent sand, silt, and clay to compare the soil particle size of the trail surface to that of the sediment collected in sediment traps.

	% Sand	% Silt	% Clay
Trail Surface	43	39	18
Collected Sediment	48	42	10
Change	+5	+3	-8

2.3.4 Data Collection

Runoff was diverted from the skid trail via the waterbar and collected and filtered by a silt fence sediment trap. Silt fences were installed using the guidelines set by Robichaud and Brown (2002). Rebar measuring approximately 14in (35.56cm) long were driven into the ground in a grid pattern (Figure 2.4) within the area of sediment collection of each silt trap to provide sediment pin measurement (Aust et al. 1991). A washer was placed loosely over the shaft of the rebar to lie on the ground surface (Figure 2.5). Depth of sediment collected was measured using a pin flag and ruler to measure the depth of sediment as it accumulates above the washer. The grid pattern of the erosion pins provided a method of establishing an area of sedimentation for each trap. The sediment depths and areas were combined to obtain an estimate of sediment volume for each trap. Measurement of sediment volume occurred on a monthly basis for twelve months. Sediment volumes were converted to mass using the bulk density of the sediment which was obtained using standard lab procedures (Blake and Hartge 1986).

Figure 2.4: Sediment trap with erosion pins in place. Note that the pins were arranged in a grid-like pattern, ensuring that each pin represents a specific amount of area on the ground.

Figure 2.5: Pins in silt fence sediment trap. Washers were placed loosely about the shaft of each pin and made flush with the surface of the ground. Washers allowed data collection to be more easily and accurately conducted by separating the surface of the ground from the collected sediment.

Bare soil percentages were collected quarterly along transects across each treatment to provide seasonal ground cover percentages. Precipitation data were recorded in daily inches from a nearby airport weather station affiliated with weatherunderground (WU, 2016). Data were collected beginning on the date of installation and continuing throughout the experiment (12 months).

2.3.5 Statistical Analysis Methods

Monthly sediment trap measurements were converted to tons ac^{-1} yr^{-1} (tonnes ha^{-1} yr^{-1}) and analyzed using JMP version 11.0 statistical software (JMP®, 2015). A Levene normality test indicated that data were not normally distributed, thus non-parametric tests were required. Differences between BMP treatments were determined using a nonparametric Wilcoxon test and a Steel-Dwass multiple comparisons test using α=0.05 (Zar, 2010). The effects of slope steepness and rock content were also analyzed using nonparametric Wilcoxon and Steel-Dwass multiple comparisons tests.

2.4 Results and Discussion

2.4.1 Erosion Rates by Treatment

Control treatments had erosion rates averaging 6.8 tons ac^{-1} yr^{-1} (15.1 tonnes ha^{-1} yr^{-1}), while Seed treatments were 2.6tons ac^{-1} yr^{-1} (5.9 tonnes ha^{-1} yr^{-1}), Mulch treatments were 0.5 tons ac^{-1} yr^{-1} (1.1 tonnes ha^{-1} yr^{-1}), and Slash treatments averaged 0.35 tons ac^{-1} yr^{-1} (0.78 tonnes ha^{-1} yr^{-1}) (Table 1). The Control treatment wass significantly different from all other treatments, showing an overall BMP effectiveness. Mulch and Slash treatments reduced erosion significantly more than just Seed treatments alone (Table 2.2). Erosion rates varied over time (Figure 2.6). Variation was likely a result of rainfall differences and vegetation growth on the treatment sites. However, variability in the Seed treatments was substantially higher than those of the Slash or Mulch treatments (Table 2.2). Overall, using BMP methods beyond the Control significantly reduced erosion. However, the application of Slash or Mulch treatments resulted in less erosion than Seed treatments (Figure 2.7). These findings support what was found in the past by Sawyers et al. (2012) and Wade et al. (2012) in the Piedmont region of Virginia. Their findings also suggest that Slash and Mulch treatments are among the most effective at reducing erosion. However, both found substantially higher rates of erosion from Control treatments (10-12 tons ac^{-1} yr^{-1}). This is possibly due to this study having a wider range of slope gradients that were averaged together.

Table 2.2: Erosion rates for each treatment after the one year study period.

Treatment	Average Erosion Rate ($t\ ac^{-1}\ yr^{-1}$)	Minimum Erosion Rate	Maximum Erosion Rate	SD
Control	6.8^a	2.5	15.3	12.9
Seed	2.6^b	0.3	6.4	4.67
Mulch	0.5^c	0.01	1.1	0.75
Slash	0.4^c	0.01	0.6	0.41

$^{a, b, c}$ *Treatments with the same letter are not significantly different based on α=0.05*

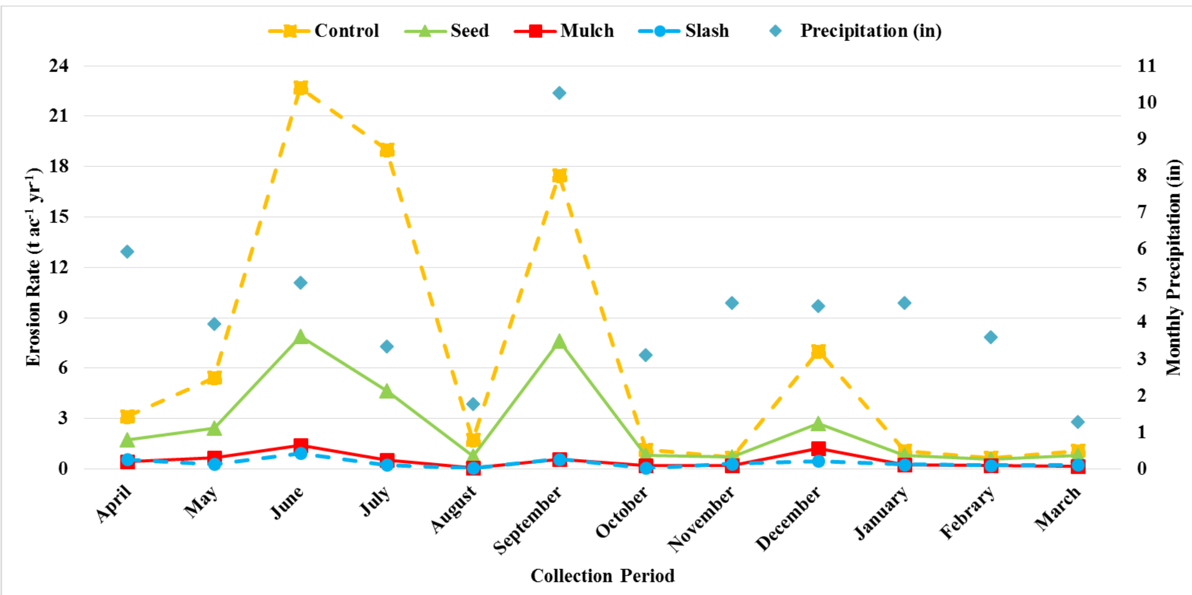

Figure 2.6: A comparison of erosion rates from skid trail treatments over the period of data collection (April 7, 2015 to April 8, 2016), as compared to rainfall amounts.

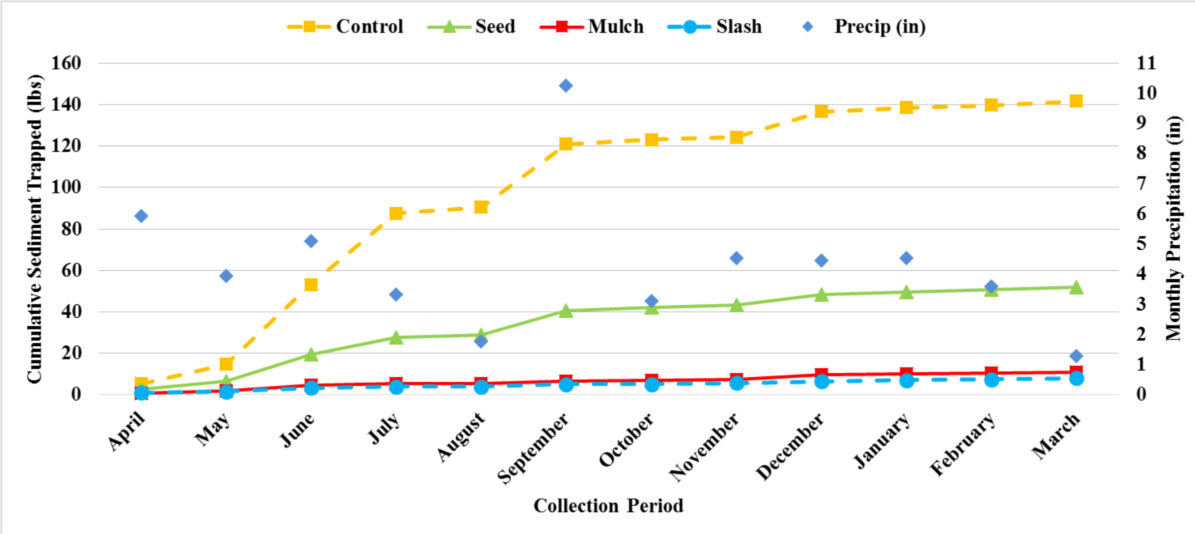

Figure 2.7: Graphical representation of the cumulative sediment collected by sediment traps in lbs for each BMP closeout method as compared to monthly rainfall amounts.

Erosion rates varied throughout the year as precipitation varied (Figure 2.6). Erosion rates started at a lower rate as on-site storage (bulldozer cleat tracks, small holes, soil settling) filled, then increased after approximately 3 months. After this increase the erosion rate diminished every monthly period, with the exception of period 6 (September 4 to October 9, 2015) due to an extreme weather event that occurred on September 29, 2015 (Figure 2.8). On this day the area received the highest rainfall amount ever recorded for this location in one day, 4.39in (11.15cm) (NOAA, 2015), resulting in the spike in erosion rates over that period (Figure 2.9). Following this period, the erosion rates continued their trend of diminishing with every month as rainfall amounts decreased and ground cover increased. There was also an increased rate of erosion during the period from December through January, however it was later determined that this was likely an effect of frost heave on the sediment surrounding the pins. This was taken into consideration when calculating yearly erosion rates.

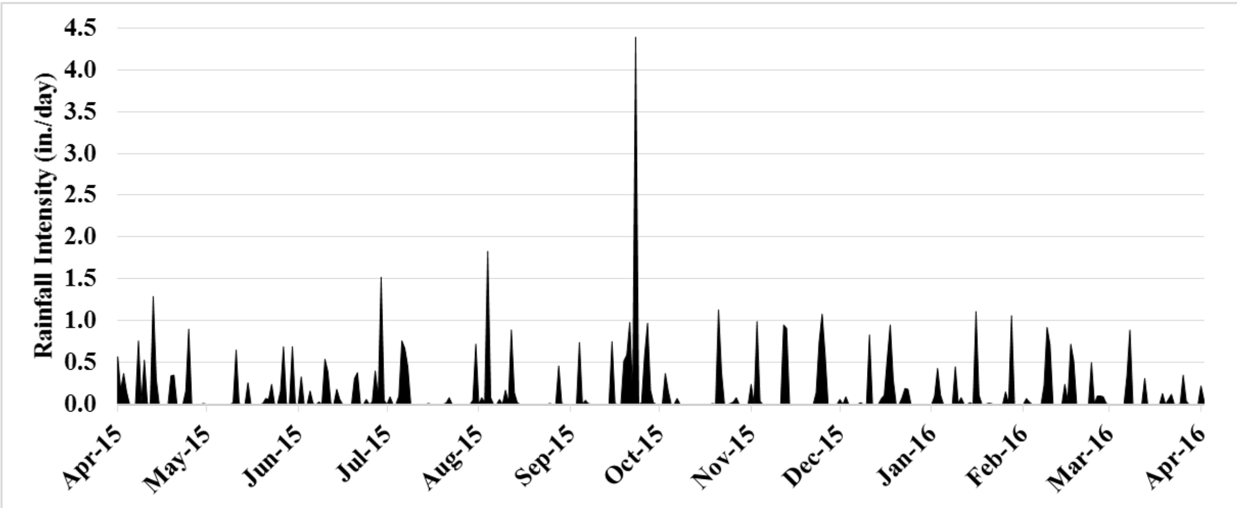

Figure 2.8: Daily rainfall intensity rates over the course of one year of data collection. The largest historic one-day rainfall event for Blacksburg, VA was recorded on September 29th, 2015.

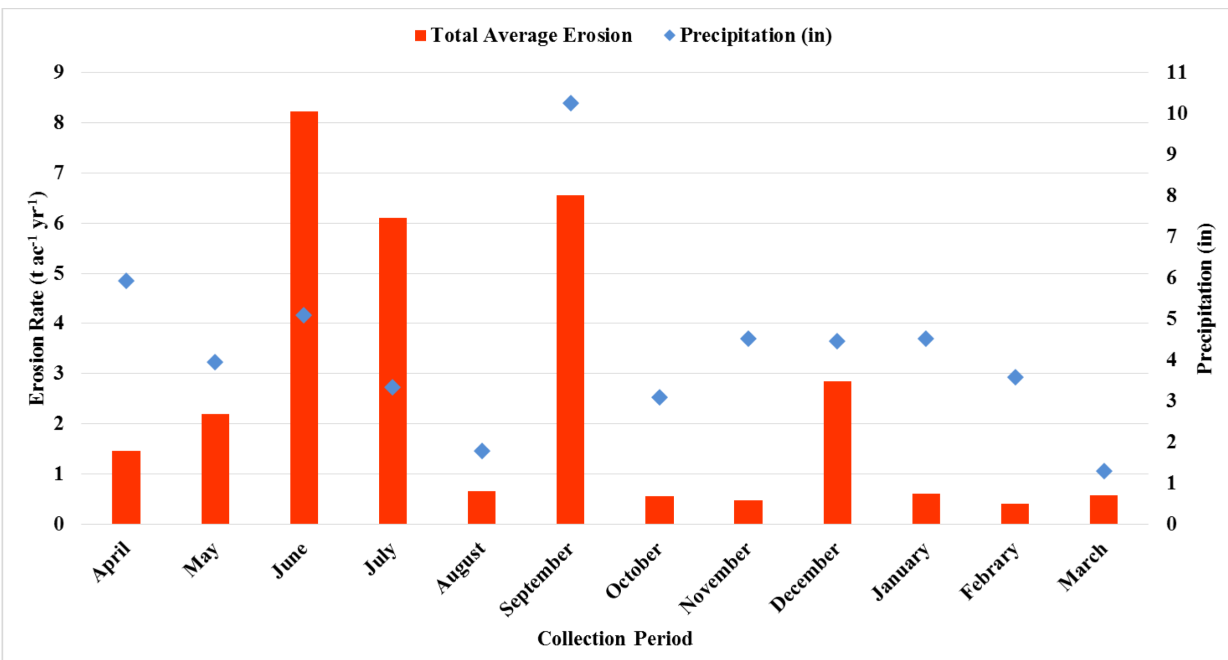

Figure 2.9: Total erosion rates across all BMP treatments as compared to monthly precipitation.

2.4.2 Changes in Ground Cover

Quarterly ground cover assessments indicated a generally increasing trend over time (Figure 2.10). The only exception was Mulch treatment; due to the initially high ground cover that decomposed or was removed by wildlife, wind, or the scouring of concentrated flow paths. Control, Seed; Mulch, and Slash treatments all resulted in increased ground cover over time (Figure 2.10). Control treatments retained the lowest percentage of ground cover that gradually increased with time as bare soil eroded away to reveal rock fragments and roots which acted as ground cover, and as natural vegetation and leaf litter accumulated on the trail surface. Ground cover in Seed treatments increased rapidly over the first season, as grass seeds germinated. The increased temperature and decreased rainfall during the summer led to some mortality of grass in the Seed treatments, however germination of natural vegetation, as well as the exposure of rock fragments and accumulation of leaf litter continued to increase the amount of ground cover. Slash treatments initially had higher rates of ground cover that slowly increased due to the exposure of rock fragments and germination of natural vegetation.

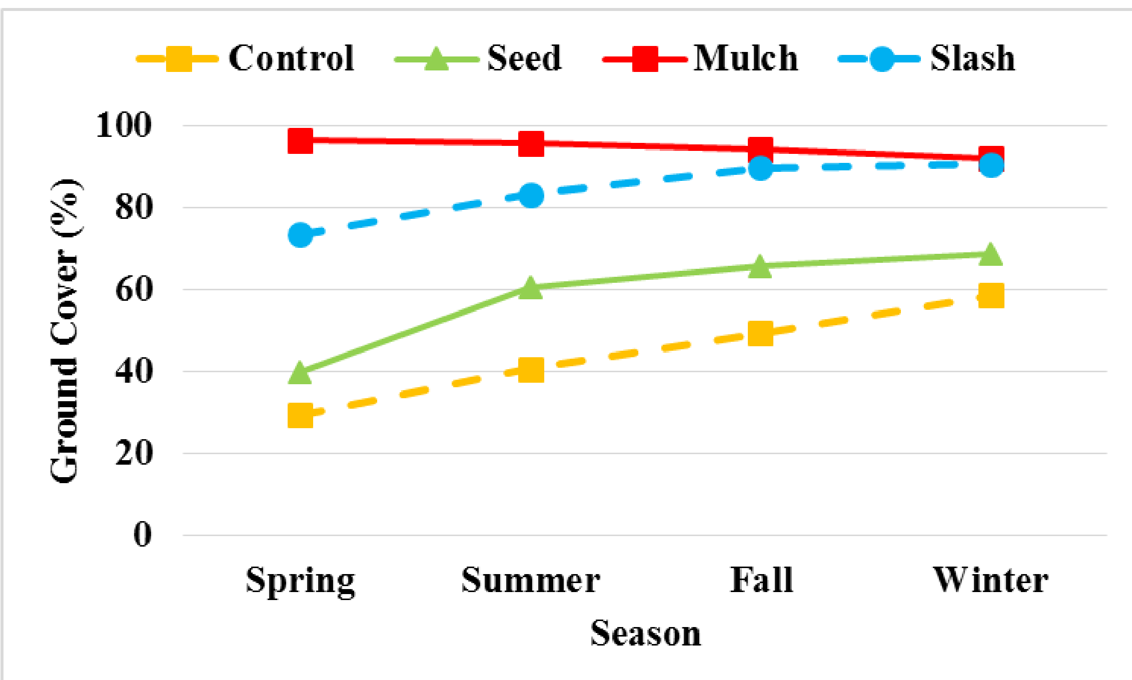

Figure 2.10: Graphical representation of average quarterly ground cover measurements for each BMP treatment beginning in April of 2015.

2.4.3 Effects of Slope Steepness and Soil Rock Content

The topography of the study site played an important role in erosion. Past studies have found that as slope increases, erosion rates also increase (Haupt, 1959). However, the results of this study did not follow this trend. Gentle slopes produced the least amount of sediment, followed by the steep slopes. Moderate slopes produced the highest rates of erosion (Figure 2.11). This was likely due to higher volumetric rock content in the soils on the steeper slopes (Table 2.3), but could also be attributed to the shorter distance between waterbars that was used on steeper slopes in order to follow recommended BMP guidelines. As the soil on the ground surface eroded, rock fragments were left behind on the surface. Rock fragments acted as a ground cover, increasing the percentage of ground cover and thus reducing erosion rates (Cerda, 2001; Kochenderfer and Helvey, 1987). Steeper slopes exhibited rock contents almost double those in gentle or moderate sloped treatments (Figure 2.12). In the Ridge and Valley physiographic province, steeper slopes often possess shallower soils with erosion pavements, thus when bladed with a bulldozer often bring the soil surface closer to parent material. Therefore higher rock contents were recorded in the steeper slopes, resulting in lower erosion rates (Kochenderfer and Helvey, 1987). Non-parametric Wilcoxon testing determined that erosion rates were not significantly correlated to slope steepness ($p=0.3083$). However, there was a negative relationship between rock fragment cover and erosion rates. This is supported by other findings by Simanton et al. (1984) and Wilcox and Wood (1989).

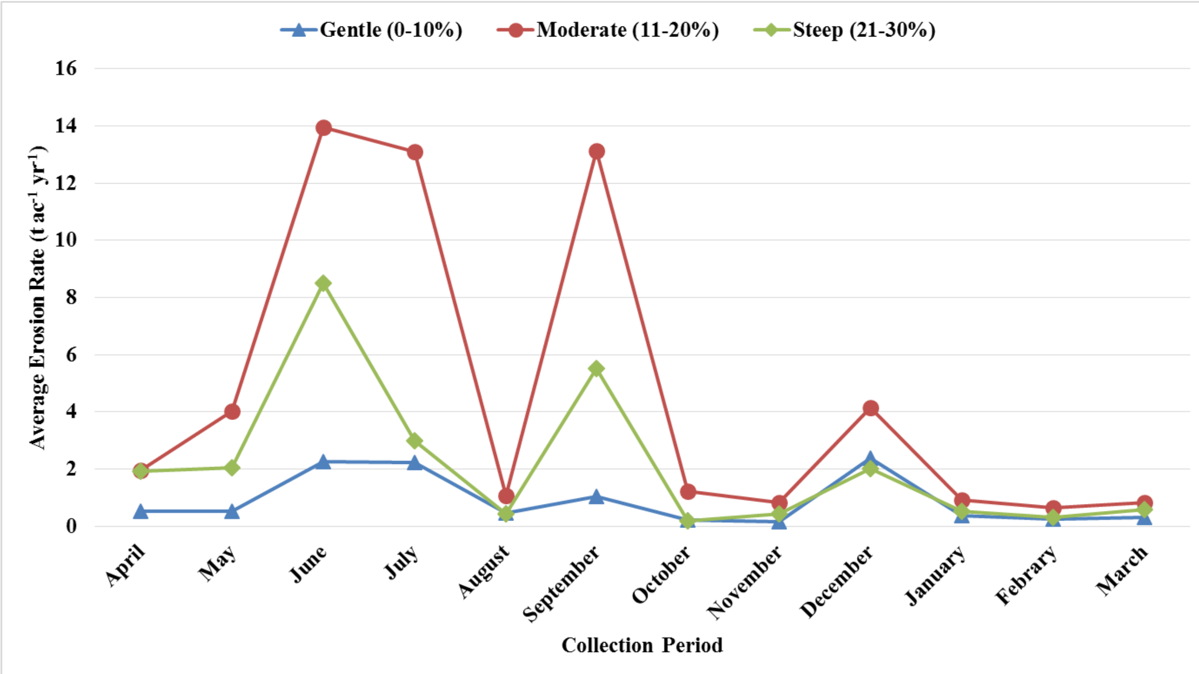

Figure 2.11: The effects of slope class upon erosion rates over the one year study period.

Table 2.3: A comparison of the volumetric rock content of the soil in each slope class.

Slope Class	Samples Taken	Mean Rock Content (%)	SD
Gentle	24	16.1	3.8
Moderate	24	16.3	5.5
Steep	24	31.2	4.3

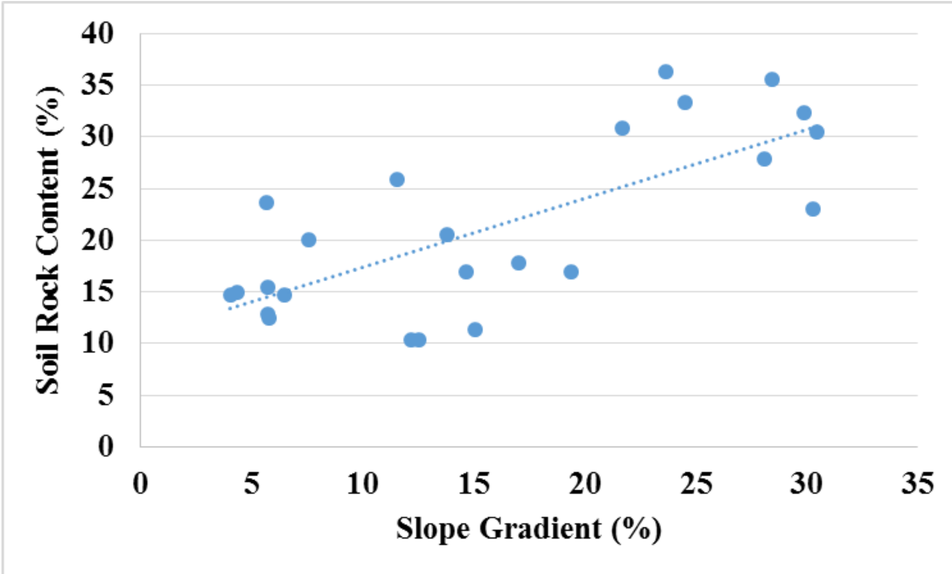

Figure 2.12: Relationship between soil rock content and slope gradient for all treatments. A line of best fit represents the positive relationship. This relationship is expressed with an R^2 value of 0.54 (pvalue<0.001).

2.4.4 BMP Costs

The final study objective was to determine how closure methods vary in costs relative to the amount of erosion prevented. Factors that were considered when determining costs include the cost of materials, labor, and machine hours. Costs were based on purchase prices for seed, fertilizer, and straw, as well as literature on machine rates and current labor costs (Conrad et al., 2012; Sawyers et al., 2012). A rate of $17.52/hour was used for labor costs, and $75/hour for machine rate. Cost of materials were as follows: $4.99/straw bale, $119.99/50lb bag of perennial ryegrass (applied at a rate of 75lbs/ac), $59.99/50lb bag of KY-31 Fescue (applied at a rate of 75 lbs/ac), and $11.99/40lb bag of 10-10-10 fertilizer (applied at a rate of 300lbs/ac). Costs were then applied to each treatment as a 50ft (15.2m) section of skid trail, and the total cost of skid trail closure for the harvest was determined, as well as cost per mile (1.6km) of skid trail closure (Table 2.4). It is important to note that the costs of Slash treatments were calculated for the methods that were used for their installation during this project. Slash treatments were applied by hand and tracked in with a bulldozer, however we can predict that operationally-applied slash can cost substantially less than what was determined by this cost analysis. This was also determined by Sawyers et al. (2012) in their analysis of overland bladed skid trail costs. Costs of each BMP closure were then compared to the erosion reduction for each treatment. For 50 ft. (15.2 m) of skid trail, the Control treatment cost $18.75, the Seed treatment cost $26.25, Mulch treatment cost $41.64, and Slash cost $28.13. This clearly shows that when comparing BMP closure methods, it was less expensive to apply seed and install waterbars to the skid trail. On a basis of erosion prevented, it was more economical to apply Slash ($73.65 per ton of erosion prevented) and install waterbars to the trail than it was to close with Seed ($88.85 per ton of erosion prevented) or Mulch ($182.67 per ton of erosion prevented). This was due to the fact that Slash prevented significantly more erosion than did Seed treatments. These findings support what Wear et al. (2013) have found in that Mulch treatments can cost more than 2x that of Slash treatments, with nearly the same effectiveness.

Table 2.4: Cost analysis of each BMP closeout method on a basis of 50ft (15.2m) treatment, entire harvest on which study was conducted, and 1mi (1.6km) of skid trail. The cost of erosion prevented is also included.

Treatment	Cost for 50ft (15.2m) Treatment (US$)	Cost for Cassady's Ridge Harvest (US$)	Cost for 1mi (1.6km) of Skid Trail (US$)	Costs of Erosion Prevented (US$/ton)
Control	18.75	1,667.00	1,980.00	N/A
Seed	26.25	2,333.82	2,771.89	88.85
Mulch	41.64	3,702.51	4,397.50	182.67
Slash	28.13	2,500.62	2,970.00	73.65

2.5 Conclusions

Utilizing waterbars to close out skid trails has been shown to reduce erosion through controlling the sheet flow of water. The erosion rates of Control treatments were significantly higher and were far more variable. In this study, Slash was the most effective in reducing erosion as it provided immediate ground cover (no wait for germination) and decomposed slowly over time. Over time, the decomposition of slash may have additional positive effects on the chemical properties of the soil. On a per-ton basis, it was also the most cost efficient at reducing erosion. In addition to this, slash had the added benefit of preventing ATV traffic from using the closed trails. However, for this reason, slash may not be suitable for use if the trail is to remain open for traffic. It may also be unsuitable if the skid trail is to serve as a fire line, as the slash serves as fuel on the ground. Mulch was also very effective at reducing erosion, as it was effective immediately, and the added benefits of the mulch and fertilizer aid the grass in germination and survival. This treatment was the most costly of the BMPs compared in this study, in both per area of treatment cost and cost of erosion prevented. However, Mulch may be the best option under certain conditions when slash is not readily available. Seed treatments proved effective in reducing erosion for the lowest per area cost, however once germinated may prove to be difficult to maintain for an extended time period due to mortality. Seed was also the least effective of the additional BMPs tested. Overall erosion rates were highest shortly after skid trail closeout, and the highest rates occurred on moderate (11-20%) slopes. Skid trail closeout should be completed immediately after harvest to minimize erosion.

These findings are significant, as in 2011 approximately 248,000 acres of forest land were harvested in Virginia (VDOF, 2011b). We can speculate that 25-30% (62,000-75,000 acres) of that forest land lies in the mountain region the state. Kochenderfer (1977) has proposed that 5-11% of an Appalachian harvest lies in skid trails, with higher percentages on steeper slopes. This amounts to 3,100 to 8,250 acres of land in skid trails across the Ridge and Valley. Following closure with waterbars, we can predict a mean erosion rate of 6.8 tons/ac/year, and can therefore estimate a soil loss of 21,000 to 56,000 tons per year from the region. By adding slash or mulch, we can reduce potential erosion to approximately 1,200 to 3,500 tons per year. This is a substantial reduction in soil erosion.

Roads and skid trails are a major cost incurred by loggers when conducting forest harvests (Conrad et al., 2012). We can apply this cost analysis to the closure of bladed skid trails in order to assist with logging cost estimates for land managers and logging industry professionals.

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3.0 COMPARISON OF TRAPPED SEDIMENT WITH SOIL EROSION MODEL ESTIMATES ON BLADED SKID TRAILS USING BEST MANAGEMENT PRACTICES IN THE RIDGE AND VALLEY PHYSIOGRAPHIC REGION

3.1 Abstract.

Forestry Best Management Practices (BMPs) are extensively used for control of forest erosion and sedimentation, yet few studies have quantified the effects of different BMPs. Studies of different BMPs used for forest roads and skid trails often rely on direct measures of erosion such as sediment traps. Although such measures provide good measures of eroded material, the implementation of such studies are labor intensive, time consuming, and costly. Thus, soil erosion models are an attractive alternative for both researchers and land managers for determining relative erosion rates in order to maximize erosion control with limited resources. However, erosion models have not been widely used for such practices, particularly across a range of BMP methodologies.

This project evaluated soil erosion rates from bladed skid trails in the Ridge and Valley physiographic region of Virginia following an operational timber harvest, and compared them to erosion model predictions produced by USLE-Forest, RUSLE2, and WEPP:Road in order to partially confirm the utility of the models for these conditions. Bladed skid trails were divided into six blocks where each block had similar slopes and soils. Each block contained four different skid trail closure BMP treatments (Control, Slash, Grass, and Mulch). All treatments had waterbars, which are considered the minimum BMP closure treatment. Skid trail characteristics were collected seasonally as input parameters for the three erosion models. Erosion model performances were evaluated based upon their statistical summaries, linear relationship with actual erosion data, their Nash-Suttcliffe Model Efficiency (NSE), and nonparametric statistical analyses. Measured erosion rates for Seed (2.6 tons ac^{-1} yr^{-1}), Mulch (0.5 tons ac^{-1} yr^{-1}), and Slash (0.4 tons ac^{-1} yr^{-1}) were significantly less than the Control (6.8 tons ac^{-1} yr^{-1}). Mulch and Slash treatments were both shown to be the most effective at reducing erosion rates. When this measured data was compared to the modeled data, USLE-Forest and

WEPP:Road models were shown to have more satisfactory NSE values, while the RUSLE2 model featured a better linear relationship to the modeled data. A nonparametric analysis of the total model averages suggests that each USLE-Forest was the most effective at modeling across all BMP methods.

Keywords. Bladed Skid Trails, Forest Operations, Soil Erosion Modeling

3.2 Introduction

The US Environmental Protection Agency lists sediment as the most damaging nonpoint-source water pollutant in the U.S. (USEPA, 2003). Forest operations, particularly prior to BMP development and implementation, can potentially produce substantial soil erosion that can lead to stream sedimentation (Yoho, 1980). Primary sources of forest soil erosion are forest roads, bladed skid trails, and stream crossings and similar areas having bare soil conditions and terrain favorable to runoff (Lakel, et al., 2006). Bladed skid trails are primarily used on steep terrain to facilitate operator safety and skidding productivity. It has been estimated that up to 84% of exposed mineral soil in a harvest is attributed to skid trails (Kochenderfer, 1977). Worrell et al. (2011) measured area in bladed skid trails on three Cumberland Plateau harvests and found that approximately 7.7% of a harvest served as bladed skid trails. Wade, et al. (2013a) evaluated erosion from bladed skid trails in the Piedmont with a range of BMPs and found erosion rates between 1.3 to 61.1 tons ac^{-1} yr^{-1} (3.0 to 137.1 tonnes ha^{-1} yr^{-1}). Bladed skid trails can have high erosion rates due to their bare soil exposure, terrain slope steepness, and low road drainage standards (Anderson and Lockaby, 2011, Grace, 2002). Factors which increase soil erosion can also potentially increase stream sedimentation and lead to stream degradation (Grace, 2005, Swift, 1985; Croke and Hairsine, 2006; Douglass and Swank, 1972).

Best management practices for forest roads and skid trails have been developed to reduce the impacts of forest operations on water quality (VDOF, 2011). These BMPs include pre-harvest planning, water control structures, streamside management zones, and the use of ground cover on forest roads and skid trails (VDOF, 2011). The effects of ground cover are analyzed in this study. Commonly suggested methods of ground cover establishment for bladed skid trails include grass seed, straw mulch, and residual tops and stems from the forest harvest (slash) (Foltz, 2012; Grushecky et al., 2009; Lyons et al., 2009; McGreer, 1981). These methods of ground cover have been found to be both effective and economical in the past (Sawyers, et al., 2012, Wade, et al., 2012a).

Physical measurement of erosion is both costly and time consuming, thus erosion models are commonly used to estimate erosion potentials (Fu et al. 2010, Wade et al. 2012b). Several models were developed to assist agricultural land managers to best evaluate possible erosion issues, and have been adapted to forest use over time (Dissmeyer and Foster 1980). Erosion models can be used by forest managers to make silvicultural, management, or even forest engineering decisions (Elliot, 2004). They are frequently modified to maintain and increase their accuracy and dependability (Fu et al, 2010). The Universal Soil Loss Equation (USLE) is a common method used to determine potential soil loss for sheet and rill erosion. Developed by the USDA in 1954 and adapted to forest land use in 1980 (Dissmeyer and Foster 1980), it is one of the most common soil loss models. Being relatively simple to use, it also provides the most basic version of soil loss modelling. The USLE model is:

$$A = RKLSCP$$

Whereas, A is the annual soil loss per unit area, R is the rainfall and runoff factor, K is the soil erodibility factor, L represents the slope-length factor, S is the slope-steepness factor, C is the cover and management factor, and P represents the support practices factor (Dissmeyer and Foster, 1980). The rainfall and runoff factor is determined based upon the average weather conditions at the location of interest. The soil erodibility factor (K) is a function of multiple soil characteristics: soil texture, organic matter content, structure, and permeability. A soil's erodibility factor can usually be found in a soil survey or soil description (USDA NRCS, 2013). However, for more accurate erodibility factor estimation, each of the characteristics can be determined and input into the soil erodibility nomograph. Slope-length factor (L) is "the ratio of soil loss from the field slope length to that from a 72.6-foot length under identical conditions" (Dissmeyer and Foster, 1980). Likewise, slope-steepness factor (S) is defined as "the ratio of soil loss from the field slope gradient to that from a 9-percent slope under otherwise identical conditions" (Dissmeyer and Foster, 1980). These two variables can be determined from a table found in A Guide to Predicting Sheet and Rill Erosion on Forest Land (Dissmeyer and Foster, 1980). Cover and management (CP) factors are based upon the amount of bare soil, presence of canopy, soil reconsolidation, organic matter content, fine roots, residual binding effects, onsite storage, and steps.

The USLE was later revised and converted to a computerized format, labelled the RUSLE or Revised Universal Soil Loss Equation. This model was first produced in the early 1990's, and RUSLE1.06 and RUSLE2 were both released in 2003. Although the algorithm from the USLE was kept, it was modified for improved accuracy by deriving soil loss factors in new ways. This revision included changes to make the model more suited for use with forest lands. Other improvements included updated rainfall coefficients, after changing some of the R factors in the eastern US based on weather data collected from more than 1,200 weather stations. Soil erodibility (K) was varied seasonally for increased accuracy. The LS factor was improved in that it takes into account the "susceptibility of the soil to rill erosion relative to interrill erosion," and the Cover factor used a new algorithm for determining cover based on prior land use, canopy cover, soil cover, and soil surface roughness (Renard et al., 1999). In Renard's study, the USLE and RUSLE were both compared on rangeland and cropland. It was found that at times, RUSLE tended to produce either lower or higher values than the USLE model on the same site, depending on what specific factors were changed. RUSLE2 has no specific data files for forest roads, however there are "highly disturbed land" files that can be modified to suit different forest road treatments (Wade et al., 2012b).

The Water Erosion Prediction Project (WEPP) is a model produced by the USDA NRCS and USFS to replace the USLE formula. This "models soil erosion as a process of rill and interrill detachment and transport" (Laflen et al., 1991). The WEPP model is potentially more attractive to users in that it estimates daily conditions that affect erosion, over the course of a year. In this, senescence, plant growth, residue accumulation and decomposition, as well as daily temperatures and soil water availability are taken into account to provide a very detailed estimate of soil loss over time. An additional benefit is the ability to model complex slopes and forest road profiles, with features such as cutslopes and fillslopes, ditches, and road surfaces (Fu et al., 2010). Four types of data files area required to run WEPP: 1) a climate file, to include data on daily precipitation and temperature, 2) a hillslope file, which can contain multiple points to describe a slope's shape, 3) a soils file, which can include multiple soil types across the hillslope, and 4) a management file containing information on soil disturbances, vegetative conditions present (Elliot, 2004). Weather data is obtained through Cligen, the USDA's weather resource. This weather file models weather data on a daily basis for more than 1,000 climates (Cligen Overview, 2015). Using the hillslope file, WEPP determines the erosion or deposition rates for at least 100 points of the hillslope if there is any runoff predicted that day (Elliot et al., 1999). Because WEPP, like other models, was originally intended for cropland or rangelands, there have been many efforts to adapt it for forest uses (Dun et al., 2009; Elliot et al., 1995; Elliot et al., 1997; Elliot et al., 2001; Morfin et al., 1996; and Tysdal et al., 1997). One of these efforts is the WEPP:Road model interface. This program allows the user to determine the amount of sediment delivered to the stream through the forest buffer and amount of sediment eroded from each portion of the road, as well as the distribution of erosion and deposition and the presence of a sediment plume in the forest (Elliot et al., 2000). At this time, the selections for cover and land use scenarios appear to limit WEPPs utility for estimation of erosion for many eastern forest management regimes (Brown et al., 2015).

There have been multiple attempts at partially confirming these three models. Wade et al. (2012b), compared sediment trap data to predictions by all three models. Erosion rates were estimated from different sections of bladed skid trail in the Piedmont of Virginia using sediment traps, and were then compared to erosion rates predicted by USLE, RUSLE2, and WEPP models. It was found that overall, all three models performed sufficiently well for identifying erosion hazards and making management decisions. When comparing the modeled data, it was determined that USLE-Forest ranged from 0.9x to 2.2x the actual erosion rates from data collected from the sediment traps. RUSLE2 ranged from 0.4x to 2x the actual erosion, and WEPP:Road ranged from 2.3x to 7.5x (Wade et al., 2012b). These data indicated that the USLE-Forest and RUSLE2 can be useful at approximating erosion rates, but WEPP:Road values should only be used for ranking purposes at this time. WEPP modelling efforts can be improved with laborious programming, but are time consuming and requires many measurements to modify the working files. Foster, et al., (2003) found similar results when comparing USLE, RUSLE1.06, and RUSLE2.

3.2.1 Research Objectives

This study is a portion of a larger study. The primary objective of this study was to compare measured erosion rates from bladed skid trails with those produced by current road and hillslope erosion models in order to partially confirm them. These models are: the Universal Soil Loss Equation (USLE-Forest), the Revised Universal Soil Loss Equation (RUSLE2), and the Water Erosion Prediction Project (WEPP:Road). Treatment effects and model accuracy were both evaluated in this study. The four BMP treatments tested were: 1) waterbars only (Control), 2) waterbars with grass seed (Seed), 3) waterbars with grass seed, fertilizer, and straw mulch (Mulch), and 4) waterbars with slash (Slash). Model suitability was determined based on a comparison of the modeled data to erosion data collected from sediment traps onsite.

3.3 Materials and Methods

3.3.1 Research Site

The study site was located in the Ridge and Valley physiographic province, on Virginia Tech's Fishburn Forest located in Montgomery County, Virginia (Figure 3.1). The site was logged in late 2014-early 2015 in a shelterwood overstory removal of upland hardwoods for three blocks and modified shelterwood pine and hardwood for three blocks. The average yearly precipitation is 40.89in (103.86cm) (NOAA, 2010).

The soils are typically very shallow, well drained silt loams, being derived mostly from shale, siltstone, and sandstone residuum and Berks, Weikert, Berks-Weikert and Clymer soil series dominate the site, (USDA NRCS, 2013). Species were primarily Chestnut oak, Scarlet Oak, White Oak, Black Oak, Yellow-Poplar, Pignut Hickory, Virginia Pine, and White Pine. Slopes range from 0% to 100%. Skid trails were laid out for this harvest in a method of logger's preference.

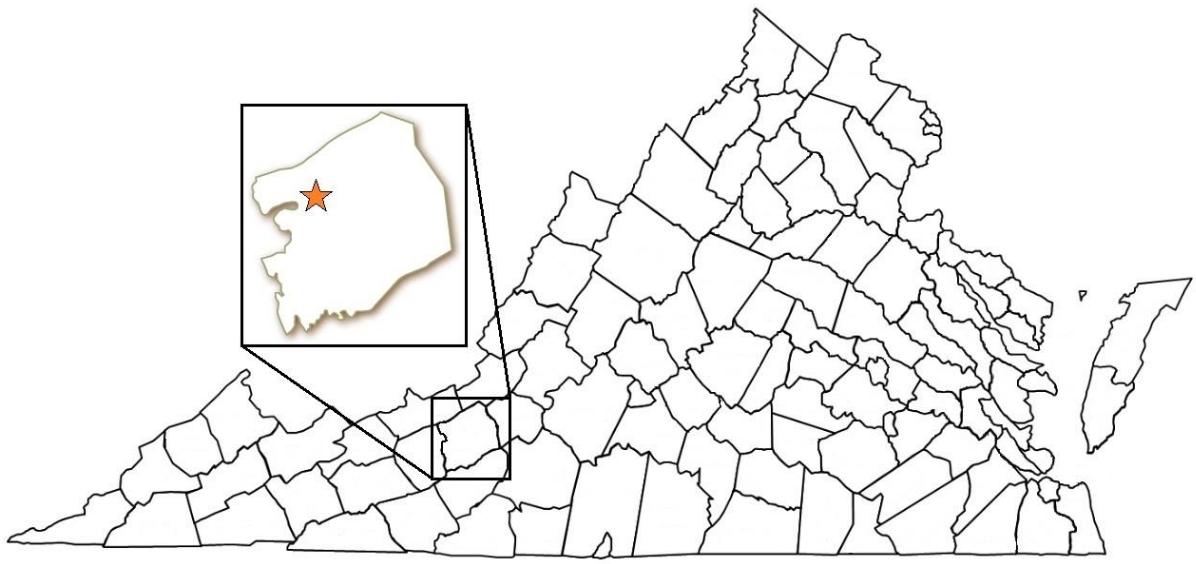

Figure 3.1: Location map of harvest site within Montgomery County, Virginia.

3.3.2 BMP Treatments

Four types of treatments were used in this study: 1) waterbars only (Control), 2) waterbars with grass seed (Seed), 3) waterbars with grass seed, fertilizer, and straw mulch (Mulch), and 4) waterbars with slash (Slash). The Control treatment contained waterbars with no ground cover to represent the minimum acceptable BMPs for skid trail closure. For the Seed treatment, grass seed was applied at the time of skid trail closeout (April 2015) using a mix of 50% perennial ryegrass (*Lolium perenne*) seed and 50% KY-31 fescue (*Festuca arundinacea*), based on suggestions from the VDOF BMP manual. Seed was spread with a hand operated cyclone type seeder to ensure 100% coverage, a rate of approximately 150 lbs per acre (33.6 kg/ha). For the Mulch treatment, the same grass seed mixture was applied, along with fertilizer and straw mulch. Mulch was spread by hand to ensure 100% coverage, at a rate of approximately 80 bales/acre (VDOF 2011). Fertilizer was added at a rate of approximately 300 lbs per acre (336 kg/ha) of 10-10-10 to provide sufficient nutrient availability for the grass. Slash treatments utilized residual slash from on-site logging operations, and was primarily composed of yellow-poplar (*Liriodendron tulipifera*), hickory (*Carya spp.*), scarlet oak (*Quercus coccinea*), chestnut oak (*Quercus prinus*), white oak (*Quercus alba*), white pine (*Pinus strobus*), and Virginia pine (*Pinus virginiana*). Slash was hand applied onto skid trails to ensure similar coverage and then compacted with a John Deere 450 bulldozer to make contact with the ground. After compaction, slash was at a depth of 2ft (0.6m) to 3ft (0.9m).

3.3.3 Erosion Model Parameters

For modelling, each experimental unit was divided into two sections. The first section being the downhill side of the upslope water bar and the actual skid trail surface, and the second being the uphill side of the downslope water bar (Figure 3.2). Since the two water bars had sides that were contributing to the area, they were accounted for in the modelling as well. The slope and length of every section was measured using a total station. The USLE was used to estimate erosion on each section, and combined in a weighted average for a total erosion estimate for each treatment. Seed and Mulch treatments had model estimates determined both before and after seed germination for a comparison, as ground cover values were measured in the field every 3 months to account for seasonal variations, the establishment of grass, and decomposition of slash and mulch. Slope, climate data, soil characteristics, and cover practices were determined for each experimental unit and input into both computer models to estimate soil erosion. Actual erosion rates were converted to tons ac^{-1} yr^{-1} in order to compare estimates provided by all three models. For each treatment area the following data were collected: ground cover, slope and slope length, rainfall, soil rock content, and percent of soil in clay, sand, and silt particle sizes.

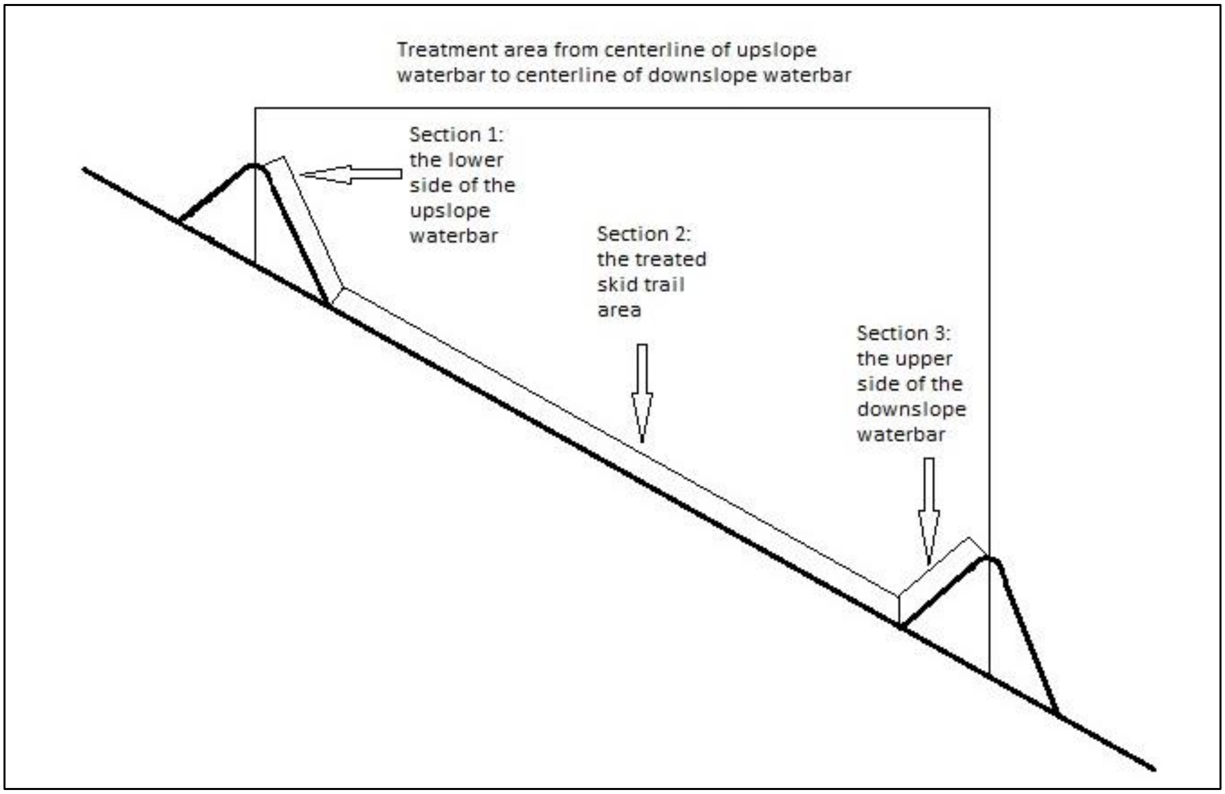

Figure 3.2: Profile of skid trail treatment. Sections 1 and 2 (lower side of top waterbar and skid trail) were modeled together; section 3 (upper side of bottom waterbar) was modeled separately and were factored together as a weighted average.

3.3.4 USLE-Forest

A rainfall runoff factor of 150 was used as it was derived from a rainfall contour map provided by the USLE-Forest manual (Dissmeyer and Foster, 1980). A soil erodibility factor of 0.43 was obtained from the Web Soil Survey for the subsoil of the Berks-Weikert complex (NRCS, 2013). A total station was used to measure the slope length and gradient for the upper and lower waterbars, and the section of bladed skid trail located between the two. Slope lengths were often too small to be found in the table provided in the USLE-Forest manual, and therefore were obtained using the equation:

$$LS=(\lambda/72.6)^{m}(65.41\sin\theta^{2}+4.65\sin\theta+0.065)$$

where λ is the slope length in feet, θ is the slope angle in degrees, and *m* is 0.2 for <1% slopes, 0.3 for 1% to 3% slopes, 0.4 for 3.5% to 4.5% slopes, and 0.5 for ≥5% slopes (Dissmeyer and Foster, 1980). Bladed skid trails were considered to be tilled soil, therefore having CP factors to include bare soil, residual binding, and soil reconsolidation; canopy effect; steps; onsite storage; invading vegetation; and contour tillage. Bare soil percentages were calculated by creating transects across the treatment, over which points were evenly spaced. At each point, the ground was determined to be either bare or covered. Ground cover was provided in the form of vegetation, straw mulch, woody residues, rock fragments, and leaf litter. These measurements were collected quarterly over one year to cover the span of four seasons. A weighted average of the four periods was used to determine a final erosion rate for each treatment.

3.3.5 RUSLE2

Erosion estimates were also derived using RUSLE2. Montgomery county weather and soil files were imported into the system to more accurately estimate soil loss. The climatic data were accessed from the NRCS database (NRCS, 2013) for Montgomery County, Virginia. Daily and monthly average rainfall rates were included in these data. Next, soils data were imported into the program. Montgomery county soil survey provided the Berks-Weikert complex as the soil series for the site (NRCS, 2013). This soil file contains information on the erodibility of the soil, the soil texture, and acceptable loss rates. For every treatment, a slope profile was created based on the measured slope and length of each section of the treatment area. Management files had to be created for each BMP treatment, as there were no existing files to represent forest roads or skid trails. All operations were set to occur in late April to coincide with the initial site installation. The “highly disturbed land/blade cut” option was chosen to represent the Control treatments. Seed treatments used this file, but with the modification of “broadcast seed operation” also used. “Fescue” and “Ryegrass” were used as the species of seed applied, and the “live surface cover” was modified to represent the percentage of ground cover contributed by the germination of the grass seed as time increased. Mulch treatments used this file; however it was modified to include the “add mulch” operation in the form of “bale straw or residue.” The type of mulch chosen in this instance was “wheat straw.” The option “specify cover directly” was chosen and modified for each treatment as was measured in the field. Slash treatments were best represented by the “highly disturbed/blade cut” option, followed by the “add mulch” operation, with “prunings, orchard and vineyard, flail shredded” chosen as the material. The cover was again manipulated by modifying the "specify cover directly" parameter, and by modifying the decomposition half-life of the material to 1800 days, as based on rates used by Wade et al. (2012b) to represent woody debris from southern Appalachian hardwood forests.

3.3.6 WEPP:Road

WEPP:Road is dependent upon four different types of files to predict soil erosion rates. The software features a database that contains basic files for each of these that can be easily modified to best represent the site. The four types of files are: 1) climate, 2) soil characteristics, 3) slope length and gradient, and 4) land management operations. A climate file for Blacksburg, Virginia was chosen as the best representative of the site conditions, as the weather station is less than 5mi (8km) away from the study site. Within the WEPP:Road soils database, the file most similar to a Berks-Weikert complex was the "Disturbed Skid Clay Loam," which was chosen for modeling on this site. Soil rock content for each treatment varied from 10-36%, and was directly correlated with slope steepness. Therefore, it was determined that rock content of the soil would be a parameter which needed modification for each treatment. Slope length and gradient values were modified for each treatment as they were measured with the total station. The "Forest Bladed Road" management file was used for the control treatments, and was modified for the others. Initial conditions were modified by their initial rill and interrill ground cover percentage, as measured in the field. Seed treatments used this base of "Forest Bladed Road" as the initial conditions and then were modified with the "fescue" and "annual ryegrass at a low fertilization rate." Mulch treatment management files used this file as a base, however "fescue residue" was added as a mulch at a rate of 3.5 tons per acre (0.788 kg m^{-2}). Similar to RUSLE2, there are no management files in WEPP:Road that represent Slash treatments. Since there are no woody residue mulch treatments, the same "fescue residue" mulch was chosen. The actual application rate (by weight) that was used to apply slash in the field was used to model this treatment. All treatments were modeled for one year.

3.3.7 Data Analysis

Treatment effects for each erosion model were analyzed using JMP statistical software (JMP, 2015). A variety of methods were used to compare the trapped and modeled estimates including: 1) summary statistics, 2) linear relationships, 3) Nash and Sutcliffe Model Efficiency (NSE) (Nash and Sutcliffe, 1970) and 4) a Steel-Dwass multiple comparisons test comparing models to each other. Summary statistics provided the mean and standard deviation for each treatment using each method of modeling. Linear relationships, and NSE were evaluated to determine the accuracy of the models when compared to the actual trapped erosion rates, and a nonparametric comparison for each pair using the Wilcoxon method was conducted to compare these models to each other.

3.4 Results

3.4.1 BMP Treatment Effectiveness

The sediment collected in traps indicated the overall effectiveness of the BMPs. Control treatments had an erosion rate of 6.8 t ac^{-1} yr^{-1} (15.1 tonnes ha^{-1} yr^{-1}), Seed had an erosion rate of 2.6 t ac^{-1} yr^{-1} (5.9 tonnes ha^{-1} yr^{-1}), and Mulch eroded at a rate of 0.5 t ac^{-1} yr^{-1} (1.1 tonnes ha^{-1} yr^{-1}). Slash treatments eroded at a rate of 0.4 t ac^{-1} yr^{-1} (0.8 tonnes ha^{-1} yr^{-1}). Each model ranked the BMP treatments as having the Control as the most erosive, and Mulch as least erosive. All models tended to over-estimate the erosion rates of slash treatments. The Control treatments represent the minimum level of BMPs that are acceptable for skid trail closeout, and eroded at rates 2.8x to 8x that of Seed treatments, the next most erodible treatment. Mulch and Slash treatments both reduced average erosion rates to minimal amounts. Adding mulch and fertilizer provided the trail with immediate ground cover, which was not attained by the Seed treatments due to the time necessary for germination. Mulch and fertilizer also aided in the retention of soil nutrients and moisture, as well as reduced predation of the grass seeds from wildlife. Slash provided immediate ground cover, and offers the additional benefits of reducing traffic on the trail, in the form of ATVs and pedestrians. Slash was also shown to provide the greatest benefit in soil erosion reduction per dollar spent in installation. This is due to the fact that no materials are needed to be purchased to install a slash treatment, since slash is already present following the harvest. For all types of treatments, as ground cover increased, soil erosion decreased. Slope and length did have effects upon the erosion rates, as did rock content of the soil. Steeper slopes in this soil series tended to contain higher rock fragment contents, which acted to increase soil cover over time.

3.4.2 Model Suitability

Models were evaluated using the four different techniques outlined above. Each of the model predictions was compared to the trapped sediment data after one year (Figure 3.3). The mean, standard deviation, and standard error of erosion rates for each BMP closeout method was determined for each model (Table 3.1). USLE-Forest produced mean values closest to the mean measured rates for the Control and Slash treatments, while RUSLE2 produced mean values closest to the mean measured rates for the Seed and Mulch treatments.

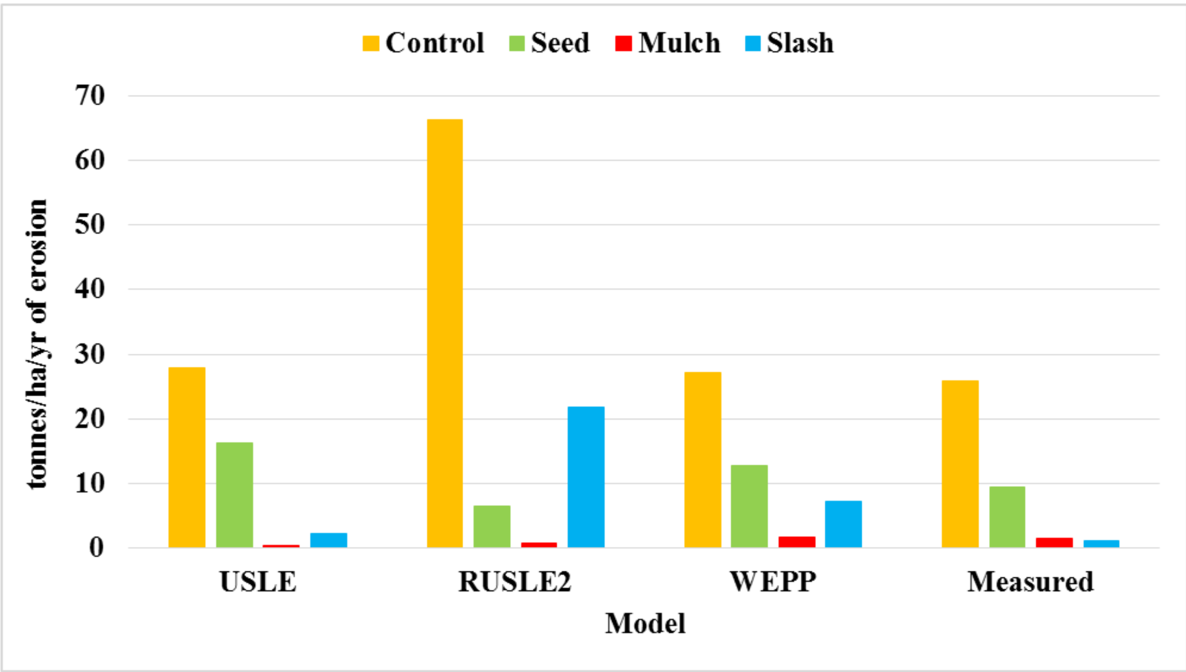

Figure 3.3: Graphical comparison of erosion predictions for each model as compared to the measured rates in each BMP class.

Table 3.1: Summary statistics for erosion estimates provided by USLE-Forest, RUSLE2, and WEPP:Road as compared to the actual measured data. Erosion rates marked by (*) are the closest to the measured values for each closeout method and those marked with (**) are furthest from the mean.

Treatment	Method	Mean Erosion Rate (t ac^{-1} yr^{-1})	Std Dev	CV (%)	Lower 95%	Upper 95%
Control	Measured	6.76	5.41	80.0	1.09	12.44
	USLE-Forest	*10.78	5.02	46.6	5.51	16.05
	RUSLE2	**29.66	13.04	44.0	15.98	43.34
	WEPP:Road	12.08	3.09	25.6	8.84	15.31
Seed	Measured	2.62	2.43	92.7	0.08	5.17
	USLE-Forest	**7.39	5.59	75.6	1.52	13.25
	RUSLE2	*2.84	1.61	56.7	1.15	4.54
	WEPP:Road	5.67	2.77	48.9	2.76	8.58
Mulch	Measured	0.49	0.44	89.8	0.03	0.95
	USLE-Forest	0.15	0.14	93.3	0.01	0.3
	RUSLE2	*0.28	0.20	71.4	0.07	0.48
	WEPP:Road	**0.72	0.31	43.1	0.39	1.05
Slash	Measured	0.35	0.25	71.4	0.08	0.61
	USLE-Forest	*1.03	0.84	81.6	0.14	1.91
	RUSLE2	**9.72	4.89	50.3	4.59	14.85
	WEPP:Road	3.23	1.61	49.8	1.55	4.92

Linear relationships were also used to determine model accuracy. Each of the sets of modeled data were compared to the data collected by sediment traps graphically. Accurate models are expected to have a linear relationship to the collected data (Laflen, et al., 2004). In this study, RUSLE2 was shown to have the highest Pearson Correlation Coefficient (R) value among the three, at 0.78 (Figure 3.4) where y is the sediment trap measured erosion rates, and x is the RUSLE2 predicted data. This R value indicates that RUSLE2 had the best estimated linear relationship with the trapped data. The linear relationship of WEPP-Road to measured data had the second highest R value of 0.77 (Figure 3.5), where y is the sediment trap measured erosion rates, and x is the WEPP:Road predicted data. Lastly, the relationship of USLE-Forest to the measured erosion data had the lowest R value (0.68) (Figure 3.6), where y is the sediment trap measured erosion rates, and x is the USLE-Forest predicted data.

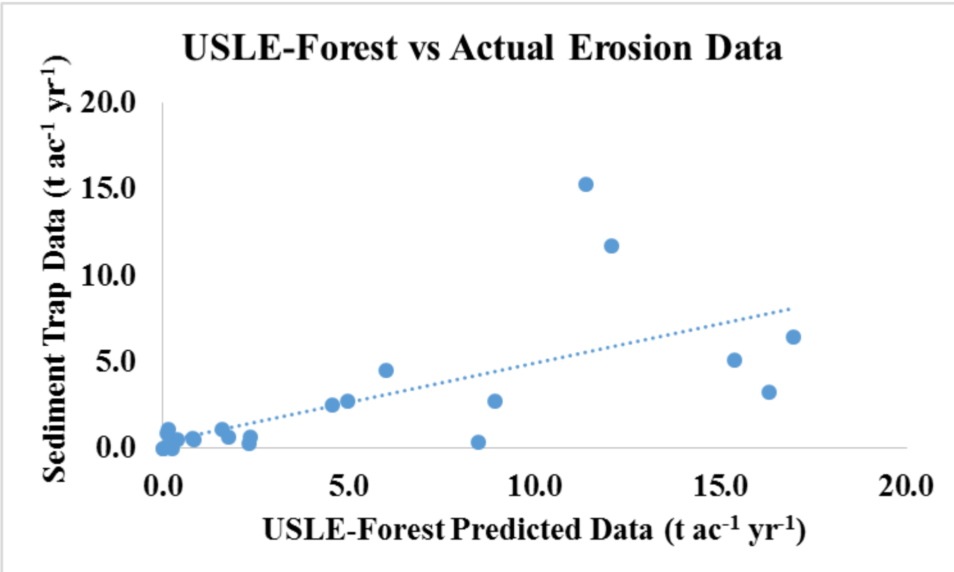

Figure 3.4: Linear relationship of RUSLE2 modeled data and actual measured erosion data.

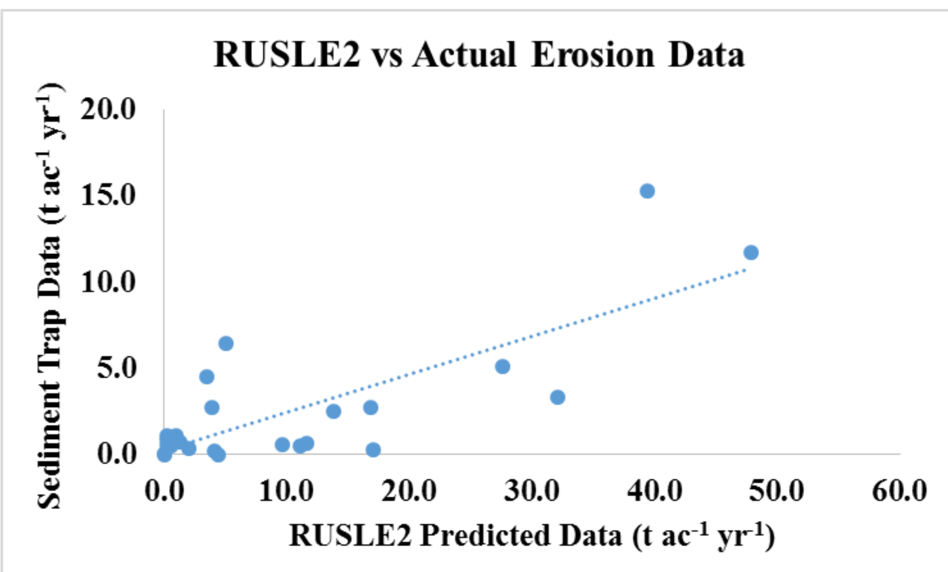

Figure 3.5: Linear relationship of WEPP:Road modeled data and actual measured erosion data.

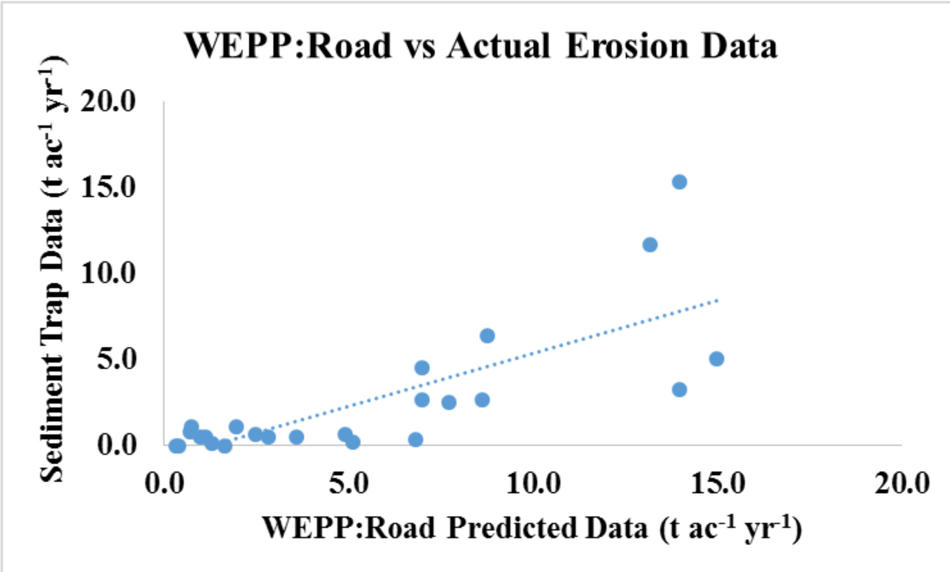

Figure 3.6: Linear relationship of USLE-Forest modeled data and actual measured erosion data.

The Nash-Sutcliffe Model Efficiency (NSE) is commonly used to evaluate hydrologic models. The range of efficiency is from -∞ to 1, with values from 0-1 indicating that the model is a good predictor of the measured values. Negative values indicate that the mean of the measured values are a better predictor than the model itself (Nash and Sutcliffe, 1970). NSE was calculated for each of the treatments and each of the models as a whole (Table 3.2). All values were negative with the exception of the WEPP-Road and RUSLE2 models at predicting mulch treatments (0.15 and 0.23). The NSE value for USLE-Forest is negative for this treatment (-0.29), however it is substantially greater in value than most other treatment categories. Waterbar only (control) treatments were found to have the lowest values for each model, indicating that all models were insufficient at predicting soil loss from bare soil treatments. As a whole, RUSLE2 has a much lower NSE value (-1174.15) than USLE-Forest (-146.53) or WEPP-Road (-115.01), indicating that it is the least applicable of the three models.

Table 3.2: A comparison of predicted erosion rates and their NSE values for the whole model and for each treatment type.

		Control	Seed	Mulch	Slash
Trapped Sediment	(tons ac^{-1} yr^{-1})	6.76	2.62	0.49	0.35
USLE-Forest	(tons ac^{-1} yr^{-1})	10.78	7.39	0.15	1.03
	NSE	-476.81	-276.44	-0.29	-4.87
Whole Model NSE			-146.35		
RUSLE2	(tons ac^{-1} yr^{-1})	29.66	2.84	0.28	9.72
	NSE	-5681.25	-8.90	0.23	-651.77
Whole Model NSE			-1174.15		
WEPP:Road	(tons ac^{-1} yr^{-1})	12.08	5.67	0.72	3.23
	NSE	-442.32	-94.39	0.15	-60.95
Whole Model NSE			-115.01		

Lastly, the models were analyzed using a nonparametric comparison for each pair using the Steel-Dwass Multiple Comparisons method (Table 3.3). It was determined that a nonparametric statistical analysis was necessary in this case because the data violate the assumptions of equal variance, homoscedasticity, and normal distribution. A Levene’s normality test confirmed this. For this method of analysis, each method was individually compared to the others. In this instance, USLE-Forest and RUSLE2 were considered to be statistically similar to the measured data (p-values of 0.74 and 0.07). This indicates that as a whole model, WEPP:Road may not be the most suitable for modeling across all treatments (p-value= 0.02). However, USLE-Forest was determined to be the most fitting model when all four closure methods were taken into consideration.

Table 3.3: Nonparametric analysis using Steel-Dwass Multiple comparisons; comparing the predicted values of each model to the measured values.

Model	Score Mean Difference	Std Err Dif	Z	p-value
USLE-Forest	4.125	4.04	1.02	0.7373
RUSLE2	9.791	4.04	2.42	0.0728
WEPP:Road	11.458	4.04	2.84	0.0237

3.5 Discussion

Results indicated that the BMPs were effective in providing ground cover necessary to reduce erosion. Generally, as ground cover increased, erosion rates decreased. It was observed in the field that rock fragments had a major impact on ground cover and therefore erosion rates, which may have been difficult for the models to assess. Slash, seed, and straw mulch have been shown to reduce erosion from skid trails and temporary roads. The benefits of slash and straw mulch are that they both provide immediate cover, especially during the months following disturbance at which one can expect erosion rates to be the highest. Slash has the added benefits of being readily available, having a longer half-life than straw mulch, and being more effective at reducing trail traffic. Both slash and straw mulch also have the ability to improve the chemical and physical properties of the soil through decomposition. This study has shown that additional ground cover BMPs may be desirable to enhance the waterbar treatment. Models were shown to have varying degrees of accuracy and suitability based upon their use. Similar conclusions were also reached by Wade et al., (2012b) and Brown et al., (2015).

USLE-Forest was slightly different than the other models in terms of management and cover practices. Whereas RUSLE2 and WEPP:Road model a specific operation and make assumptions based upon its effects, USLE-Forest models these effects directly. This played a large role in the accuracy of the model. However, many field measurements are required to produce a feasible value from this model. Soils, ground cover, and canopy cover must all be measured in the field. However, this does allow for a more “field available” prediction, whereas RUSLE2 and WEPP:Road both require the use of computer software. The USLE was shown to be the most user-friendly of the three models, in that it can easily be performed with a manual in the field, with relatively minimal training.

RUSLE2 was determined to be the least suitable of the three models assessed, in that its NSE values, means and standard deviations, and nonparametric p-values are all insufficient for it to be deemed accurate in this instance. Several factors affecting the model accuracy are the aforementioned rock content of the soils. While soil files were accurate enough for the model, it did not take into account the increased soil ground cover from the high soil rock content over time. Other factors include the fact that operations are modeled as such instead of the effects that those operations had upon the ground surface. The primary reason for poor performance of RUSLE2 would be the fact that there are no management files available for bladed roads or slash treatments.

WEPP:Road was shown to be the most conforming of the three models based on NSE and linear relationships. This can be attributed to a number of factors. This is the only model that takes into account soil rock content in its analysis, which could have helped to make predictions more accurately. In addition to this, there are road and road treatment files available, which gives WEPP:Road an advantage over RUSLE2. One major disadvantage to WEPP is that it does not feature any wood or wood-fiber based mulches to represent slash treatments. Both WEPP:Road and RUSLE2 are at a disadvantage, in that when compared to USLE-Forest, they are difficult to learn initially. They also require the use of a computer, which is not always practical for field management decisions.

3.6 Conclusion

The primary objective of this study was to evaluate models based on their accuracy when compared to erosion data collected in the field. After having modeled 24 experimental units over the course of a year using all three models, they were analyzed to determine accuracy. Four BMP treatments were compared to show that Seed, Mulch, and Slash were able to significantly reduce the amount of soil erosion from a bladed skid trail. Mulch and Slash were both the most effective at reducing soil erosion, as they provide immediate ground cover. Based on the Nash-Suttcliffe Model Evaluation, USLE-Forest and WEPP:Road were shown to be the better of the two models used on this site. RUSLE2 was insufficient for the use in modeling bladed skid trails, having over-predicted almost every value. However, of all the soil erosion models, RUSLE2 featured the best linear relationship with the measured erosion data. This is because even though the model produced inaccurate values, it did so at a rate consistently higher than the actual measured data. USLE-Forest was shown through nonparametric statistical analysis to be the most similar to the measured data when taking all treatments into consideration. Each model was able to rank the BMP treatments as having the Control as the most erosive, and the Mulch treatment as least erosive. All models overestimated the erosion rates for Slash treatments, with RUSLE2 placing it as the second-highest erosion rate.

While all three models underperformed in this study, USLE-Forest and WEPP:Road were shown to have been the best suited for this site. With improvements in management and soil files for RUSLE2 and WEPP:Road, we can expect model accuracy to drastically increase, therefore broadening their applicability to more varied sites.

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4.0 CONCLUSIONS

4.1 Study Objectives

This study had three objectives. The first was to evaluate the effectiveness of four different bladed skid trail closure BMPs in the Ridge and Valley physiographic province, by measuring erosion rates produced by each type of BMP. The four different cover types examined were: 1) waterbars with bare soil (Control), 2) waterbars with grass seed (Seed), 3) waterbars with fertilizer, grass seed, and straw mulch (Mulch), and 4) waterbars with slash from logging operations (Slash). The second objective was to compare the measured erosion rates of these four treatments to predicted erosion rates obtained from three different soil erosion models: the Universal Soil Loss Equation (USLE-Forest), the Revised Universal Soil Loss Equation (RUSLE2), and the Water Erosion Prediction Project (WEPP-Road). These three models were compared to determine model accuracy. The final study objective was to document costs of the various treatments to determine the economic feasibility of each method of bladed skid trail closure.

4.2 Objective 1

The first objective of this study was to measure the erosion rates from four different bladed skid trail closure methods, and evaluate their efficiency. All four treatments featured waterbars installed using VDOF recommendations, with varying ground cover types. Control treatments provided an average erosion rate of 6.8 tons ac^{-1} yr^{-1}, with rates up to 73.5 tons ac^{-1} yr^{-1} following installation and during extreme rainfall events. Ground cover for this type of treatment averaged 44.6 percent, and increased with time due to exposure of rock fragments, increase of leaf litter, and invasion of natural vegetation. Seed treatments provided an average erosion rate of 2.6 tons ac^{-1} yr^{-1}, with rates reaching 27.2 tons ac^{-1} yr^{-1}. Adding grass seed added ground cover, but not consistently over time. The grass seed required time to germinate, and the grass suffered heavy mortality rates over the summer season. The average ground cover for this treatment throughout the year was 58.9 percent. Mulch treatments (adding fertilizer and straw mulch to the grass seed) increased the initial ground cover to 94.8 percent, which stayed very consistent and only slowly decreased over time. Due to high rates of ground cover, Mulch treatments averaged 0.5 tons ac^{-1} yr^{-1} with an extreme of 3.8 tons ac^{-1} yr^{-1}. The added fertilizer and mulch reduced erosion rates by adding immediate ground cover to the treatments; the seed and fertilizer also increased grass germination and survival rates by reducing predation, increasing soil nutrients, and retaining moisture. Slash treatments were found to reduce erosion rates to an average of 0.4 tons ac^{-1} yr^{-1}, with the highest rate being 1.8 tons ac^{-1} yr^{-1}. Slash was also found to increase immediate ground cover, which over the course of data collection averaged 84.4 percent. Slash also has the additional advantage of benefitting soil properties, reducing unwanted traffic on the skid trail after closure, and lasting longer on the ground than straw, due to a longer half-life.

All BMP treatments were found to significantly reduce the rate of erosion from bladed skid trails, with Mulch and Slash treatments outperforming Seed treatments. Rates of erosion were substantial following project installation, and were found to decrease over time; generally as ground cover also increased. Total erosion rates were also dependent upon rainfall; as monthly rainfall increased, the rates of erosion did so as well.

Slope was a critical factor in determining erosion rates. All treatments were sorted into three slope classes: Gentle (0-10% slope), Moderate (10-20% slope), and Steep (>20% slope). As found in previous studies, as slope increases, we can expect an increase in erosion rates as well. However, in this study, we found that slopes in the steep class featured erosion rates lower than those of the moderate classes. At times, steep slopes saw erosion rates that were more similar to the gentle slopes than the moderate slopes. After ground cover and soil analysis, it was determined that the steeper slope soils had a higher soil rock content than the soils in moderate or gentle slopes and had shorter distances between water control structures. This higher soil rock content increased ground cover following initial soil erosion, thus reducing erosion rates.

These findings are significant, as in 2011 approximately 248,000 acres of forest land were harvested in Virginia (VDOF, 2011). We can speculate that 25-30% (62,000-75,000 acres) of that forest land lies in the mountain region of the state. Kochenderfer (1977) has proposed that 5-11% of an Appalachian harvest lies in skid trails, with higher percentages on steeper slopes. This amounts to 3,100 to 8,250 acres of land in skid trails across the Ridge and Valley. Following closure with waterbars, we can predict a mean erosion rate of 6.8 tons/ac/year, and can therefore estimate a soil loss of 21,000 to 56,000 tons per year from the region. By adding slash or mulch, we can reduce potential erosion to approximately 1,200 to 3,500 tons per year. This is a substantial reduction in soil erosion.

4.3 Objective 2

The second objective of this study was to compare the measured erosion rates to predicted erosion rates modeled by three different soil erosion models. Each treatment was modeled by all three models, and was tested for significant difference. Each part of the treatment was broken up into three different sections, to represent the lower side of the upper waterbar (Section 1), the trail surface (Section 2), and the upper side of the lower waterbar (Section 3). The first and second sections were modeled together to represent the flow path of water, and the third section was modeled by itself. Slope length and grade were measured with a total station, and ground cover measurements were taken quarterly.

The first model to be compared was USLE-Forest. This model is the oldest and most basic of the three models compared. It takes into account current ground cover conditions, rainfall, soil erodibility, and the length and grade of the slope. The second model compared was RUSLE2. This model is used more to evaluate erosion from agriculture than from bare roads. Rainfall, soil erodibility, slope length and gradient, and management practices were factors in the model. The major problem with this model is that instead of modeling the current ground cover conditions, the model simulates management operations and the conditions following the operation. Problems arose in the lack of data files to adequately model Slash treatments. The third model compared was WEPP:Road, which also models operations instead of current conditions. This model is very similar to RUSLE2, in that files for soils, rainfall, slope length and gradient, and cover and management practices are used in a computer simulation. Specific cover management files also had to be created to accurately represent ground cover conditions.

USLE-Forest was found to be the only model to be statistically similar to the measured data. RUSLE2 had the best linear relationship to the measured data (R=0.78), but tended to severely overestimate the erosion rates of the Control and Slash treatments. Models were also evaluated with the Nash-Sutcliffe Model Efficiency test, showing that USLE-Forest (-146.53) and WEPP:Road (-115.01) both outperformed RUSLE2 (-1174.15). The Mulch treatment was most accurately modeled across all models, while both RUSLE2 and WEPP:Road failed to adequately model Slash treatments. While this shows that current erosion models are adequate at modeling soil loss, there need to be modifications made to better suit them for use on low-standard roads and skid trails.

4.4 Objective 3

The third objective of this study was to determine the costs associated with the closeout of the skid trail treatments. Costs were determined based upon current market prices for materials and machine hours as well as national averages of labor costs. Costs were determined for each treatment installation, as well as the entire harvest on the Fishburn Forest had the entire bladed skid trail system been closed out using each particular method, as well as on a per-mile basis. Costs were then compared to the erosion rates to determine the cost of preventing soil erosion. Control closure treatments cost $1,980.00 per mile of bladed skid trail; Seed treatments cost $2,771.89 per mile; Mulch closure costs $4,397.50 per mile; and closing with Slash costs $2,970.00 per mile when done by hand. The most economical method of closure would be to use Seed, as it costs less than either Mulch or Slash.

When comparing the closure methods based on cost of erosion prevented, it becomes apparent that soil erosion was most significantly reduced by Slash and Mulch. It was found that while cheapest on a per acre basis, Seed closure was not the least expensive on a basis of erosion prevented. All treatments were compared to the Control closure method in regards to both erosion produced and total cost to determine the difference between both. It was found that Seed treatments cost $88.85 per ton of erosion prevented, while Mulch treatments cost $182.67 per ton of erosion prevented. This is due to the increased cost of materials necessary to close out the trails. Slash treatments cost $73.65 per ton of erosion prevented, making Slash the most economical from an environmental standpoint. This is due to the fact that additional materials are not required to be purchased, only machine labor is necessary. This cost analysis was conducted using the methods of treatment application that were used in the study. It is to be noted that Slash treatments could cost substantially less from an operational perspective than what was calculated in this study.

Roads and skid trails are a major cost incurred by loggers when conducting forest harvests (Conrad et al., 2012). We can apply this cost analysis to the closure of bladed skid trails in order to assist with logging cost estimates for land managers and logging industry professionals. Slash has been shown in several studies (Sawyers et al., 2012; Wade et al., 2012) to be both economical and effective at reducing erosion. For this reason, slash is highly recommended to forest managers for the closure of temporary forest roads and skid trails. In situations in which slash is not readily available, seed and mulch may be used to adequately reduce erosion rates from bare soil. While seed only has been determined to adequately reduce erosion over waterbars only, it may not be sufficient at sensitive harvest areas such as stream crossing approaches or areas with a high erosion potential such as steep slopes. In these cases, a more appropriate method of closure would be slash or seed and mulch. It is imperative for land managers to use sufficient ground cover, along with appropriate water control features to adequately close out bladed skid trails.

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