Evaluation of Best Management Practices for Bladed Skid Trail Erosion Control and Determination of Erosion Model Accuracy and Applicability

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ABSTRACT

Sediment is one of the leading non-point source pollutants in the U.S and has detrimental effects on biological communities such as aquatic communities; human use such as recreation; and natural processes such as flood water storage. For silvicultural operations, the majority of sediment is produced from erosion on highly disturbed areas, such as skid trails, haul roads, and log landings. Erosion from silvicultural activities not only has the potential to introduce sediment into waterways but can also decrease site productivity through the removal of topsoil. In order to minimize erosion from silvicultural operations, forestry Best Management Practices (BMPs) have been developed, but efficacies of various BMP options are not well documented. This study evaluated five closure and cover BMPs for the control of erosion on bladed skid trails through both field based measurements with sediment traps and soil erosion modeling. The erosion models used were the Universal Soil Loss Equation for Forestry (USLE – Forest), the Revised Universal Soil Loss Equation version 2 (RUSLE2), and the Water Erosion Prediction Project for Forest Roads (WEPP – Forest Roads). Erosion model predictions were also regressed against field based results to determine accuracy. The bladed skid trail BMP treatments evaluated were: 1) water bar only (Control); 2) water bar and grass seed (Seed); 3) water bar, grass seed, and straw mulch (Mulch); 4) water bar and piled hardwood slash (Hardwood Slash); and 5) water bar and piled pine slash (Pine Slash). Field based results show that the Control treatment was the most erosive (137.7 tonnes/ha/yr), followed by the Seed treatment (31.5 tonnes/ha/yr), Hardwood Slash treatment (8.9 tonnes/ha/yr), Pine Slash treatment (5.9

tonnes/ha/yr), and finally the Mulch treatment was the most effective erosion control technique (3.0 tonnes/ha/yr). Model accuracy results show that RUSLE2 performed the best overall. Both USLE – Forest and WEPP – Forest Roads under predicted values on the Control treatment, where erosion rates were very high. WEPP – Forest Roads under predicted these values the most. All models generally show that the Control was the most erosive followed by the Seed, Hardwood Slash, Pine Slash, and Mulch treatments.

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Chapter 1. Introduction and Literature Review

Introduction

For silvicultural operations, areas that have undergone major surface soil disturbance, such as roads and decks, are prone to erosion (Aust and Blinn, 2004). During operational forest management activities these disturbed areas can constitute a large percentage of the total harvested area. In the Central Appalachians, ground based skidding operations' log landings and roads occupy approximately 10% of the harvested area (Kochenderfer, 1977; Worrell et al., 2010). In the western United States, Rice et al. (1972) developed similar estimates for the percentage of harvested areas in landings, roads, and trails. It was estimated that ground based tractor operations had 8.4% and 9.0% of the area in landings, roads, and trails in California, and Idaho, respectively. The Federal Water Pollution Control Act of 1972 and subsequent amendments specify that forestry activities should minimize non-point source pollution (NPSP) from forest operations (Shepard, 2006). Therefore, forestry Best Management Practices (BMPs) have been developed to mitigate erosion, which is usually the main type of NPSP from forest operations (Aust and Blinn, 2004). The BMPs used for roads, skid trails, and logging decks include: 1) proper planning, construction, and location; 2) control of grade; 3) control of water; 4) surfacing; and 5) road or trail closure (Swift, 1985; Swift and Burns, 1999; Grace, 2005). Trail closure is of particular importance because trails are often built to lower standards than permanent roads, and represent a "higher risk for soil erosion" (Grushecky et al., 2009). Water control structures such as water bars are used to divert water flow from the roadway and dissipate it over the adjacent forest floor. The spacing interval of water bars is dependent on the slope of the trail; as the slope increases the desirable distance between bars decreases (Virginia Dept. For., 2002). Cover BMPs such as seeding, and seeding and mulching often reduce the amount of erosion by providing stability to the soil. The cover provided also decreases overland flow velocity and causes deposition of sediment before it reaches a waterway. Mulching provides immediate cover while the effects of seeding are not evident until the seed germinates (Wade et al., 2010). Piling slash on skid trails can also be a means of providing immediate cover, however there has been limited research into the effectiveness of slash as a soil stabilizer. A study conducted on volcanic soils in the west showed that piled slash reduced soil erosion by 99% when compared to bare mineral soil (McGreer, 1981).

Sedimentation

The Environmental Protection Agency recently emphasized that non-point source pollution is one of the greatest threats to our nation's water quality (USEPA, 2003). NPSP is one of the primary reasons that 40% of our rivers, streams, and estuaries are too polluted for recreational needs (Henley et al., 2000; USEPA, 2003). Sedimentation also has been identified as a detrimental process for lotic habitats (Henley et al., 2000; Virginia Department of Environmental Quality, 2007). Sedimentation derived from land uses such as agriculture, forestry, and urban development are the leading sources of NPSP (Yoho, 1980; USEPA, 2003).

NPSP can increase both sedimentation and turbidity in water bodies. Sedimentation is defined as the process whereby substrata are covered and interstitial spaces of the substrata are filled by deposited sediment (Henley et al., 2000). Larger particles such as silts, sands, and gravels are usually associated with sedimentation. As the velocity of the water slows, these larger particles fall out of suspension and deposit on the stream bottom. Turbidity is caused by particles and dissolved substances in water, including organic and inorganic particulate and suspended matter, and dissolved substances that contribute to the color of water. Particles that remain in suspension are generally fines such as clays (Henley et al., 2000). The abiotic sources of suspended matter can be both directly eroded material and material that has settled on the stream bottom and then become re-suspended in periods of high flow. High levels of sediment in a water body can cause permanent alterations to the aquatic environment and can affect organisms as small as phytoplankton, and as large as fish.

As sediment settles into interstitial spaces between coarse fragments, the available living space for macroinvertabrates decreases (Lenat et al., 1981). If a large amount of sediment fills the interstitial spaces then an impermeable layer forms that can also cause reductions in hyporheic oxygen levels due to the inhibition of interstitial water circulation (Beschta and Jackson, 1979; Gordon et al., 1992; Henley et al., 2000). Ryan (1991) concluded that a 12% to 17% increase in interstitial sediment may account for a 16% to 40% reduction in the abundance of invertebrates. Also, sedimentation negatively affects species that require the interstitial spaces for spawning purposes, such as lake trout (Sly, 1988). If sedimentation occurs after spawning has taken place then the survival of the eggs can be reduced due to decreased oxygen levels as a result of inadequate water circulation, and the available spawning sites will be reduced if sedimentation occurs prior to spawning (Muncy et al., 1979).

Turbidity decreases light penetration of the surface of the water. As less light is available, the photosynthetic production of plants decreases (Kirk, 1985; Ryan, 1991). This reduced photosynthetic production then transfers up through the lotic food web and affects a multitude of organisms. Increased turbidity also affects the success of predators, such as trout and sunfish, that depend on visual search strategies and it has been shown that the abundance of these species decline with elevations in turbidity (Gardner, 1981; Berkman and Rabeni, 1987; Henley et al., 2000). Predator species that depend on visual search strategies often will avoid areas that experience high levels of turbidity (Lloyd et al., 1987).

Turbidity can also lead to decreased dissolved oxygen levels; as turbidity levels increase, the amount of light available to plants for photosynthesis decreases leading to a decrease in oxygen production. Also, oxygen is more easily dissolved in waters that have low levels of suspended solids. As the amount of suspended solids increases, as in the case of turbid water, the capacity of the water to dissolve oxygen decreases. Turbidity can also increase water absorption of solar energy due to increased albedo thereby increasing stream temperature and colder water has the capability of dissolving more oxygen (Murphy, 2007). Furthermore, one of the significant sources of sediment comes from stream bank erosion, which is often a result of the removal of vegetation along the bank. When riparian vegetation is intact, it forms a canopy over the stream and maintains cool water temperatures by providing shade. The removal of the riparian vegetation exposes the stream to increased direct sunlight and subsequently leads to increased water temperatures (Verry et al., 2000; Virginia Department of Environmental Quality, 2007). Streams also become wider as a result of stream bank erosion, creating more surface area that is exposed to sunlight. These increased stream temperatures lead to lower oxygen levels available to aquatic life by increasing the rate of oxygen demand for organic debris and decreasing the solubility of atmospheric oxygen in the water (Ringler and Hall, 1975).

Erosion Processes

There have been numerous studies conducted to quantify the amounts of erosion and sediment that are produced on forestland (Douglas and Swank, 1972; Patric, 1976; Yoho, 1980; Grace, 2005). These studies indicate that harvesting operations have slight and short term increases in soil erosion as compared to undisturbed forests, and that the majority of the erosion is caused by highly disturbed areas, such as logging decks, forest roads, and skid trails (Reid and

Dunne, 1984; Kochenderfer and Edwards, 1997; Grace et al., 1998). The erosion that does occur can be minimized by implementing BMPs.

Soil erosion, caused by water, is driven by three processes: 1) detachment; 2) transportation; and 3) deposition. Detachment is defined as the detachment of soil particles from the soil mass. Transportation is defined as the movement of the detached particles downslope by floating, rolling, dragging, or splashing. Deposition occurs as the particles fall out of suspension at some place at a lower elevation (Brady and Weil, 2008). There are three types of water erosion that are generally accepted: 1) interrill; 2) rill; and 3) gully. Interrill erosion includes raindrop splash and erosion from shallow overland flow, and rill erosion is the detachment and transport of soil by a concentrated flow of water (Laflen et al., 1991; Foltz et al., 2008). Gully erosion is similar to rill erosion, however the volume of water is greater and more concentrated and the cutting action of the flow is deeper, forming larger channels (Ward and Elliot, 1995; Brady and Weil, 2008). Water erosion can also increase the nutrient loading in confined stream bodies. Clay sized particles and organic matter are typically the most chemically reactive materials in soil. They are also the most easily transported particles. Therefore sediment entering water bodies often times has higher concentrations of chemicals such as trace elements and phosphorus than does the whole soil (Ward and Elliot, 1995; Wynn et al., 2000).

Rainfall energy plays a significant role in soil erosion and has three main effects: 1) it detaches the soil; 2) it destroys granulation; and 3) it some cases it can cause appreciable amounts of soil particle transportation (Brady and Weil, 2008). Exposed bare soil is especially susceptible to the effects of rainfall energy and therefore forestry BMPs have been designed to reduce rainfall impact (Virginia Dept. For., 2002).

Soil erodibility and critical shear stress are used frequently in models of soil erosion (Foltz et al., 2008). The soil erodibility value reflects soils' ability to resist detachment and is often termed the soil erodibility or K value. Laflen et al. (1991) define soil erodibility as the susceptibility or resistance of a soil to detachment. Values for soil erodibility are used in empirical soil erosion models such as the Universal Soil Loss Equation (USLE), and process based erosion models such as the Water Erosion Prediction Project (WEPP).

Shear stress (τ) refers to the force of energy applied to a surface, and is a measure of the force of flowing water. The critical shear stress (τ_c) is the minimum hydraulic shear stress required to initiate sediment movement (Van Klaveren and McCool, 1998) and is a determinant for both sediment detachment and transport. Critical shear stress is often used as a variable to estimate the sediment detachment capacity of overland flow (Foltz et al., 2008), with the sediment detachment capacity of overland flow increasing as the shear stress of the overland flow increases over the critical shear stress value. Foster et al. (1995) represent the sediment detachment capacity (D_c) with the following equation: $D_c = K_r \cdot (\tau - \tau_c)$, where K_r is the soil erodidibility factor. In turn, D_c is used in a widely used rill erosion model based on the detachment rate (D_r): $D_r = D_c \cdot (1- G/T_c)$, where G is the sediment load per unit width, and T_c is the transport capacity of the overland flow (Foster et al., 1977). Presently, there are several different hydraulic variables being used to calculate the sediment transport capacity. Of these variables, one of the most commonly used is the shear stress of shallow flow based on the bed load formula of Yalin (1963): $\tau = \rho ghS$, where τ is the shear stress, ρ is the water mass density, g is the gravity constant, h is the depth of flow, and S is the tangent bed slope (Zhang et al., 2009). Several studies have been conducted to evaluate the Yalin formula and they concluded that the formula is adequate in estimating the sediment transport capacity (Foster and Meyer, 1972; Alonso et al., 1981; Julien and Simmons, 1985).

Sediment deposition will occur when the sediment load (G) exceeds the sediment transport capacity (Zang et al., 2009). This can occur when the overland flow encounters obstructions, such as debris, that slow down the velocity thus decreasing the transport capacity. Forestry BMPs have been designed to reduce erosion by limiting sediment detachment and transport, and to increase deposition by protecting the soil against rainfall impact, providing soil stabilization, routing flow off of roads into the litter layer, and maintaining stream side management zones (SMZs).

Forestry Best Management Practices (BMPs)

Different BMPs are designed to be implemented at different periods during silvicultural operations. These periods include pre-harvest, harvest, and post-harvest/closure. This study focused on skid trail closure so closure BMPs are discussed.

BMPs are designed to reduce the amount, depth, and velocity of water movement; increase the stability of soil; and increase infiltration rates. To accomplish this, water diversion structures such as water bars and dips (both rolling and broad based); and cover management practices such as grass seeding, and additions of mulch, gravel, and logging debris/slash can be utilized.

Water bars are earthen structures constructed at certain intervals along the road to capture water and divert it off of the road surface into non-road areas. The spacing of water bars is dependent on the grade of the road or trail. As the road grade increases the distance between the water bars decreases. Water bars should be constructed at a sufficient height so that water flow will not overtop them, rendering them less effective. Water bars should also be constructed at a

30 to 40 degree angle to the centerline of the road to ensure that water diverted off the road will retain sufficient velocity to reach the outlet. Another important advantage of water bars is that they may create conditions on the road that physically restrict vehicular traffic. Continued vehicular travel will decrease a road's likelihood to rehabilitate completely (Virginia Dept. For., 2002).

Vegetation acts as a soil stabilizer and soil cover and since a large percentage of soil erosion occurs shortly after disturbances, seed should be sown immediately after the completion of silvicultural operations (Grace, 2002). Grass is commonly propagated with seed, which may be either exotic or native species. Exotic species, such as fescue, are often used because they tend to germinate more quickly and reliably (Grace et al., 1998). However, as sustainable forestry and biodiversity are becoming more prevalent issues, there has been a small shift towards use of native species, particularly on publicly managed forests. Seed should be applied to any bare soil exceeding 3% slope, such as road surfaces, cut and fill slopes, and logging decks. To promote germination, soil compaction caused by machinery and vehicular traffic may need to be remediated. This can be accomplished by ripping, discing, scarifying with a dozer blade, or sub-soiling the roadbed. Fertilizer should be applied to correct for any nutrient deficiencies, which can be diagnosed by simple soil tests. Mulch should also be applied to provide cover, and increase soil moisture, thus providing better germination potential. However if the area to be seeded is consistently wet then the mulch may actually inhibit growth by increasing the soil moisture to a point where seed mortality begins (Maynard and Hill, 1992). If mulch, such as hay or straw, contains seed it can help with vegetation establishment by providing an additional source of seed. Mulch serves to promote germination and also protects soil surfaces from the erosion forces of rainfall. Mulch intercepts and dissipates the energy of rainfall and also helps to slow any overland flow causing deposition of larger particles. The protection that mulch offers occurs immediately after application and is useful in areas that are prone to high erosion rates (McGreer, 1981; Burroughs and King, 1989; Grace et al., 1998; Grace, 2002; Lyons and Day, 2009). Logging debris and slash can also be used as a soil cover. Slash applied to road surface and compacted, so that there is contact with the ground, will help stablize the soil (McGreer, 1981). Many southern state BMP manuals have included the utilization of logging slash as a recommendation for stabilization of bare soil during both active harvesting operations and harvest closure (Virginia Dept. of For., 2002; North Carolina Division of Forest Resources, 2006; Georgia Forestry Commission, 2009; West Virginia Division of Forestry, 2009).

A BMP audit conducted by the Virginia Department of Forestry (Virginia Dept. For., 2009) spanning five quarters, beginning in the last quarter of 2007 and ending in the last quarter of 2008, indicated that BMP compliance for roads and skidding is of particular concern. For the three regions in Virginia (Eastern, Central, and Western), average BMP compliance for roads and skidding was 78.7 and 76.3 percent, respectively (Virginia Dept. For., 2009). These values reflect the potential for improvements. The audit indicates that BMP compliance is particularly low for BMPs related to road and trail drainage.

Undisturbed Forest Conditions

The erosion rates from undisturbed forests are essentially inconsequential, with the average erosion rate being less than 0.2 tonnes/ha/year (Patric, 1976; Yoho, 1980). The low erosion rates of undisturbed forests can be attributed to minimum overland flow, which is caused by undisturbed forest soils having intact litter layers which increase surface storage and infiltration rates. Often times the infiltration rates exceed the maximum rainfall rates (Yoho, 1980). The litter layer and canopy also intercept and dissipate the energy of rainfall.

The erosion rates of undisturbed forests are well within what is termed the geologic norm (Patric, 1976). All land is subject to natural erosion and the geologic norm is an estimate of this natural erosion rate. Data collected since World War II suggest regional erosion rates ranging from 5.1 cm per 1000 years in the Mississippi Basin to 4.1 cm per 1000 years on the south Atlantic and eastern Gulf Coasts (Sheldon and Ritter, 1964). Using the estimate of 2250 tonnes/ha of soil per 17 cm furrow slice, these estimates of the geologic norm would range from 0.41 tonnes/ha/yr to 0.68 tonnes/ha/yr (Patric, 1976). These estimates are averages for the whole landscape. In the North Carolina piedmont, areas with dense vegetative cover had a soil loss rate of less than 0.25 cm per 1000 years. In the Georgia piedmont areas under intense cultivation had soil erosion rates of 203 cm per 1000 years, while adjacent areas covered in herbaceous vegetation had immeasurable soil loss (Trimble, 1974).

When compared to other land activities such as agriculture and construction, forestland erosion rates seem even more minimal. In the southeast the tolerable soil losses from agricultural row crop fields are 2.3-11.3 tonnes/ha/yr (Yoho, 1980). In a study that developed a sediment budget for a piedmont watershed in southeastern Georgia, agricultural row crops were predicted to have a soil loss rate of approximately 20 tonnes/ha/yr (Jackson et al., 2005). Studies have been conducted to estimate the amount of soil erosion caused by European settlement in the southeastern piedmont. Trimble (1974) suggests that early European settlement agricultural practices caused average topsoil losses between 14 – 18 cm for Alabama, Georgia, South Carolina, North Carolina, and Virginia respectively. Also the erosion from agricultural lands is generally sheet erosion where the top, more productive, layer of soil is removed. Soil erosion associated with forestland is rill or gully, which is primarily composed of less fertile mineral soil (Yoho, 1980).

Urban construction sites disturbed by earth moving equipment produce sediment levels that vary from 300 to 1200 fold greater than careful clearcutting (Yoho, 1980). Instream sediment concentrations from construction sites in the Maryland piedmont can range from 3000 to over 150,000 ppm, while the highest observed concentrations of sediment in agricultural and natural catchments are 2000 ppm. The sediment yields from construction sites can range from several hundred to a maximum of 550 tonnes/ha/yr (Wolman and Schick, 1967).

Harvesting Conditions

Water Yield

Increased erosion rates after silvicultural activities are partially caused by the increase in water yield caused by the removal of vegetation and subsequent decrease in evapotranspiration and interception (Swindel et al., 1982; Riekerk, 1983). Generally, water yield increases are positively correlated to silvicultural treatment intensity. As the percentage of basal area removed increases, so does water yield. These increases in water yield usually occur the first year after harvesting then decrease as vegetation begins to re-establish (Douglass and Swank, 1972).

Experiments conducted by Douglass and Swank (1972) in the eastern hardwood forests suggest that the greatest increases in water yield will occur during the growing to early dormant season when the demand for water is the greatest and flows are normally the least. Their studies were conducted at four different sites in the Appalachian Mountains: 1) Coweeta Hydrologic Laboratory in Franklin, NC; 2) Fernow Experimental Forest in Parsons, WV; 3) Leading Ridge in State College, PA; and 4) Hubbard Brook Experimental Forest in West Thornton, NH. They looked at the different responses in water yield to different harvesting levels. Harvesting levels included 100% clearcuts, and selection harvests ranging from 12% to 85% basal area removed. For the clearcut areas the water yield increased an average of 29.7 cm the first year after treatment. The selection harvest water yield increases ranged from 0 to 16.5 cm and generally increased as the percentage basal area removed increased (Douglass and Swank, 1972).

Arthur et al. (1998) compared harvest operations with BMPs to harvests without BMPs. Their research found that harvesting operations without BMPs increased the water yield more than harvesting operations with BMPs. The harvesting operation not utilizing BMPs produced 48% more water than predicted over an eight year post harvest time period. The harvest operation using BMPs produced 37% more water than predicted over the same time span.

In a paired watershed study conducted by Swindel et al. (1982), the effects of clearcutting slash pine (*Pinus elliottii*) in the pine flatwoods of coastal north Florida on water yields were examined. The study compared two harvesting treatments on two watersheds. One treatment consisting of minimal clearcut harvesting and site preparation treatments and the other was a more intensive clearcut and site preparation. These watershed treatments were then compared to an undisturbed control. The authors found that both harvesting treatments increased the water yield over the control, but the minimal treatment affected water tables less than the more intensive treatment. The data suggested that the water yield levels in the minimal treatment watershed would return to pre-treatment levels within the year following harvesting, bedding, and planting. In the case of the maximum treatment watershed, the water yield increases were more pronounced and were predicted to be more persistent.

Beasley and Granillo (1988) conducted a study in the Gulf Coastal Plain of Arkansas to observe the effects of two harvesting treatments on water yield and sediment yield. The two treatments were: 1) clearcut and mechanically site prepared; and 2) selectively cut. The clearcut treatment increased the water yield over an undisturbed control. This increase was statistically significant the first year after treatment but was not the following three years. The selective harvest did not have any statistically significant changes over the control (Beasley and Granillo, 1988).

Sediment Production

Silvicultural operations can increase sediment export. Removal of the forest canopy can decrease interception and evapotranspiration rates and thus affect the hydrology of the site (Douglass and Swank, 1972; Swindel et al., 1982; Kochenderfer and Edwards, 1997; Arthur et al., 1998; Wynn et al., 2000). Silvicultural activities may also change the erosion pattern of the site and thus cause erosion rates to increase above natural rates (Wynn et al., 2000). The erosion rates following felling of trees are less than within more highly disturbed areas within the harvest operation. The presence of residual stems, leaf litter, and residual slash across the harvesting site tends to maintain high infiltration rates, reduce rainfall impact, and bar any sediment movement downslope (Grace, 2005). Even though harvesting operations can produce bare and compacted soils, these potential erosion sites are generally not contiguous. If soil is displaced, more than likely it will come to rest on intervening undisturbed ground rather than move out of the watershed (Rice et al., 1972).

Sediment export from harvests varies by region, site, and topography. The amount of sediment loss is influenced by a variety of factors including soil type, precipitation, slope, aspect, silvicultural activities, and BMP compliance. In eastern Kentucky Arthur et al. (1998) observed a sediment flux of 0.5 tonnes/ha for a clearcut harvest with BMPs for the first 17 months after harvest, and 1.2 tonnes/ha for a clearcut without BMPs over the same time frame. Riekerk (1983) evaluated two levels of site preparation following clearcutting in southeastern slash pine (*Pinus elliottii*), longleaf pine (*Pinus palustris*), and pond cypress (*Taxodium distilchum*) stands. Following clearcutting, subsequent site preparation techniques consisted of either less intensive site prep (chop, bed, and planting), or more intensive site prep (stump removal, burn, windrow, disk, bed, and planting). The less intensive site preparation produced 2.3 mg/L of suspended sediment as compared 11.7 mg/L of suspended solids in the more intensive treatment (Riekerk, 1983).

In a paired watershed study, Wynn et al. (2000) compared the water quality from loblolly pine (*Pinus taeda*) stands in the coastal plain of Virginia , that were harvested using all appropriate BMPs versus no-BMPs. The BMPs applied were: 1) pre – harvest planning; 2) a 15.2 m streamside management zone (SMZ) was left on each side of the perennial stream; 3) water bars were installed on skid trails at the completion of harvest; and 4) log landings were seeded with grass. Sediment production was monitored for two periods after harvesting: 1) post harvest and 2) post site preparation. The no BMPs watershed produced an average of 9.8 tonnes/ha/yr and 7.7 tonnes/ha/yr for the post harvest and post prep periods, respectively. The BMP watershed produced an average of 0.56 tonnes/ha/yr and 0.62 tonnes/ha/yr for the post harvest and post prep periods, respectively. Throughout this study the sediment yields remained constant for the BMP watershed compared to the no BMP watershed, indicating that the BMPs applied were effective at minimizing sediment loss (Wynn et al., 2000). The results from this study were similar to other studies. Fox et al. (1983) measured sediment export of 13 tonnes/ha/yr from watersheds with intensive mechanical site preparation, and Douglas and Goodwin (1980) found sediment yields of over 9 tonnes/ha/yr from site prepared southeastern piedmont sites.

Streamside Management Zones (SMZs) are a useful BMP to minimize the export of sediment into streams by slowing down overland flow by use of a riparian buffer maintained along stream banks. The reduced velocity can cause greater infiltration and reduce the transport capacity of the flow thus causing sediment deposition (Keim and Schoenholtz, 1999; Carroll et al., 2004). The effectiveness of SMZs can vary by topography, parent material of the soil, and hydrology (Keim and Schoenholtz, 1999). In the loessial bluff forests of the lower Mississippi Valley, SMZs effectively reduced the total suspended solids (TSS) concentrations in logged areas, however they did not trap sediment from outside the riparian area (Keim and Schoenholtz, 1999). SMZs also function to reduce thermal pollution by maintaining a forested canopy over stream channels (Carroll et al., 2004). The widths of SMZs can depend on site conditions such as slope, and hydrology, and a larger width SMZ is not necessarily more effective than a smaller width (Lakel et al., 2006a). Harvesting within SMZs can be conducted without reducing the effectiveness (Keim and Schoenholtz, 1999) and a greater revenue can be realized by the landowner if active management is undertaken (Lakel et al., 2006b).

Road Sediment

Erosion rates from roads and trails depend on factors such as climate, slope, aspect, and soil characteristics such as type, parent material, compaction, and shear stress. The erosion from roads and trails can be partitioned into three areas: 1) fillslope, 2) traveledway, and 3) cutslope and ditch. Burroughs and King (1989) estimated that 60% of erosion occurs on fillslopes, 25% from traveledways, and 15% from cutslopes and ditches. Erosion rates are generally highest immediatley after construction and then decrease rapidly. In Idaho, Rice et al. (1977) reported that the initial sedimentation rate for the first 7 months after road construction averaged 29.1 tonnes/ha/yr, and then decreased to approximately 1.1 tonnes/ha/yr 6 years later.

Erosion rates can be reduced by implementing BMPs. Water control structures such as broad based dips, or water bars can be utilized to remove water from the roadway and distribute it into the undisturbed forest litter. Cover BMPs can also be used to aid in soil stabilization and reduce the velocity of the water. Cover BMPs include grass seeding, mulching, slash application, and gravel (Virginia Dept. For., 2002; North Carolina Division of Forest Resources, 2006; Georgia Forestry Commission, 2009; West Virginia Division of Forestry, 2009).

Kochenderfer and Helvey (1987) conducted a study in the Central Appalachians to evaluate the effectiveness of gravel for reducing soil losses from minimum standard roads. The road segment used for monitoring was a newly constructed road that was built so as not to exceed the maximum allowable grade, and to avoid negative control points such as stream channels, rock ledges, and property lines. Broad based dips were used to remove water from the roadbed and divert it across the adjacent undisturbed forest floor. Three replications of the following treatments were imposed: 1) surfacing with 7.6 cm clean gravel ranging in size from 3.8 to 7.6 cm; 2) surfacing with 7.6 cm crusher run gravel; and 3) no surfacing. The measurements were then compared to a high standard road graveled with 2.5 cm crusher run. Over a 4 year monitoring period the mean soil loss from the ungraveled treatment was 107 tonnes/ha/yr, ranging from 31.8 tonnes/ha/yr to 182.3 tonnes/ha/yr. The 7.6 cm clean gravel treatment had a mean soil loss of 12.9 tonnes/ha/yr, ranging from 4.8 tonnes/ha/yr to 24.3 tonnes/ha/yr. The 7.6 cm crusher run gravel treatment had a mean soil loss of 22.9 tonnes/ha/yr, ranging from 5.2 tonnes/ha/yr to 70.5 tonnes/ha/yr. Average soil loss reduction for 7.6 cm washed gravel and 7.6 cm crusher run over the unsurfaced treatment were 88% and 79%, respectively. The average soil loss over the four year period for the high standard road was 13.4 tonnes/ha/yr, ranging from 6.4 tonnes/ha/yr to 23.8 tonnes/ha/year.

Swift (1984a) looked at the effectiveness of different gravel depths at Coweeta Hydrologic Laboratory in Franklin, NC. The treatments were: 1) 5 cm of crushed rock; 2) 15 cm of crushed rock; 3) 20 cm large stone; 4) bare soil; and 5) grass. He found that the mean soil loss rates, calculated on a storm basis as amount of soil lost divided by precipitation, were 1.1 tonnes/ha of roadbed/cm rain for the bare soil, 1.2 tonnes/ha of roadbed/cm rain for the 5 cm of crushed rock, 0.59 tonnes/ha of roadbed/cm rain for the grass, 0.09 tonnes/ha of roadbed/cm rain for the 15 cm of crushed rock, and 0.18 tonnes/ha of roadbed/cm rain for the 20 cm of large stone. These results show that 5 cm of gravel proved to be inadequate and was no better than no surfacing at all, and that grass can provide partial control at a considerably less cost. Burroughs et al. (1985) found that sediment produced from a graveled road, surfaced with 10 cm of hard gneissic crushed rock, was approximately 10.8 kg per cm of rainfall. Sediment produced from an unsurfaced road segment of the same slope was approximately 51.2 kg per cm of rainfall. This equates to a 79% reduction in sediment by surfacing the road.

Erosion rates from fillslopes are initially high and then decrease over time (Megahan, 1974). As time passes the initially unconsolidated material in the fillslopes begins to consolidate and stabilize, easily erodible silts and sands are removed, and vegetation begins to germinate. These factors work in conjunction to decrease erosion rates. Therefore it is important to stabilize fillslopes as soon as possible after initial construction to reduce soil loss (Burroughs and King, 1989). The effectiveness of treatments is directly related to the percent cover that the treatment provides, and to a lesser extent the steepness of the slope. However, as slope increases it is harder to establish or maintain cover (Burroughs and King, 1989). Common soil stabilization treatments include mulching and re-vegetating. The effectiveness of any cover treatment will be negated if the drainage from the travelway is allowed to flow across the fillslope, causing rills and gullies to form (Burroughs and King, 1989). The effects of seeding fillslopes are not evident until grass begins to germinate. Swift (1984b) collected data on fillslope sediment for 9.5 months following road construction and logging, during which time the fillslopes were not seeded. This data was then compared to the data collected during 13.3 months following seeding. The average reduction in sediment production was 66%. Grace et al. (1998) compared three erosion control techniques on cut and fill slopes in the Talladega National Forest in Alabama: 1) erosion mats; 2) native grass, and 3) exotic grass. They found that the erosion mat reduced sediment yield by 88%, native grass by 81%, and exotic grass by 87%. The effectiveness of each treatment was directly related to the amount of coverage provided. The erosion mat was the most effective because it provided 100% coverage initially. The exotic seed mixture was better able to germinate than the native mixture and able to provide cover more quickly and therefore was more effective.

The erosion processes for cutslopes are similar to those of fillslopes. Cutslopes, however, are prone to additional soil loss by dry raveling, and bank sloughing (Burroughs and King, 1989). Dry raveling is a general term that describes the down-slope movement of individual particles by rolling, sliding, and bouncing and can be a dominant hillslope sediment transport process on steep arid and semiarid landscapes (Gabet, 2003). Dry raveling occurs in the summer months, especially on noncohesive soils (Megahan, 1978). Bank sloughing is more pronounced when soils are saturated and often occurs during in the spring snow melt (Burroughs and King, 1989). If a road is outsloped and does not have an inner ditch then the sediment produced by cutslopes is likely to stabilize at the base of the cutslope and not have an effect on water quality. Ditches can act as gullies and carry runoff and sediment offsite. Often times, ditches are drained over the fillslope causing extensive erosion. Ditches must also be maintained and these maintenance activities disturb the stabilized sediment and can cause further erosion from the cutslope.

Treatments applied to fillslopes can also be used to reduce erosion on cutslopes. Swift (1984b) collected sediment erosion rates on cutslopes, and found that there was an 89% reduction in cutslope sediment production 13.3 months after seeding compared to 9.5 months prior to seeding. Grace (1998) also monitored sediment production from cutslopes having different treatments, and found that there were significant differences between each of the treatments. Erosion mats were 98% effective, exotic grass mixtures were 88% effective, and the native grass mixture was 44%.

There has been limited research into piling slash on roads and trails as a cover and closure BMP. Slash is an inexpensive, easily accessible material to place on trails and roads to provide soil stabilization. When trampled down by heavy equipment, slash maintains good contact with the soil helping to hold the soil in place and reduce the velocity of water moving along the trail or road. The slash also forms a canopy over the trail to intercept rainfall energy. McGreer (1981) evaluated the effectiveness of slash as a soil stabilizer. In this study, seven experimental plots were established to determine the erosivity of the “ash cap” topsoil and underlying sandy loam subsoil. The plots were 15.2 m long and 3 m wide. Three soil conditions on 15% and 45% slope were tested: 1) ash with a disturbed litter layer; 2) ash with the litter layer bladed away; and 3) the underlying subsoil exposed. The seventh plot was formed on a 50% slope where the exposed subsoil was covered with slash. The first year results show that the sediment produced on the slash treatment was 2.4 tonnes/ha compared to 164.7 tonnes/ha from an exposed subsoil treatment on a 40% slope.

Mulched waste wood is also an option for providing cover and surface to roads and trails. Lyons and Day (2009) evaluated waste wood produced from right-of-way clearing as a surface material for haul roads during wet weather conditions. They compared the results from the waste wood treatments to a bare soil road surface. They found that the mulched waste wood provided a good running surface and extended the operability time of the road over that of a bare soil road. Sediment data was not collected but mulched roads have the potential to reduce sediment production because the mulch is more permeable than most gravels. In addition to the potential reduction in environmental problems, mulched waste wood can provide a cost effective alternative to increase the operability time of all-weather temporary roads in areas where the cost of gravel or the distance to a gravel source is limiting (Lyons and Day, 2009).

Highly disturbed areas are more prone to erosion because they have a large amount of bare soil exposed to rainfall energy, reduced infiltration rates due to compaction and altered soil structure, and unnaturally steep slopes. All these conditions combine to create conditions that are likely to cause soil particle detachment and transport and potential water quality issues (Kochenderfer, 1977; Reid and Dunne, 1984; Kochenderfer and Edwards, 1997; Grace et al., 1998). BMPs have been developed to protect water quality by preventing soil from reaching waterways and have been shown to effectively reduce sediment delivery to streams (McGreer, 1981; Arthur et al., 1998; Wynn et al., 2000). BMPs come in the form of diversion structures that remove runoff from roadways and trails, cover BMPs that provide stabilization to the soil, and closure BMPs that prevent access to areas and allow the site to rehabilitate.

Soil Erosion Models

Soil erosion models have been developed to predict erosion rates from both hillslopes and roads. Erosion prediction methods are also used to evaluate management practices and erosion control techniques (Elliot, 2004). The most widely used erosion model is the Universal Soil Loss Equation (USLE) (Elliot et al., 1999). The USLE was originally designed to predict erosion rates from agricultural lands but has since been adapted to predict erosion from forested lands (USLE – Forest) (Dissmeyer and Foster, 1984). As more experiments have been conducted and more data has become available, the USLE has been continually updated. The Revised Universal Soil Loss Equation (RUSLE) uses the same process of predicting erosion rates as the USLE, but provides improved measures on calculating input variables (Renard et al., 1991). Another prominent soil erosion model is the Water Erosion Prediction Project (WEPP). WEPP is a product of an interagency collaboration involving the U.S. Department of Agriculture's Forest Service, Agricultural Research Service, Natural Resource Conservation Service, and the U.S. Department of the Interior's Bureau of Land Management, and the U.S. Geological Survey.

USLE

The USLE was developed to predict long term average soil losses based on site and management conditions. Originally designed to predict sheet and rill erosion from agricultural lands, the USLE has been adapted to predict erosion rates from forested land (USLE – Forest). The model predicts sheet and rill erosion based on 6 factors: rainfall and runoff factor (R), soil erodibility factor (K), slope length factor (L), slope steepness factor (S), cover and management factor (C), and the support practice factor (P). The R value is the number of rainfall erosion index units, plus a factor for runoff from snowmelt or applied water where such runoff is significant. K is the soil loss rate per erosion index unit for a specified soil as measured on a unit plot. L is the ratio of soil loss from the field slope length to that from a 22 m length under identical conditions. S is the ratio of soil loss from the field slope gradient to that from a 9 percent slope under otherwise identical conditions. C is the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled, continuous fallow. P is the ratio of soil loss with a support practice like contour disking to that with straight-row farming up and down the slope (Dissmeyer and Foster, 1984). Erosion is predicted by the formula A = R * K * L * S * C * P, where A is the amount of soil loss per unit area per year. It is important to note that the USLE is not capable of estimating deposition by overland flow or channel flow, nor gully or stream channel erosion, or sediment delivery to water bodies. Also, since the values for these factors are long term averages, the model is not very accurate at determining storm specific erosion rates (Dissmeyer and Foster, 1984).

The USLE has been used in a variety of different studies to quantify the amount of soil loss. Jackson et al. (2005) used the model to develop a sediment budget for a Georgia piedmont watershed, by estimating the amount of erosion from a variety of land uses. Mishra and Deng (2009) used the model in conjunction with GIS software to develop sediment erosion estimates for the Amite River Basin in Southeastern Louisiana and Southwestern Mississippi. The R factor was estimated using an annual R factor map and the remaining values were estimated using soil maps, land use and land cover maps, and a digital elevation model of the Amite River Basin (Mishra and Deng, 2009). The USLE is not only used in the United States but is widely used across the world. Krishna Bahadur (2009) used the USLE equation to map soil erosion susceptibility in the Upper Nam Wa Watershed, Nan Province, Thailand. GIS was incorporated in this study to derive the input values for the equation by remote sensing techniques. Erosion estimates were calculated two ways: the potential erosion was calculated by using only the R, K, L, and S factors and ranged from 0 to 726 tonnes/ha/yr. The second method is termed the “actual erosion” and is computed using all of the factors. The computed values ranged from 0 to 562 tonnes/ha/yr (Krishna Bahadur, 2009).

RUSLE

The Revised Universal Soil Loss Equation (RUSLE) was released in the early 1990's and has evolved into the current RUSLE1.06c, which was released in 2003. RUSLE1.06 is land use independent and applies to any land that has exposed mineral soil and experiences Hortonian flow. RUSLE2 was also released in 2003 and is land use independent (Foster et al., 2003). RUSLE uses the same formula as the USLE to predict sheet and rill erosion: A=R*K*L*S*C*P. However, as more data has become available the derivation of the factors has improved. RUSLE offers improved isoerodent maps for calculating the R factor. Isoerodent maps of western United States have been greatly improved by analyzing data from more than 1,000 locations. Also R values were reduced where flat slopes occur in regions of long intense rainfall, such as that occurs in the southeastern United States, because ponded water reduces the erosivity of the raindrop impact. Also an R equivalent approach is being used in the Pacific Northwest to reflect the combined effect of thawing soil and rain or snow or partly frozen soil. Erosivity is computed for 15 day intervals, allowing land managers to identify periods when the site is more susceptible to erosion and then adjust management activities (Renard et al., 1991; Toy et al., 1999). RUSLE provides improved ways to calculate the K factor. Previously K values of most soils for a specific site could be calculated using a nomograph. RUSLE provides a new equation to calculate the K factor on soils that were not previously covered by the nomograph. RUSLE also provides a time varying approach for calculating K. RUSLE recognizes that as seasons change, the erodibility of the soil will vary. For example, soil erodibilty will be highest in the spring during the freeze-thaw actions and lowest in mid fall to winter when soils become frozen. Also K values reflect rock fragments in the soil to account for rock effects on permeability and runoff (Renard et al., 1991; Toy et al., 1999). RUSLE also recognizes that time to soil consolidation is different for different areas. For example in the eastern U.S. soil reconsolidation is estimated to be seven years, while in the western U.S. it may be as long as 15-25 years (Toy et al., 1999). RUSLE provides new equations to reflect slope length and slope steepness. The S factor in RUSLE1.06c is based on a much larger data set and the relationship better fits data from highly disturbed lands than does the USLE relationship. The exponent n in the slope length L factor $(\lambda/22.1)^n$ in RUSLE1.06c varies with land use and soil texture. This exponent in RUSLE2 is computed with equations that are functions of slope steepness, soil biomass, soil consolidation, ground cover, and soil texture (Foster et al., 2003). RUSLE has a more nearly linear slope steepness relationship than the USLE and provides greater accuracy on steeper slopes. RUSLE provides an improved sub-factor approach for calculating C. Variables used in RUSLE1.06c and RUSLE2 include percent canopy cover and fall height, surface roughness, ground cover provided by stones, litter, basal area, live vegetation touching the ground, other material on soil surface, plant community type, average annual plant production, and time since soil was mechanically disturbed (Foster et al., 2003). Finally RUSLE provides improved P factor values for the effects of contouring, terracing, stripcropping, and management practices for rangeland (Renard et al., 1991). In addition to the improved derivation of the factors, RUSLE also calculates deposition on concave slopes at dense vegetation strips, in terrace channels, and in sediment basins using process based equations (Foster et al., 2003).

Larson et al. (1997) used RUSLE to estimate the amount of erosion from agricultural crops in Minnesota and compared these results to actual erosion rates. They found that over a 10 year period RUSLE was 93%, 91%, 38% of the actual rates of three cropping regimes. Like the USLE, RUSLE use is not limited to the U.S. but is used worldwide. Kouli et al. (2009) incorporated RUSLE into a GIS framework to estimate the soil erosion on nine watersheds in Northwestern Crete. The study area was primarily agriculture, with the remaining land in pasture, and natural vegetation coverage. As in previous studies using GIS to calculate soil erosion, the authors used remote sensing techniques to derive the input variables. The authors estimate that the mean soil loss for the watersheds range from 70 tonnes/ha/yr to 186.4 tonnes/ha/yr, with the maximum soil loss being 3,770 tonnes/ha/yr and the minimum being 0 tonnes/ha/yr. These estimates coincide with measured rates from watersheds of similar characteristics (Kouli et al., 2009).

WEPP

WEPP is a process based, continuous simulation erosion model designed to estimate erosion from hillslopes and forest roads. It is a complex computer program that describes the processes that lead to soil erosion. These processes include infiltration and runoff, soil detachment, transport, and deposition; and plant growth, senescence, and residue decomposition. For each simulation day, the model calculates the soil water content in multiple layers, plant growth, and residue decomposition. For each day of precipitation or snowmelt, WEPP determines if it is rain or snow and calculates the appropriate infiltration and runoff. If runoff occurs, WEPP routes it over the surface and calculates erosion and deposition rates for at least 100 points on the hillslope. It then estimates the average annual sediment yield from the slope (Elliot et al., 1999). The hillslope can have a complex shape, and can include numerous soils and plant types along the hillslope. Each segment that has homogeneous slope, soil, or management regime characteristics is known as an Overland Flow Element (OFE) (Elliot and Foltz, 2001). WEPP requires four sets of input files: 1) a climate file, which includes data on daily precipitation, and temperatures; 2) a slope file, which contains a minimum of two points that describe a hillslope's slope; 3) a soil file, which contains data describing the texture and other physical and erodibility properties of the soil; and 4) a management file that contains descriptions of plant communities, surface disturbances, and surface conditions at the start of simulation (Elliot, 2004).

To develop climate data, CLIGEN, a stochastic weather generator which produces daily estimates of precipitation, temperature, dewpoint, wind, and solar radiation for a single geographic point, using monthly parameters derived from the historic measurements, is used (USDA. 2009). CLIGEN can estimate daily conditions from one to 999 years (Elliot et al., 1999). WEPP allows the user to create a site specific slope profile by entering slope length and slope steepness for at least two points on the hillslope. WEPP provides soil data for many different locations and the user may chose to use one of the existing profiles or manipulate the data for site specific conditions. A cover management file can be created or downloaded from a provided database by the user to model site conditions. This file contains information on vegetation, type of disturbance, and initial conditions. From this information WEPP is able to model plant growth, senescence, and decomposition.

WEPP is such a complex program and requires many parameters to run; therefore, the USDA Forest Service has developed simplified internet web interfaces. Two of these interfaces, WEPP: Road and Disturbed WEPP, are designed for forested conditions. The user is able to choose between a small list of input variables that are representative of forested conditions. This allows the user to quickly and easily compare the soil erosion rates of different operations (Elliot and Foltz, 2001).

WEPP: Road predicts erosion rates for forest roads. The information in the data base used to develop WEPP: Road is primarily based on newly constructed roads, so the results may tend to over predict erosion rates for roads that are older, have little traffic, and no recent maintenance activities (Elliot and Foltz, 2001). WEPP: Road assumes that runoff and sediment generated by the road traveledway is routed over a fillslope and across a forested buffer (Elliot, 2004). The interface assumes there are three overland flow elements (OFEs), and the user can assign soil and management characteristics for each. Four types of soil are available to choose from: 1) sandy loam; 2) clay loam; 3) silt loam; and 4) loam. The user will also need to choose a climate file from a short list available on the input screen. The user may also use another interface known as Rock:Clime to customize climate information for a specific site (Elliot, 2004; Elliot and Foltz, 2001). Four road templates are available to choose from: 1) insloped with rocked or vegetated ditches; 2) insloped and bare ditch; 3) outsloped and unrutted; and 4) outsloped and rutted. The three choices for road surfacing are: 1) native; 2) graveled; and 3) paved. The user then specifies the road length, road width, and buffer length. The output from WEPP: Road presents the average precipitation, the average annual runoff from the buffer, and the sediment delivered from both the eroding part of the road prism and the bottom of the buffer. An optional extended output shows the distribution of erosion and deposition along the road, fill, and buffer, the presence of a sediment plume in the buffer, and particle size distribution on hillslope and in the delivered sediment (Elliot and Foltz, 2001).

Disturbed WEPP allows the prediction of soil loss from skid trails, prescribed fires, wildfires, early years of vegetation and soil recovery following prescribed or wildfire, and forest conditions having young, thinned, harvested, and mature trees. Three conditions are also available for rangeland, which include short or sod forming grasses, tall or bunch grasses, and shrubs for sage and pinyon juniper plant communities (Elliot, 2004). Disturbed WEPP allows for two OFEs so that users can study combinations of uphill and downhill disturbances. For each OFE the user must select values for the climate, soil, vegetation type, surface cover, and topography. Climate files and soil data are chosen in the same manner as in WEPP: Road. Soil surface cover is inputted for all conditions except mature forest, which is assumed to be 100% (Elliot and Foltz, 2001; Elliot, 2004). To ensure that the correct cover conditions are generated the user is allowed to adjust the cover input so that the desired conditions are obtained. Eight vegetation conditions are available with separate files containing initial conditions and plant descriptions. Disturbed WEPP predicts mean values and the first, second, fifth, tenth, and twentieth greatest annual values for precipitation, runoff, erosion, and sediment yield.

In a study conducted by Elliot (2002), sediment Total Maximum Daily Loads (TMDLs) for forest conditions were predicted using WEPP. Soil erosion rates were predicted for hillslopes following a wildfire, and hillslopes following a forest operation. The results indicate that the sediment yield following a wildfire was greater than the sediment yield following a forest operation. Results also indicate that the increased number of disturbances from active forest management result in lower long term average sediment delivery rates than would occur following less frequent wildfire disturbances (Elliot. 2002).

Soil erosion models provide a cost effective way of estimating erosion from the landscape and evaluating erosion control measures. In the studies mentioned above, researchers incorporated models into GIS to evaluate the erosion potential over large areas and from this information are able to identify problematic areas and take the necessary steps to alter cultural practices and policy to reduce the risk (Kouli et al., 2008; Bahadur, 2009). Models also provide land managers a powerful tool to cost effectively evaluate erosion control measures. Like any other models the USLE, RUSLE, and WEPP are only useful when they are used in the correct manner. Users must recognize that these models are designed to produce annual rate estimates and are not accurate at predicting erosion rates for short periods or individual storms.

Study Objectives

This study has two objectives. The first objective is to compare the effectiveness of five closure and cover BMPs for the control of erosion on bladed skid trails through field based techniques. The following treatments were applied: 1) water bar only (Control); 2) water bar and grass seed (Seed); 3) water bar, grass seed, and straw mulch (Mulch); 4) water bar and piled hardwood slash (Hardwood Slash); and 5) water bar and piled pine slash (Pine Slash).

The second objective is to evaluate the accuracy and applicability of three erosion models by making model predictions for each treatment and then comparing those predictions to the field based erosion rates through linear regression. The models used were: 1) the Universal Soil Loss Equation for Forestry (USLE - Forest) (Dismeyer and Foster, 1984); 2) the Revised Universal Soil Loss Equation version 2 (RUSLE2); and 3) the Water Erosion Prediction Project for Forest Roads (WEPP – Forest Roads).

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Chapter 2. Evaluation of Bladed Skid Trail Closure Best Management Practices for Erosion Control

Abstract

Sediment is one of the leading non point source pollutants in the U.S. In silvicultural operations, the majority of sediment is produced from highly disturbed areas, such as skid trails, haul roads, and log landings. In response to potential sediment from silvicultural operations, forestry Best Management Practices (BMPs) have been developed, but efficacies of various BMP options are not well documented. This study evaluated five closure and cover BMPs for the control of erosion from bladed skid trails. Bladed skid trail BMP treatments evaluated were: 1) water bar only (Control); 2) water bar and grass seed (Seed); 3) water bar, grass seed, and straw mulch (Mulch); 4) water bar and piled hardwood slash (Hardwood Slash); and 5) water bar and piled pine slash (Pine Slash). Treatments were installed on 15.2 m by 3 m sections of bladed skid trail. Runoff from trails was routed into geotextile sediment traps known as Dirtbags® by a system of open topped gutters. Sediment was filtered from runoff in the Dirtbags® and weights were recorded monthly to ascertain periodic erosion rates. During a 13 month period, the Control treatment (137.7 tonnes/ha/yr) was the most erosive, followed by the Seed (31.5 tonnes/ha/yr), Hardwood Slash (8.9 tonnes/ha/yr), Pine Slash (5.9 tonnes/ha/yr), and finally the Mulch treatment (3.0 tonnes/ha/yr). Results indicate that Mulch, Pine Slash, and Hardwood Slash treatments were similarly effective BMP treatments for bladed skid trails, but Seed and water bar (Control) treatments are less effective for steeper bladed skid trail segments.

Keywords
Forestry BMPs, bladed skid trail, erosion

Introduction

Sedimentation has clearly been identified as one of the most important sources of non-point source pollution (NPSP) in the United States (USEPA, 2003). Increased sedimentation can impair the natural functions of streams and rivers to a point where they become unsuitable for aquatic organisms (Henley et al., 2000; Virginia Department of Environmental Quality, 2007) and no longer optimally serve recreational needs (Henley et al., 2000; USEPA, 2003). Sedimentation derived from land uses such as agriculture, forestry, and urban development are the leading sources of NPSP (Yoho, 1980; USEPA, 2003).

Within silvicultural operations, sediment is generally derived from areas that experience the most soil surface disturbances. Highly disturbed areas are more prone to erosion due to large amounts of bare soil exposed to rainfall energy, reduced infiltration rates due to compaction and altered soil structure, especially on steep slopes. These combined conditions are likely to allow soil particle detachment and transport and potential water quality issues (Kochenderfer, 1977; Reid and Dunne, 1984; Kochenderfer and Edwards, 1997; Grace et al., 1998). These disturbed areas include log decks, skid trails, and haul roads and commonly represent approximately 10% of the harvest area (Rice et al., 1972; Kochenderfer, 1977). Typical erosion rates experienced by roads and trails can range between 12.9 tonnes/ha/yr to 107 tonnes/ha/yr (Kochenderfer and Helvey, 1987).

The increase in sediment transport on forest roads and trails can be attributed to several factors. Increased water yields, caused by the removal of vegetation and subsequent decrease in evapotranspiration and interception (Swindel et al., 1982; Riekerk, 1983) can accelerate erosion. Generally water yield increases are positively correlated to silvicultural treatment intensity. As the percentage of basal area removal increases, so does growing season water yield. Increases usually occur the first year after harvesting then decrease as vegetation begins to re-establish (Douglass and Swank, 1972). Through haul road and skid trail construction the erosion pattern of the site may be altered causing concentrated water flow. The increase in concentrated flow can cause erosion rates to increase above natural rates (Wynn et al., 2000).

As a result of the Federal Water Quality Control Act of 1972, forestry Best Management Practices (BMPs) have been developed and implemented to reduce the offsite movement of sediment. The BMPs used for roads, skid trails, and logging decks include: 1) proper planning, construction, and location; 2) control of grade; 3) control of water; 4) surfacing; and 5) road or trail closure (Swift, 1985; Swift and Burns, 1999; Grace, 2005). Trail closure is of particular importance because trails are often built to lower standards (e.g. steeper, less water control, more bare soil) than permanent roads, and represent a “higher risk” for soil erosion. Typical closure BMPs include installing water control structures and applying cover. Water control structures such as water bars are used to divert water flow from the roadway and dissipate it over the adjacent non-road area. The spacing interval of water bars is dependent on the slope of the trail; as the slope increases the distance between bars decreases. Cover BMPs such as seeding, and seeding and mulching reduce the amount of erosion by providing stability to the soil. The cover provided also decreases overland flow velocity and causes deposition of sediment before it reaches a waterway. Mulching provides immediate cover while the effects of seeding are not evident until the seed germinates and becomes established. Piling slash on skid trails can also be a means of providing immediate cover and is recommended in several southeastern states’ BMP manuals (Virginia Dept. of For., 2002; North Carolina Division of Forest Resources, 2006; Georgia Forestry Commission, 2009; West Virginia Division of Forestry, 2009), however there has been limited research into the effectiveness of slash as a soil stabilizer. One study conducted on volcanic soils in the west showed that piled slash reduced soil erosion by 99% when compared to bare mineral soil (McGreer, 1981).

Study Objectives

The objective of this study was to evaluate the effectiveness of five closure and cover BMPs on the reduction of sediment production from bladed skid trails. The treatments applied were: 1) water bar only (Control); 2) water bar and grass seed (Seed); 3) water bar, grass seed, and straw mulch (Mulch); 4) water bar and piled hardwood slash (Hardwood Slash); and 5) water bar and piled pine slash (Pine Slash).

Materials and Methods

Study Site

The study site was located in the upper Piedmont physiographic province at Reynolds Homestead Forest Research and Extension Center in Patrick County, Virginia (Figure 1). The

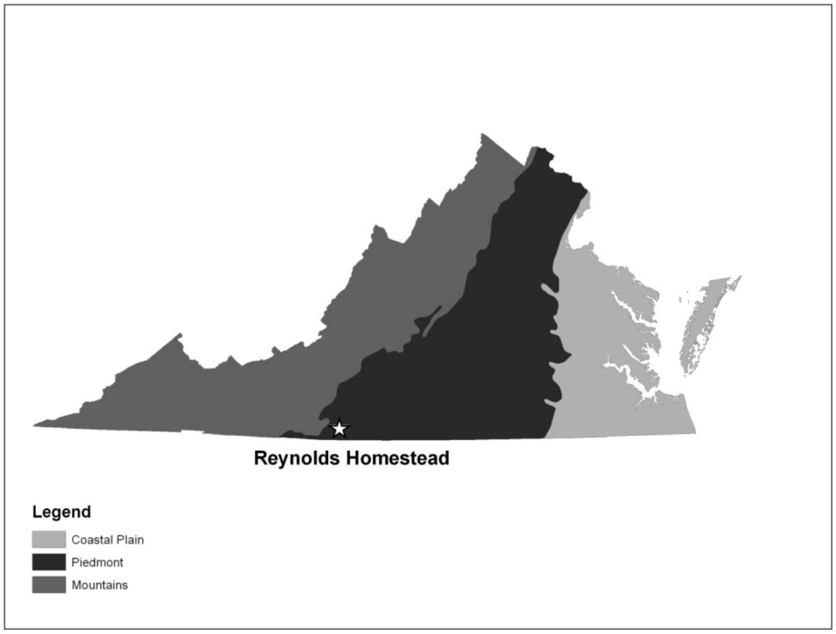

Figure 1. Reynolds Homestead Forest Research and Extension Center is located in Patrick County, VA in the Upper Piedmont Physiographic region.

research center is approximately 300 hectares in size and is managed by Virginia Polytechnic Institute and State University. Patrick County is characterized by gently rolling terrain. The typical temperature in January ranges from -1.8°C to 9.0°C. In July, the temperature typically ranges from 17.8°C to 29.7°C. The average precipitation is 151.9 cm with 125.2 cm being rainfall and the remaining 26.7 cm being snowfall (Patrick County, Va, 2009). The treatments were installed in a 5 hectare clearcut with side slopes of 15-20%. The stand was harvested in the winter of 2004 and spring of 2005. Prior to harvesting the stand was composed of Virginia pine (*Pinus virginiana*) and a mixture of hardwood species. Prior to study installation, a site prep spray was conducted on August 4th, 2008, followed by a prescribed burn on November 7th, 2008. As a result of the application of herbicide and fire, all woody vegetation was deadened when the study was installed. The dominant soil series on the site is mapped as a Fairview sandy clay loam, fine, kaolinitic, mesic Typic Kanhapludults. This soil is formed from residuum from mica schist and mica gneiss and is very deep, well drained, and has an erodibility index of 0.28 (NRCS Soil Survey, 2009).

Treatments

Treatments were installed on segments of bladed skid trail. There were a total of six bladed skid trails built with five treatments per trail. The study was designed as a Randomized Complete Block Design with Repeated Measures with the trails being designated as the blocks and having a total of thirty experimental units (Figure 2). Skid trail centerlines were flagged prior to construction. A John Deere 450E was used to construct all trails and water bars.

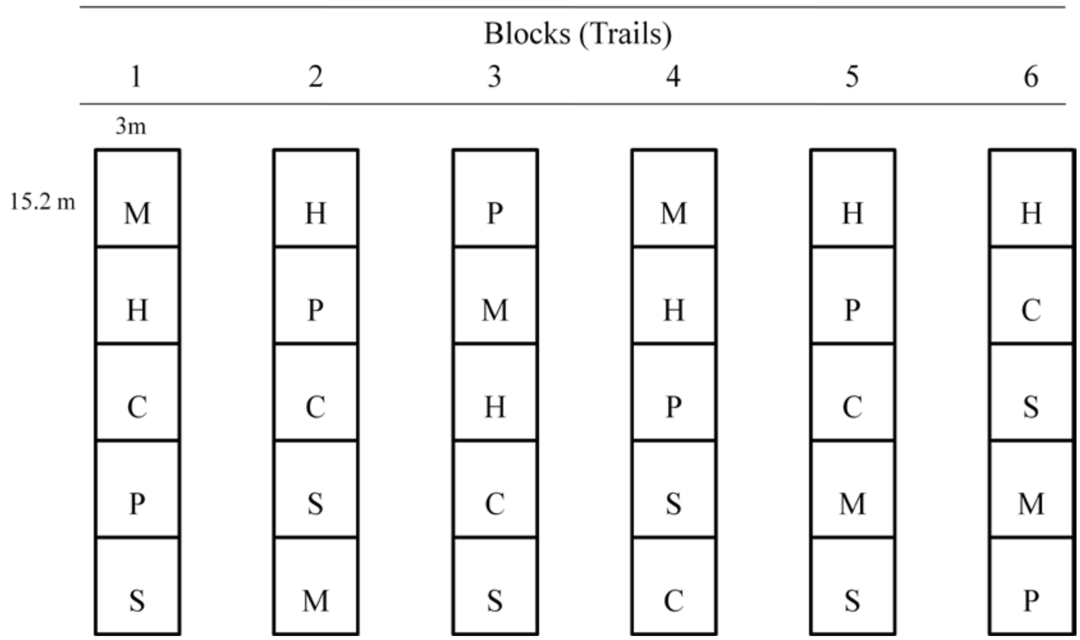

Figure 2. Idealized treatment layout for the Randomized Complete Block Design with Repeated Measures where C = Control; S = Seed; M = Mulch; H = Piled Hardwood Slash; P = Piled Pine Slash.

Trails were constructed with slopes ranging between 10% - 20%. Experimental units were approximately 15.2 meters (50 ft) in length by 3 meters (10 ft) in width and had water bars installed at the head and base of the treatment slope. Berms were maintained along the sides of each unit to ensure that no runoff produced from the treatment escaped and that no runoff from outside the experimental unit area entered. Five treatments were installed.

The Control treatment consisted of only water bars and represented the commonly prescribed minimal closure BMP in the southeast (Virginia Dept. For., 2002; Georgia Forestry Commission, 2009). Water bars were installed approximately at a 45 degree angle to the treatment slope with a small bulldozer (John Deere 450E). A high degree angle is preferable for water bar installation to ensure that runoff diverted by the water bar has enough velocity to reach the outlet. Treatment water bars were built 0.6 to 0.9 meters (2 to 3 feet) in height. This is a typical height of operational water bars. Water bars built less than 0.6 meters in height are susceptible to being overtopped by water, thus reducing effectiveness.

Seed treatments consisted of the Control plus an application of grass seed. The seed mixture used was provided by Plum Creek Timber Company, Inc. and consisted of winter rye (*Lolium multiflorum*) (35%), timothy (*Phleum pratense*) (10%), orchard grass (*Dactylis glomerata*) (10%), perennial rye (*Lolium perenne*) (10%), medium red clover (*Trifolium pratense*) (20%), and annual rye (*Lolium spp.*) (15%). This mixture is used by Plum Creek Timber Company, Inc. to close skid trails on their company lands in West Virginia. To promote germination, lime was applied at a rate of 2.3 tonnes/ha (1 ton/acre), and a 10-10-10 fertilizer was applied at a rate of 227 kg/ha (200 lbs/acre). Seed was applied at a maximum recommended rate to ensure establishment, ≈ 300 kg/ha (265 lbs/acre), and was reapplied on treatments where germination and establishment was less than 40%. This reseeding is not an operational technique; rather it was to ensure that the treatment evaluation was not based on poor establishment conditions.

Mulch treatments consisted of the Control plus an application of grass seed and straw mulch. The application of seed, lime, and fertilizer was the same as in the Seed treatment. Straw was applied after the application of seed at a rate that initially gave 100% coverage. On a 15.2 m by 3 m slope length this equated to two straw bales, ≈ 8 tonnes/ha (3.5 tons/acre).

The Hardwood Slash treatments consisted of the Control plus an application of hardwood slash. The hardwood slash was comprised of small pole size trees from an adjacent stand. The trees were harvested during March and April of 2009. The diameters of the slash sections ranged from 2.5 cm (1 in) to 15.2 cm (6 in) and the lengths ranged from 1.2 m (4 ft) to 3 m (10 ft). Species used included white oak (*Quercus alba*), scarlet oak (*Quercus coccinea*), hickory (*Carya spp.*), yellow poplar (*Lirodendron tulipifera*), American beech (*Fagus grandifolia*), sourwood

(*Oxydendrum arboreum*) and red maple (*Acer rubrum*). Slash was applied, using front end forks mounted on an agricultural tractor. Subsequently, the 1 m high slash was tracked down by a bull dozer to break up the slash, ensuring adequate ground contact.

The Pine Slash treatments consisted of the Control plus an application of pine slash. The majority of the pine slash originated from a nearby study and was composed of loblolly pine (*Pinus taeda*). The remaining pine slash was cut on the property in May of 2009 and consisted of Virginia pine and white pine (*Pinus strobus*). The lengths and diameters of the pine slash were similar to the hardwood slash and the application was the same as that of the hardwood slash.

Data Collection

To collect and quantify the amount of sediment generated by the treatments, gutter systems and Dirtbags® were used. Dirtbags® are a geotextile sediment traps produced by ACF Environmental, located in Richmond, Virginia (Figure 3). They are designed to capture and filter sediment from construction sites, but have been adapted for use on bladed skid trails. In a study conducted by Smith and Fenton (1992), a similar device was successfully used to sample sediment on skid trails in New Zealand. This study used Dirtbags® that measured

Figure 3. Dirtbags® installed on bladed skid trail.

approximately 1.2 m (4 ft) x 1.8 m (6 ft) and handled approximate flow rates of 3900 liters/minute/m^2 (ACF Environmental, INC). As water flows through the Dirtbag® sediment is filtered out, and captured, similarly to the way that sediment fences capture sediment moving downslope.

Dirtbags® are designed for use on construction sites where water from retention ponds is pumped into the bag and the sediment is filtered out and the clean water drains off site. The continual pressure exerted on the bags, from the inflowing water, forces suspended sediment within the bag against the inner bag walls. This action forms a seal within the bag and helps increase the capture efficiency of the Dirtbag® (Robert Connelly, pers. comm., ACF Environmental, Sept. 2, 2010). In the application of Dirtbags® in this study, the Dirtbags® were seldmom fully inflated with water. Therefore the capture efficiency was lower than when Dirtbags® are deployed in their intended manner, so the capture efficiency rate had to be calibrated in a small sub-study. This amount was determined by taking 2.3 kg (5 lbs) of soil from the study site, suspending it in water, and pouring into a smaller 0.6 m (2ft) x 0.6 m (2ft) Dirtbag® and allowing it to filter out. This process was replicated three times at varying flow rates. After the water filtered out and Dirtbags® had dried, the amount of sediment retained was compared to the amount initially input. The average soil loss from the three replications was 30%. Therefore a correction factor of 1.3 was applied to all Dirtbag® data.

This study was installed during May and June of 2009 and data collection began in June, 2009 and continued into July of 2010. Dirtbag® weights were recorded monthly for a total of 13 measurements. To capture sediment from the treatments, runoff was funneled into the Dirtbags® through a system of open-topped gutters placed in a trench at the foot of the water bar at the base of the treatment slope (Figure 4). For each treatment there were two sections of gutters. Gutters were constructed out of 15.2 cm diameter schedule 40 PVC pipe. The first section was installed

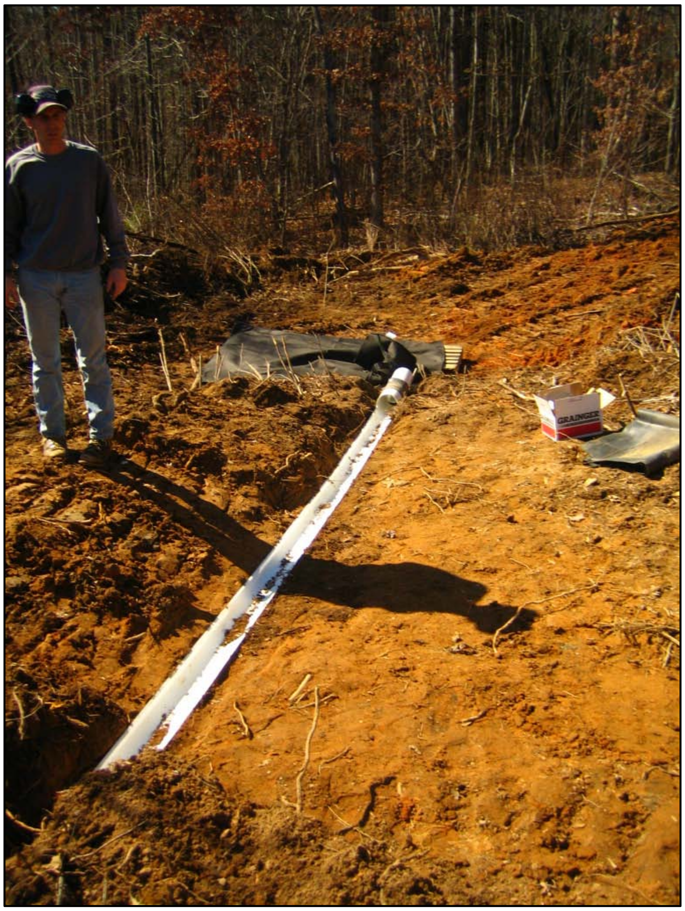

Figure 4. Gutter system installed at treatment base.

in the trench and spanned the width of the bladed skid trail. This section was horizontally cut in half so that it had an open top. The last 0.3 m (1 ft) of this section was left intact so that it could be coupled with the second piece. The second piece was a 0.9 m (3 ft) section, whose purpose was to carry the runoff into the Dirtbag® and was partially inserted into the Dirtbag® and secured via a hose clamp. The portion of this piece that was inserted into the Dirtbag® was horizontally divided in half to help the runoff distribute evenly into the bag. The portion that remained outside the Dirtbag® was left intact to couple with the first piece. The two sections were connected by wrapping a section of rubber mat around the joining ends and tightening with hose clamps. To help facilitate water drainage, Dirtbags® were placed on wooden pallets that elevated the Dirtbags® off the ground and increased the surface area available for drainage.

Dirtbag® weights were measured monthly with a HA crane scale manufactured by Citizen Scales INC., located in Edison, New Jersey. The scale had a weight capacity of 544 kg (1200 lbs), and was mounted on a metal arm attached to the blade of a John Deere 450E dozer. In addition to correcting for the sediment being lost through the Dirtbag®, weights were also corrected for the water weight of the sediment within the bag and the water weight of the bag's fabric.

A Hydrosense, manufactured by Campbell Scientific Australia, was used to collect TDR (Time-Domain Reflectometry) readings during weighing on every Dirtbag® to determine the volumetric moisture content of the sediment within the bag. To ensure that the TDR readings were accurate, soil samples were collected from the Dirtbags® periodically throughout the study and analyzed for moisture content. A regression analysis was then used to determine the relationship between TDR readings and soil moisture as determined from soil samples. A direct comparison between the two was not appropriate because the water content determined by the TDR was volumetric content and the water content determined by the soil samples was gravimetric content. To normalize the two into gravimetric water content, sediment bulk density samples were taken from Dirtbags®, and determined to be 1.2 g/cm^3. TDR readings were converted into gravimetric water content by dividing by bulk density values for regression analysis. The linear relationship between TDR readings and soil moisture samples was: Gravimetric Soil Moisture (%) = 1.89 (converted TDR readings), with a reported R^2 of 0.86. As a result of the regression analysis all TDR readings taken throughout the study were converted into gravimetric water content and then increased by 89% to determine the moisture weight of the sediment.

The water weight that the Dirtbag® fabric absorbed was also taken into consideration. This was accomplished by using three qualitative moisture classes for the Dirtbag® at the time of weighing. The moisture classes were: 1) dry; 2) moist; and 3) wet. Using smaller Dirtbags® (0.6 m x 0.6 m), correction factors based on the surface area of the bag were developed for each moisture class. Moisture classes were recreated on the smaller Dirtbags® and their weight was measured. From this, a weight per surface area of bag was calculated and used to correct for the water weight of the bags in the field. When Dirtbags® were classified as dry they were estimated to weigh 0.55 kg/m^2, when they were moist they were estimated to weigh 1.12 kg/m^2, and when they were wet they were estimated to weigh 2.65 kg/m^2.

Rainfall was monitored by an onsite Natural Resource Conservation Service weather station which recorded rainfall in 1 hour increments. Rainfall data, taken in 15 minute intervals, was collected from a National Climatic Data Center weather station located in Woolwine, VA, approximately 39 km to the northwest of the study site. Data from the NCDC weather station were collected for a one year period beginning in May of 2009 and ending in April 2010.

Ground cover data was collected along transects for each treatment multiple times throughout the study. Three transects were established perpendicular to the slope and spaced at 3.7 m (12 ft) intervals. A fourth transect was established on the slope of the water bar at the foot of the treatment. Ground cover data was collected at points, established at 0.3 m intervals, along each transect. Ground cover was collected shortly after the study was installed and then at quarterly intervals throughout the rest of the study.

Statistical Analysis

This study was designed as a Randomized Complete Block Design with Repeated Measures. The data analyzed were the monthly Dirtbag® weight measurements that had been converted from kg/ha to tonnes/ha and the repeated measure was time (monthly measurements). The data were analyzed in SAS v9.2 statistical software (SAS Institute 2008) using the Proc GLIMMIX procedure. Treatment differences were determined by using a Tukey means separation test and were considered significant based on an alpha of 0.05.

Results and Discussion

Overall the Control treatment was the most erosive treatment with an average erosion rate of 137.7 tonnes/ha/yr. The second most erosive treatment was the Seed treatment with an average rate of 31.5 tonnes/ha/yr, followed by the Hardwood Slash treatment with an average rate of 8.9 tonnes/ha/yr, Pine Slash treatment with an average rate of 5.90 tonnes/ha/yr, and the Mulch treatment had the lowest rate at 3.0 tonnes/ha/yr (Table 1). The Control treatment was significantly different from all other treatments. The Seed treatment was similar to the Hardwood Slash treatment but different from the Pine Slash and Mulch treatment. The Pine Slash, Hardwood Slash, and Mulch treatments were all similar (Table 1).

Table 1. Average erosion rate (tonnes/ha/yr) for each treatment. Treatments with the same letter are not significantly different based on $\alpha = 0.05$.

Treatment	tonnes/ha/yr		Replication	Monthly Samples Taken	Stnd Dev
Control	137.7	a	6	13	18.2
Seed	31.5	b	6	13	9.2
Hardwood Slash	8.9	bc	6	13	1.5
Pine Slash	5.9	c	6	13	1.1
Mulch	3.0	c	6	13	0.6

The highest erosion rates were seen at the onset of the study, during May, June, and July of 2009 and then again towards the completion of the study, January through July of 2010 (Figure 5). The pattern of erosion rates depicted in Figure 5 can be primarily attributed to the

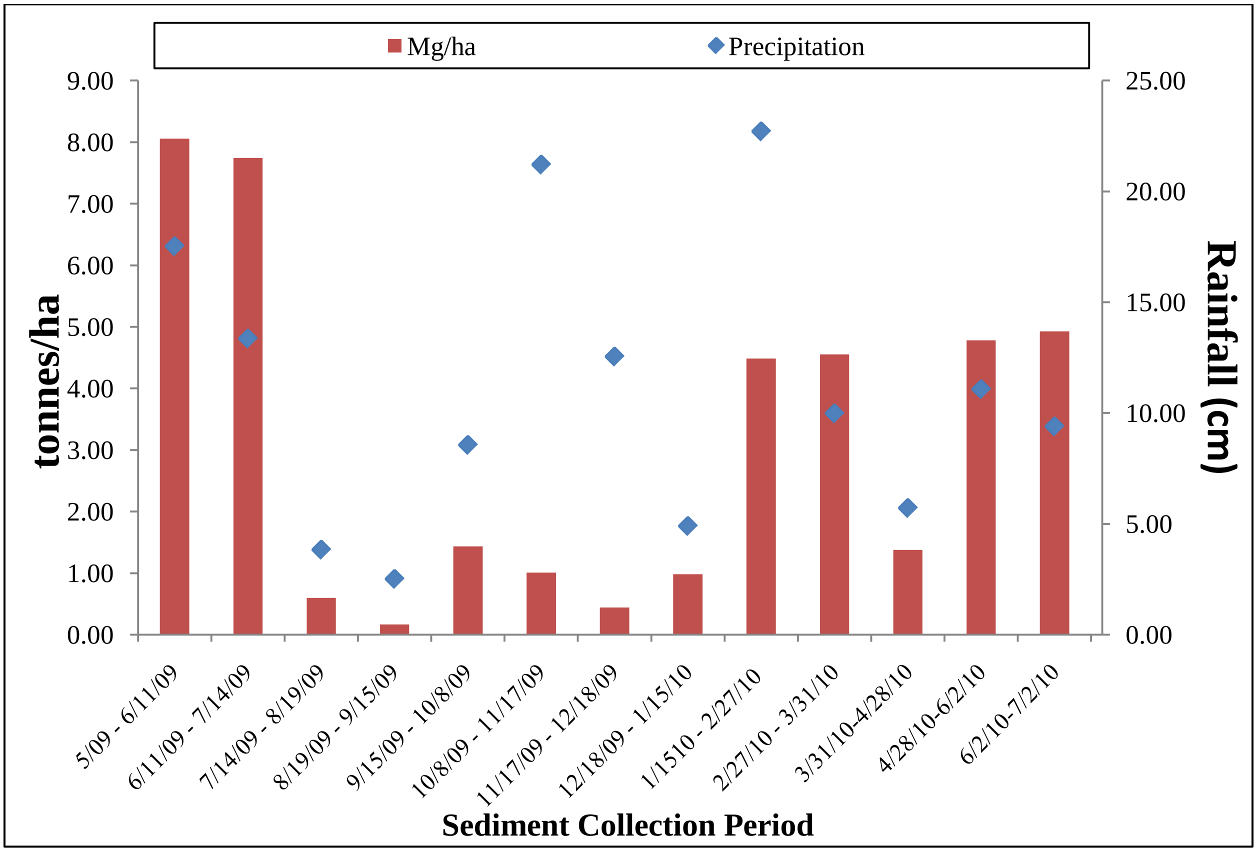

Figure 5. Average erosion rates (tonnes/ha) across all treatments for each sediment collection period. Also plotted on the secondary Y axis is the amount of rainfall received during each sediment collection period (cm).

Control treatment (Figure 6). The Control treatment had high initial rates that decreased during the fall of 2009 and then increased again beginning in mid winter and into the spring and early summer of 2010. The Seed treatment had high initial rates of erosion but decreased as grass became established on the treatments and rates remained low through the duration of the study. The Slash and Mulch treatments initially had low erosion rates and rates remained low and consistent throughout the study.

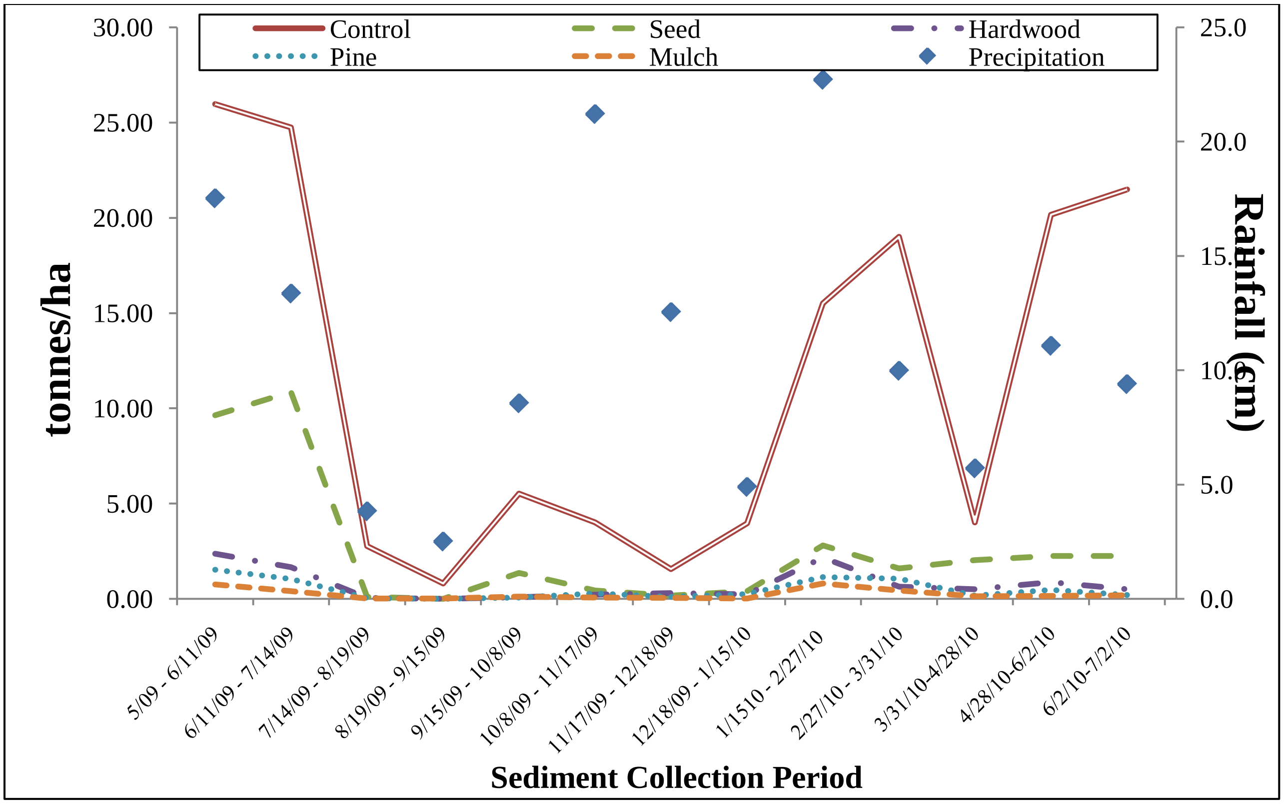

Figure 6. Average erosion rates (tonnes/ha) for each treatment for each sediment collection period. Also plotted on the secondary Y axis is the amount of rainfall received during each sediment collection period (cm).

Significant treatment effects were also seen at different times throughout the study. Significant treatment differences were seen during sediment collection periods 1, 2, 5, 9, 10, 12, and 13 (Table 2). In periods 1 and 2 the Control and Seed treatments were different from all others. In period 5, the Control and Seed treatments were similar to one another but different from all others. In periods 9, 10, 12, and 13 the Control treatment was different from all other treatments. Periods where significant treatment differences are evident coincide with periods where erosion rates were high on the Control.

Ground cover measurements were collected multiple times throughout the study. Measured ground cover took into account mulching agents, sown grass, natural vegetation, and any other naturally occurring agent that was considered substantial enough to be able to reduce

Table 2. Erosion rates for each treatment during each sediment collection period. Within each sediment collection period, treatments with the same letter are not significantly different based on α = 0.05.

Collection Period		Rainfall (cm)	Control (tonnes/ha)		Seed (tonnes/ha)		Hardwood Slash (tonnes/ha)		Pine Slash (tonnes/ha)		Mulch (tonnes/ha)		p Value
1	5/09 - 6/11/09	17.5	26.0	a	9.64	b	2.37	c	1.52	c	0.76	c	0.001
2	6/11/09 - 7/14/09	13.4	24.7	a	10.86	b	1.66	c	1.04	c	0.41	c	<0.0001
3	7/14/09 - 8/19/09	3.8	2.8	a	0.11	a	0.06	a	0.04	a	0.03	a	-
4	8/19/09 - 9/15/09	2.5	0.8	a	0.00	a	0.00	a	0.00	a	0.01	a	-
5	9/15/09 - 10/8/09	8.6	5.5	a	1.36	a	0.09	b	0.07	b	0.13	b	0.03
6	10/8/09 - 11/17/09	21.2	4.0	a	0.44	a	0.22	a	0.29	a	0.07	a	-
7	11/17/09 - 12/18/09	12.5	1.6	a	0.17	a	0.30	a	0.11	a	0.06	a	-
8	12/18/09 - 1/15/10	4.9	4.0	a	0.41	a	0.25	a	0.26	a	0.03	a	-
9	1/1510 - 2/27/10	22.7	15.5	a	2.80	b	2.17	b	1.14	b	0.80	b	<0.0001
10	2/27/10 - 3/31/10	10	19.0	a	1.61	b	0.64	b	1.07	b	0.45	b	<0.0001
11	3/31/10-4/28/10	5.7	4.0	a	2.04	a	0.50	a	0.17	a	0.14	a	-
12	4/28/10-6/2/10	11.1	20.2	a	2.25	b	0.87	b	0.47	b	0.15	b	<0.0001
13	6/2/10-7/2/10	9.4	21.5	a	2.25	b	0.51	b	0.21	b	0.18	b	<0.0001
	Stnd Dev		9.7		3.5		0.8		0.5		0.3		

rainfall impact. Since there was no addition of mulching agent during the study, any changes in cover were assumed to be a result of natural or planted vegetation establishment, or other natural feature. Ground cover generally increased on all the treatments throughout the first nine months of the study (Table 3). Increases in ground cover were primarily a result of vegetation, natural or planted, becoming established; however, cover also increased because erosion exposed underlying rock and debris fragments which provided soil armor. Data collected in July 2010, at the completion of the study showed a decrease in ground cover on all treatments; primarily a result of vegetation not reestablishing on the treatments after the winter dieback. This highlights a potential advantage of slash as compared to grass seed.

The study site received 143.3 cm of rainfall, which is in the normal range of rainfall as reported by the Patrick County, VA soil survey (NRCS Soil Survey, 2009), over the thirteen

Table 3. Percent cover data collected for each treatment at multiple intervals throughout the study period.

	Measurement Date				
	June 3 2009	December 17 2009	March 19 2010	July 8 2010	
Treatment	Percent Cover (%)				Stnd Dev
Control	9.5	18.5	21.1	18.3	5.1
Seed	31.3	45.1	38.3	35.6	5.8
Hardwood Slash	65.1	84.1	85.8	78.1	9.4
Pine Slash	79.6	89.7	91.5	87.5	5.3
Mulch	83.3	84.3	86.8	79.5	3.0

month study period, with the summer months receiving 11.2 cm, the fall months receiving 41.6 cm, the winter months receiving 31.5 cm, and the spring months receiving 58.0 cm. Rainfall data collected from a National Climatic Data Center weather station located in Woolwine, VA was used to assess rainfall intensity. Data collected from May, 2009 through April, 2010 show that more intense rain events occurred in the spring and less intense events occurred during the fall months (Figure 7), which helps to explain the increase in erosion rates seen towards the conclusion of the study. The effects of the high amount of rainfall the study site received in late fall to early winter were not great because rain events during this time period were often low intensity, between 1 to 2 cm per hour.

The water bar only Control treatment was the most erosive treatment evaluated. Overall it had an erosion rate of 137.7 tonnes/ha/yr (Table 1). The highest erosion rates were seen in sediment collection periods 1 and 2 (Table 2). These periods coincided with high amounts of rainfall, low percent ground cover, and unconsolidated soil particles. The average ground coverage for the Control treatments, as determined by the first measurement of ground cover, was 9.5% (Table 3).

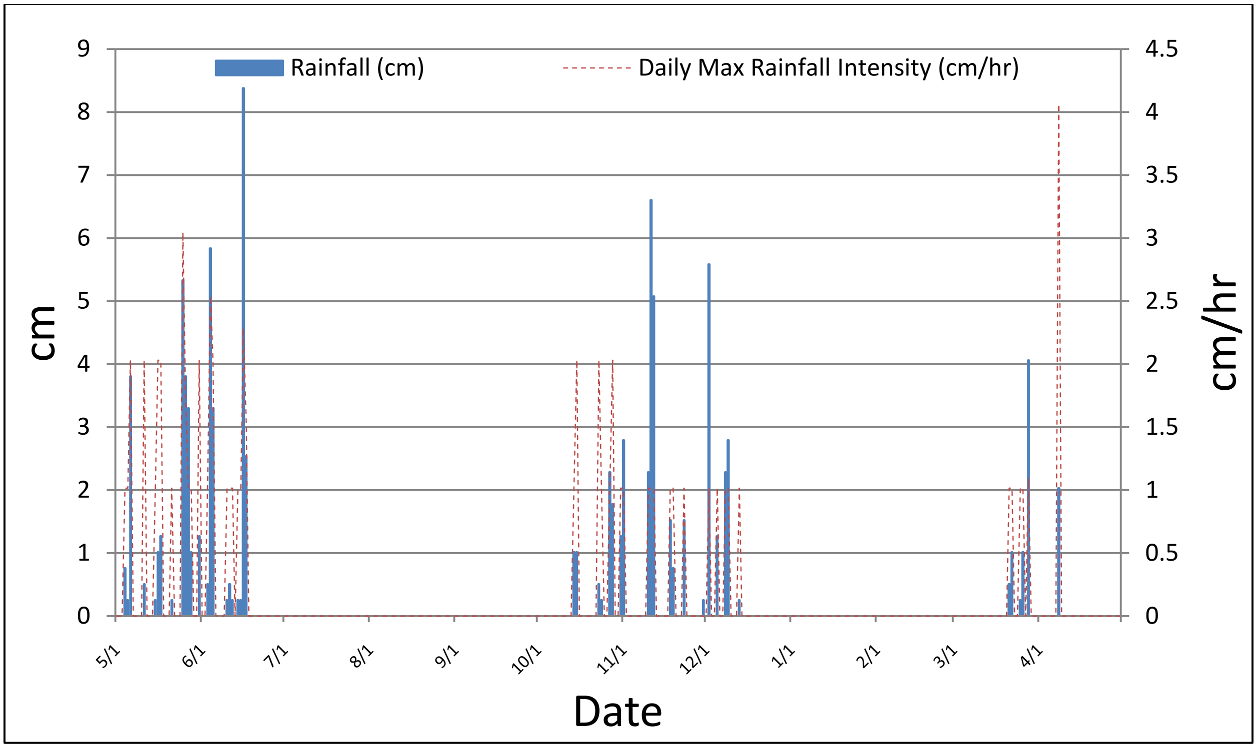

Figure 7. Rainfall intensity data was collected from a NCDC weather station in Woolwine, VA. Results indicate more intense rain events occur in Spring to early Summer.

Over the next sediment collection periods 3 and 4, from July 14th to September 15th, 2009, the erosion rates on the Control treatment were much less than the first 2 periods. The rainfall amounts were less over these two periods than the previous two periods, with periods 3 and 4 receiving 3.8 cm and 2.5 cm, respectively. Also, by this time the more easily erodible soil particles had been eroded leaving the more resistant soil. Furthermore, natural vegetation establishment also reduced erosion rates.

Over sediment collection periods 5 through 8 (September 15th – January 15th, 2010) the erosion rates remained low, peaking at 5.5 tonnes/ha (Table 2). By this time the remaining surface soils were less prone to the erosivity of overland flow. Natural vegetation and soil reconsolidation helped to keep erosion rates minimal even during high rainfall events. The second highest amount of rainfall, 21.2 cm, was received during sediment collection period 6

(October 8th – November 11th 2009); however these rain events were likely of low intensity. Ground coverage data taken in December, 2009 also indicated that the ground cover had nearly doubled from 9.5% to 18.5%.

The erosion rates on the Control treatment steadily increased over the remaining collection periods, from January, 2010 till the end of the study in July, 2010, except for the 11th period. Increased erosion rates during these periods were probably due to several factors, such as the effects that freeze thaw action had on the saturated soil during winter and early spring (Brady and Weil, 2008) in combination with higher amounts of rainfall during more intense rain events. A decrease in ground cover was also seen towards the end of the study. Ground coverage collected in July indicated a decrease in cover from 21.1% to 18.3%. The decrease in erosion rates seen during the eleventh period were primarily a result of low amounts of rainfall, with this period, from April 1st to April 28th, only receiving 5.7 cm. Overall the Control treatment had the most variable erosion rates throughout the study and seemed to be more easily influenced by climatic conditions (Figure 6).

The Control treatment, water bar only, represents a commonly prescribed BMP in the southeast, and is generally considered the minimum level of BMP implementation. The high erosion rates found in this study indicate that water bars alone may not be adequate in areas where water quality and erosion are major concerns, such as stream approaches and steep road grades. In areas where water quality is less critical, water bars should be installed as outlined in state BMP manuals. Spacing of the water bars is dependent on the slope of the skid trail, i.e. the steeper the slope the closer the water bars should be to one another. Water bars should also be installed so that they route trail runoff over non-road areas that will slow down the velocity of the runoff causing deposition of any sediment.

The Seed treatment was the second most erosive treatment with an average erosion rate of 31.5 tonnes/ha/yr (Table 1). However, this treatment reduced erosion by 77% when compared to the Control treatment. Similar to the Control treatment, the highest erosion rates seen on the Seed treatments occurred during the first two sediment collection periods due to high amounts of rainfall and unconsolidated bare soil. Erosion rates on the Seed treatments were not as high as those on the Control treatments due to the amount of ground cover provided by the sown grass. The first measurement of ground cover showed that the Seed treatments had an average coverage of 31.3%, compared to the Control treatment at 9.5% (Table 3).

Due to the establishment of vegetation, from the 3rd sediment collection period till the conclusion of the study, July 14th, 2009 till July 2nd, 2010, erosion rates decreased and remained below 3.0 tonnes/ha. Once grass became established the variability between period erosion rates greatly decreased (Figure 6). The highest amount of erosion seen after period 2 occurred during period 9, 2.8 tonnes/ha (Table 2), when rainfall amounts where high and the soil was undergoing the freeze thaw action.

Grass can be a very effective erosion control treatment, however the beneficial effects are dependent upon grass establishment. Grass establishment on bladed skid trails can be difficult and may require soil amendments such as lime and fertilizer. In this study adequate germination was not achieved on blocks 3 through 6 after the first application of grass seed and additional applications were necessary. Ground coverage data indicated that the average cover on the Seed treatments was 31.3% shortly after the treatments had been installed and grass had partially become established. Coverage data collected in December 2009 showed that throughout the remainder of the summer and into fall, vegetation on the treatments became better established and the cover on the treatments increased to 45.1%. The next two ground cover measurements, collected in March and July of 2010, indicated that the average ground cover on the treatments decreased to 38.3% and 35.6%, respectively (Table 3). This likely was a result of grass failure and lack of re-establishment.

Results also show that any amount of vegetation establishment is beneficial. Grass never became fully established on any of the Seed treatments, with the highest amount of coverage being 45.1%. In spite of this low amount of coverage the Seed treatments reduced erosion amounts by 77% when compared to the Control. Once grass had become established erosion rates decreased below 3 tonnes/ha even during periods receiving high amounts of rainfall.

The Hardwood Slash treatment had the third highest erosion rate, at 8.9 tonnes/ha/yr (Table 1). The erosion control provided by the Hardwood treatment was immediate, occurring within the first sediment collection period, and consistently low, remaining below 3.0 tonnes/ha. The highest erosion rates were seen in sediment collection period 1 (2.37 tonnes/ha) and then peaked again in sediment collection period 9 (2.17 tonnes/ha) (Table 2).

Ground cover data collected shortly after the installation of the treatments indicated that the Hardwood Slash treatments had an average coverage of 65.1%. Like the Seed and Control treatments, ground cover increased on the Hardwood treatments throughout the remainder of the summer and into fall of 2009. Average cover collected in December was 84.1%. This increase in coverage was due to natural vegetation invading the treatments and becoming established in the gaps left by the slash. Ground cover data collected in March 2010 showed the average cover slightly increased during late winter to a value of 85.8%. Through spring to early summer of 2010, the average cover decreased to a value of 78% (Table 3).

The coverage on the Hardwood treatments was more variable than other treatments, indicating that other factors such as invading natural vegetation played an important role.

Hardwood slash is more flexible, especially if applying directly after harvesting, and less easily compacted than pine slash. Hardwood slash is less uniform and can leave gaps where bare soil is exposed and natural vegetation can take root. The 19% increase in cover between the summer and winter of 2009 was likely due to vegetation establishment in these gaps. The decrease seen at the end of the study was likely due to vegetation dieback.

The Pine Slash treatment had the fourth highest erosion rate, at 5.9 tonnes/ha/yr (Table 1). Like the Hardwood Slash treatment, the erosion control provided by the Pine Slash treatment was immediate and remained consistently low throughout the study period. Similar to all other treatments, the highest erosion rates occurred within the first sediment collection period, 1.52 tonnes/ha. Erosion rates also peaked again in sediment collection period 9 at 1.14 tonnes/ha (Table 2).

Overall the Pine Slash treatments had the highest ground cover. The four ground cover measurements showed that the Pine Slash had 79.6%, 89.7%, 91.5%, and 87.5%, respectively (Table 3). In this study the pine slash was more easily compacted with the dozer, which caused it to have better contact with the soil, thus providing more effective coverage. These results indicate that Pine Slash coverage was less variable and less dependent on natural vegetation establishment.

Overall, the Hardwood and Pine Slash treatments performed very similarly. The Hardwood Slash treatment reduced erosion by 94% and the Pine Slash treatment reduced erosion by 96% as compared to the Control treatment. These results are similar to the results of McGreer (1981). When slash is applied to bladed skid trails it protects bare soil from the impacts of raindrops, intercepts rainfall, and reduces the velocity of overland flow causing deposition of sediment. The erosion protection offered by both the Hardwood Slash and Pine Slash treatments occurred directly after application. This is advantageous over applications of grass seed where the erosion control will only occur once grass has become established. Slash is also an easily available mulching source in harvesting operations. Depending on the type of harvesting operation being undertaken and equipment available, slash may prove to be more cost effective than applying straw mulch. Applying slash to skid trails also inhibits unwanted vehicular traffic. During skid trail closure it is important to limit vehicular access to allow the trails to rehabilitate. Build up of slash on skid trails will also introduce nutrients back into the soil over time as the slash decomposes. Infiltration rates will also increase on trails as an organic A horizon begins to develop. On publicly managed forest lands, where biodiversity issues may be present, use of non-native grass seed may be seen as detrimental and slash would be a better alternative.

During one year of measurement, no statistical differences were seen between the Hardwood Slash and Pine Slash treatments. The Pine Slash treatment had lower erosion rates than the Hardwood Slash treatment primarily because it provided better ground coverage because pine slash is more brittle than hardwood slash and was more easily trafficked and compacted to provide better contact with the bare soil. Pine slash also is more consistent in leaf area than hardwood. Deciduous hardwood slash that is applied during the spring and summer months is likely to provide better coverage than hardwood slash applied during winter months when the leaves are off. Pine needles are present year round, and pine slash applied in the winter months should provide the same coverage as pine slash applied in the summer months.

This study was of short duration. If measurements were continued for several years the treatments might differ more due to different decomposition rates. For example Pine Slash might become more effective because it has a slower decomposition rate and would therefore be more persistent over multiple years. Barber and Van Lear (1984) examined the decomposition rate of loblolly pine debris and estimated that loblolly pine debris would lose 50% of its weight in 10 years. Onega and Eickmeier (1991) examined decomposition rates of woody debris in Southern Appalachian deciduous forests and found litter to have a half life of 3.4 years and tree boles to have a half life of 6.3 years. These comparisons do not take slash size into account. However, over multiple years it may prove difficult to determine the effects of slash decomposition due to confounding factors such as invading vegetation and soil reconsolidation.

The Mulch treatment was the most effective treatment evaluated. It had an average erosion rate of 2.98 tonnes/ha/yr (Table 1). Like the other treatments, the Mulch treatment had high initial erosion rates of 0.70 tonnes/ha. In sediment collection period 9 the erosion rates increased above this level to 0.80 tonnes/ha (Table 2). Throughout the study the erosion rates on the Mulch treatment were consistently low.

The Mulch treatments had the second highest average ground cover. Shortly after study installation the treatments had an average coverage of 83.3%. Cover values collected in December, 2009, 84.3%, indicate grass becoming established. Cover values continued to increase into March, 2010, 86.8%, and then decrease from March until July, 79.5% (Table 3).

The effectiveness of the Mulch treatment is primarily due to two reasons. The straw mulch provides better germination sites for grass seed by increasing the soil moisture and providing cover to the seed. Grass establishment on the Mulch treatments was better and occurred more rapidly than on the Seed treatments, and was more persistent throughout the year. The cover also decreases overland flow and protects against erosion much in the same manner as the Slash treatments. However, straw mulch is less persistent than piled slash. It is capable of being moved off site by strong winds and has a faster decomposition rate than slash.

Conclusion

Following silvicutural operations skid trail closure commonly consists of water bar installation as prescribed by state BMP manuals (Virginia Dept. For., 2002). Water bars offer a degree of erosion control, however, the effects of any BMP that leaves bare soil exposed can vary over time due to climatic conditions, such as rainfall amounts, rainfall intensity, and freeze thaw actions. This study found that the water bar only (Control) treatment had the most variability in periodic erosion rates. In areas where soil erosion is less tolerable, such as stream approaches, water bars alone should not be the only BMP implemented. In combination with water bars, BMPs that enhance soil stability should be applied. Establishing grass on skid trails can be very effective at stabilizing the soil, but ensuring there is adequate germination can be difficult. Multiple applications of seed along with application of fertilizer and lime may be needed. Erosion control is also not immediate and only occurs after seed has germinated. Applying a mulching agent is the best way to prevent erosion from occurring. Slash and Mulch treatments were the most effective at erosion control because they provided the most ground cover, which served to stabilize the soil by providing protection from rainfall impact and reduction in overland flow velocity. The protection offered by the Slash and Mulch treatments is immediate and therefore these treatments should be considered in areas that are highly susceptible to erosion, such as steep grades and fill slopes.

In forest applications, slash in the form of tree tops and limbs is a readily available cover agent. The protection provided by slash is very similar to that provided by straw mulch. Slash also has a slower decomposition rate than does straw mulch and therefore has a longer residual lifespan. This study covered a time span of thirteen months, but if these treatments were to be followed for a longer time period it is likely that the erosion rates of Slash treatments would level out with the erosion rates of the Mulch treatments. Eventually as the straw mulch decomposes, the erosion control provided by Slash treatments may surpass that of the Mulch treatments. Over time, slash decomposition will introduce nutrients back into the soils and a buildup of organic matter will help an organic layer develop and increase infiltration rates.

No statistical differences were shown between the Hardwood Slash and Pine Slash treatment, however when both a supply of hardwood and pine slash is available, pine slash may be preferable. Pine slash was shown to offer better ground coverage than hardwood slash because it is more brittle and more easily tracked down by equipment. Hardwood slash is more flexible therefore it will not break as easily, leaving holes and gaps where bare soil can be exposed. Natural vegetation is likely to establish in these gaps, so the effectiveness of hardwood slash is not greatly reduced. Since this study is of relatively short duration, no conclusive results can be shown that show that pine slash is more persistent over multiple years than hardwood slash. Yet, when the decomposition rates are examined, with pine slash having a slower rate, it is likely that pine slash would last longer.

Erosion rates were highest directly following skid trail construction. Since soils are highly susceptible to erosion after soil disturbance BMPs should be installed immediately after harvesting is completed in a certain area and should not be left until the completion of the entire harvesting operation. Erosion rates were also high during spring months, which experience higher intensity rain events. The Control erosion rates were high during these periods, while the Slash and Mulch treatments maintained low rates. BMPs that provide soil cover, such as the Slash and Mulch treatments, should be utilized during these critical periods.

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Chapter 3. Comparison of USLE – Forest, RUSLE2, and WEPP – Forest Roads erosion models for evaluation of bladed skid trail erosion

Abstract

Sediment is an important pollutant from silvicultural operations and bladed skid trails are major sources of sediment. Several models have been developed to evaluate erosion from forest activities. This study is part of a larger study in which bladed skid trail closure BMPs were evaluated by field measurements. The bladed skid trail BMPs evaluated were: 1) water bar only (Control); 2) water bar and grass seed (Seed); 3) water bar, grass seed, and straw mulch (Mulch); 4) water bar and piled hardwood slash (Hardwood Slash); and 5) water bar and piled pine slash (Pine Slash). This study used three erosion models to evaluate the BMPs while also using linear regression and a model efficiency test to compare the accuracy and applicability of the models to predict actual erosion from the treatments. The erosion models used were the Universal Soil Loss Equation for Forestry (USLE – Forest), the Revised Universal Soil Loss Equation Version 2 (RUSLE2), and the Water Erosion Prediction Project (WEPP – Forest Roads). For each model, predictions were made for each treatment replicated six times for a total of thirty predictions. Results showed significant treatment differences within each model, with the Control being the most erosive followed generally by the Seed, Hardwood Slash, Pine Slash, and Mulch treatments. Model predictions were then regressed against actual erosion data to determine accuracy and applicability. Results showed that all models represented erosion adequately.

Keywords
USLE, RUSLE2, WEPP, bladed skid trails, erosion

Introduction

Sediment is one of the most important sources of non point source pollution (NPSP) in the United States (USEPA, 2003). Increased sedimentation can impair the natural functions of streams and rivers so they become unsuitable for aquatic organisms (Henley et al., 2000; Virginia Department of Environmental Quality, 2007) and no longer optimally serve recreational needs (Henley et al., 2000; USEPA, 2003). Sedimentation derived from land uses such as agriculture, forestry, and urban development are the leading sources of NPSP (Yoho, 1980; USEPA, 2003).

In response to the increased erosion potential from silvicultural operations, forestry Best Management Practices (BMPs) have been developed. Forestry BMPs are mainly focused on highly disturbed areas within a silvicultural system that are prone to erosion, such as roads, logging decks, and skid trails. BMPs are designed to reduce erosion by decreasing the amount and velocity of water thus decreasing its energy, and maintaining soil stability. Common BMPs used for roads, skid trails, and logging decks include: 1) proper planning, construction, and location; 2) control of grade; 3) control of water; 4) surfacing; and 5) road or trail closure (Swift, 1985; Swift and Burns, 1999; Grace, 2005a). Bladed skid trail closure is important because skid trails are typically built to lower standards than haul roads and have the potential to be a greater source of sediment. Typical trail closure BMPs include installing water bars, and seeding with or without the application of straw mulch.

Soil erosion models have been developed to predict erosion rates from both hillslopes and roads. Erosion prediction methods are also used to evaluate management practices and erosion control techniques (Elliot, 2004). Erosion models provide a cost effective and time efficient way to evaluate the performance of forestry BMPs. There are generally three types of soil erosion models in use: 1) empirical; 2) conceptual; and 3) physics based (Merritt et al., 2003). Empirical models such as the Universal Soil Loss Equation (USLE) are the simplest type of model and base predictions on statistical relationships between observed responses and independent variables (Fu et al., 2010). Data requirements and computations are usually less than conceptual or physics based models and due to their simplicity they are useful over a wide spatial scale (Merritt et al., 2003). Conceptual models, such as the Sediment River model (SedNet) represent catchments as a series of internal storages. Conceptual models represent flow paths through the catchment by incorporating transfer mechanisms of sediment and runoff generation. This type of organization allows the models to illustrate the effects of land use change without requiring large data sets. Physical or process based models, such as the Water Erosion Prediction Project (WEPP), represent the most complex models in use. They base estimates on physical equations that describe sediment generation in a catchment. The complexity of the model requires hundreds of parameters to run and allows for many sources of uncertainty. Physical models also tend to be site specific and may not work well over a large spatial scale (Merritt et al., 2003).

Soil Erosion Models

The most widely used erosion model is the USLE (Elliot et al., 1999). The USLE is an empirically based model that was developed from over 10,000 plot scale observations (Fu et al., 2010). The large database used to develop the USLE renders it useful over a large spatial scale. The USLE was originally designed to predict erosion rates from agricultural lands but has since been adapted to predict erosion from forested lands (USLE - Forest) (Dissmeyer and Foster, 1984). The model was developed to predict long term average soil losses for a given site in a specific management condition. The USLE predicts sheet and rill erosion based on six factors: rainfall and runoff factor (R), soil erodibility factor (K), slope length factor (L), slope steepness factor (S), cover and management factor (C), and the support practice factor (P). Often L and S

(LS), and C and P (CP) are combined and treated as single variables. Erosion per unit area (A) is calculated by the formula: A= R*K*LS*CP. The USLE is not capable of estimating deposition by overland flow or channel flow, nor gully or stream channel erosion, or sediment delivery to water bodies. Also, since the values for these factors are long term averages, the USLE is not intended for use for storm specific erosion rates (Dissmeyer and Foster, 1984).

The USLE has been used in a variety of different studies to quantify soil loss rates. Jackson et al. (2005) used the model to develop a sediment budget for a Georgia piedmont watershed, by estimating the amount of erosion from a variety of land uses. Mishra and Deng (2009) used the USLE in conjunction with GIS software to develop sediment erosion estimates for the Amite River Basin in Southeastern Louisiana and Southwestern Mississippi. Due to its wide spatial applicability the USLE is used internationally. Soil erosion susceptibility in the Upper Nam Wa Watershed, Nan Province, Thailand was mapped by use of the USLE by Krishna Bahadur (2009).

As more experiments have provided more data, new versions of the USLE have been continually generated. The Revised Universal Soil Loss Equation (RUSLE) was released in the early 1990’s and has since evolved into RUSLE version 2 (RUSLE2). RUSLE2 uses the same process of predicting erosion rates as the USLE, but provides improved measures on calculating input variables (Renard et al., 1991). RUSLE2 uses the same formula as the USLE to predict sheet and rill erosion, however as more data has become available the derivation of the factors has improved.

Through the addition of more than 1,000 locations RUSLE2 offers improved isoerodent maps for calculating the R factor. Also, R values were reduced where flat slopes occur in regions of long intense rainfall, such as what occurs in the southeastern United States, because ponded water reduces the erosivity of the raindrop impact. Also an R equivalent approach is being used in the Pacific Northwest to reflect the combined effect of thawing soil and rain or snow on partly frozen soil. Erosivity is also computed for 15 day intervals, allowing land managers to identify periods when the site is more susceptible to erosion and then adjust management activities (Renard et al., 1991; Toy et al., 1999). RUSLE2 provides improved ways to calculate the K factor. Improvements include the inclusion of soils not previously covered by the USLE, a time varying approach to calculation, and K values that reflect rock fragments in the soil to account for rock effects on permeability and runoff (Renard et al., 1991; Toy et al., 1999). RUSLE2 also recognizes that time to soil consolidation is different for different areas and provides new equations to reflect slope length and slope steepness. The slope length (L) factor is computed by the equation $(\lambda/22.1)^n$ where λ is the slope length in meters and n is computed with equations that are functions of slope steepness, soil biomass, soil consolidation, ground cover, and soil texture (Foster et al., 2003). RUSLE2 also has a more nearly linear slope steepness relationship than the USLE and provides greater accuracy on steeper slopes. RUSLE2 provides an improved sub-factor approach for calculating C where variables used include percent canopy cover and fall height, surface roughness, ground cover provided by stones, litter, basal area, live vegetation touching the ground, other material on the soil surface, plant community type, average annual plant production, and time since soil was mechanically disturbed (Foster et al., 2003). Finally RUSLE2 provides improved P factor values for the effects of contouring, terracing, stripcropping, and management practices for rangeland (Renard et al., 1991). In addition to the improved derivation of the factors, RUSLE2 also calculates deposition on concave slopes at dense vegetation strips, in terrace channels, and in sediment basins using process based equations (Foster et al., 2003).

To make model estimates, four types of files are needed. A slope file describing the hillslope's slope characteristics, a climate file describing climatic characteristics such as rainfall and temperature, a soil file describing the soil characteristics, and a management file that describes land use and surface characteristics. Similar to the USLE, RUSLE2 has had wide use both domestically (Larson et al., 1997) and internationally (Kouli et al., 2009).

Another prominent soil erosion model is the Water Erosion Prediction Project (WEPP). WEPP is a physical based model, which is a product of an interagency collaboration involving the U.S. Department of Agriculture's Forest Service, Agricultural Research Service, Natural Resource Conservation Service, and the U.S. Department of the Interior's Bureau of Land Management, and the U.S. Geological Survey. In this study WEPP was specifically used to model erosion from forest roads and is designated as WEPP – Forest Roads.

WEPP – Forest Roads is a process based, continuous simulation erosion prediction model designed to estimate erosion from hillslopes and forest roads. It is a complex computer program that describes the processes that lead to soil erosion. These processes include infiltration and runoff, soil detachment, transport, and deposition; and plant growth, senescence, and residue decomposition. For each simulation day, the model calculates the soil water content in multiple layers, plant growth, and residue decomposition. For each day of precipitation or snowmelt, WEPP – Forest Roads calculates the appropriate infiltration and runoff. For rain or snow WEPP – Forest Roads routes runoff over the surface and calculates erosion and deposition rates for at least 100 points on the hillslope. It then estimates the average annual sediment yield from the slope (Elliot et al., 1999). The hillslope can have a complex shape, and can include numerous soils and plant types along the hillslope. Each segment that has homogeneous slope, soil, or management regime characteristics is known as an Overland Flow Element (OFE) (Elliot and Foltz, 2001).

WEPP – Forest Roads requires four sets of input files to make predictions. WEPP – Forest Roads needs a climate file including data on daily precipitation and temperatures, a slope file containing a minimum of two points that describe a hillslope, a soil file containing data describing the texture and other physical and erodibility properties of the soil, and a management file that contains descriptions of plant communities, surface disturbances, and surface conditions at the start of simulation (Elliot, 2004).

To develop climate data, CLIGEN, a stochastic weather generator that produces daily estimates of precipitation, temperature, dew point, wind, and solar radiation for a single geographic point, using monthly parameters derived from the historic measurements, is used (USDA, 2009). CLIGEN can estimate daily conditions from one to 999 years (Elliot et al., 1999). WEPP – Forest Roads provides a database with 2600 CLIGEN parameter files for locations within the US. WEPP – Forest Roads allows the use of these files and also for the creation of CLIGEN parameter files for areas that do not have an associated CLIGEN parameter file (USDA. 2003). WEPP – Forest Roads allows the user to create a site specific slope profile by entering slope length and slope steepness for at least two points on the hillslope. WEPP – Forest Roads provides soil data for many different locations and the user may chose to use one of the existing files or manipulate the data for site specific conditions. A cover management file can be created by the user to model site conditions. This file contains information on vegetation, type of disturbance, and initial conditions.

Study Objectives

The goal of this study is to compare the effectiveness of five closure and cover BMPs for bladed skid trails by use of three soil erosion models: 1) the Universal Soil Loss Equation for Forestry (USLE - Forest) (Dissmeyer and Foster, 1984); 2) the Revised Universal Soil Loss Equation version 2 (RUSLE2); and 3) the Water Erosion Prediction Project for Forest Roads (WEPP – Forest Roads). Model accuracy was determined by comparing the erosion estimates made by the erosion models to the erosion rates calculated in a field based study that evaluated the same treatments.

Materials and Methods

This study is part of a larger study where closure and cover BMPs were evaluated by direct measurement of erosion. The treatments applied were the same as those being evaluated in this study: 1) water bar only (Control); 2) water bar and grass seed (Seed); 3) water bar, grass seed, and straw mulch (Mulch); 4) water bar and piled hardwood slash (Hardwood Slash); and 5) water bar and piled pine slash (Pine Slash).

Study Site

This study was conducted at Reynolds Homestead Forest Research and Extension Center in Patrick County, Virginia in the upper Piedmont physiographic region. Reynolds Homestead is managed by Virginia Polytechnic Institute and State University. Patrick County has gently rolling terrain with the typical temperature in January ranging from -1.8°C to 9°C. In July, the temperature typically ranges from 17.8°C to 29.7°C. The average precipitation is 151.9 cm with 125.2 cm being rainfall and the remaining 26.7 cm snowfall (Patrick County, Va, 2009). The treatments were installed in a 5 hectare clearcut with side slopes of 15-20%. The dominant soil series on the site is Fairview (sandy clay loam, fine, kaolinitic, mesic Typic Kanhapludults).

This soil is formed from residuum from mica schist and mica gneiss and is very deep, well drained, and has an erodibility index of 0.28 (NRCS Soil Survey, 2009).

Six bladed skid trails were constructed and BMP treatments were randomly assigned to each trail. The field based study was arranged as a Randomized Complete Block Design with the bladed skid trails serving as the blocks (Figure 1). Thus, there were six replications of the five treatments for a total of thirty experimental units. Experimental units, or treatments, measured 15.2 m (50 ft) in length by 3 m (10 ft) in width. Water bars were constructed at the top and base of each treatment segment to ensure that only runoff generated within the treatment was measured. Runoff was captured at the base of the treatments in a system of gutters and then routed into geotextile devices known as Dirtbags ® where sediment was filtered out of the water and captured. Dirtbag ® weights were recorded monthly.

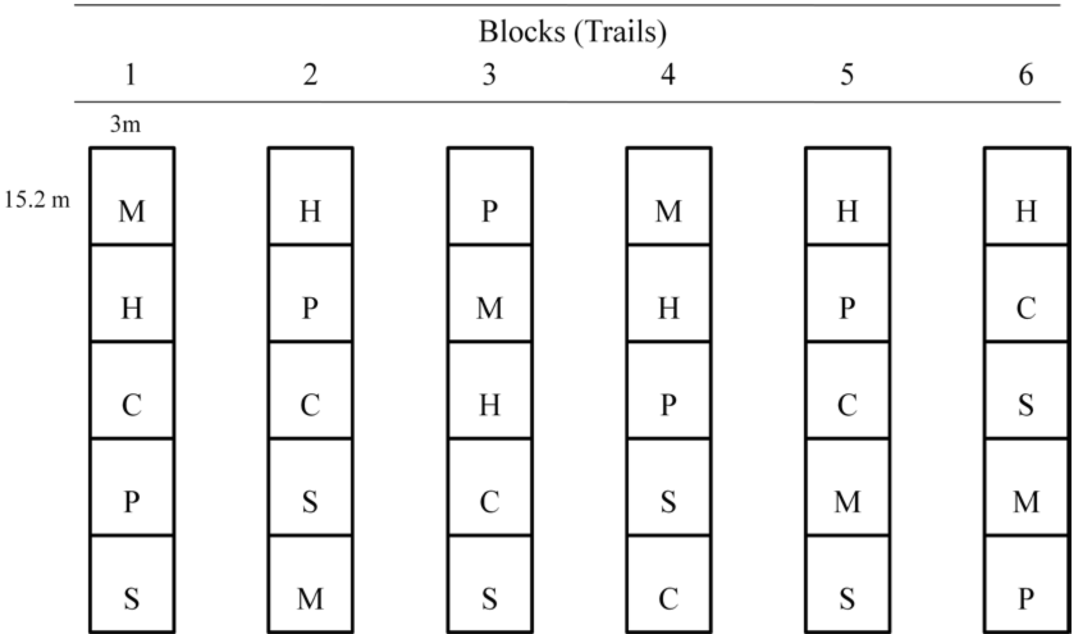

Figure 1. Idealized treatment layout for the Randomized Complete Block Design for bladed skid trails where C = Control; S = Seed; M = Mulch; H = Piled Hardwood Slash; P = Piled Pine Slash.

Erosion Model Parameters

This study used soil models to estimate erosion for each experimental unit, based on site and climatic data. This data included cover and management characteristics and slope and length measurements. For more accurate model estimates, treatment areas were divided into two segments (Figure 2 and Figure 3) and estimates were made for each segment and then a weighted

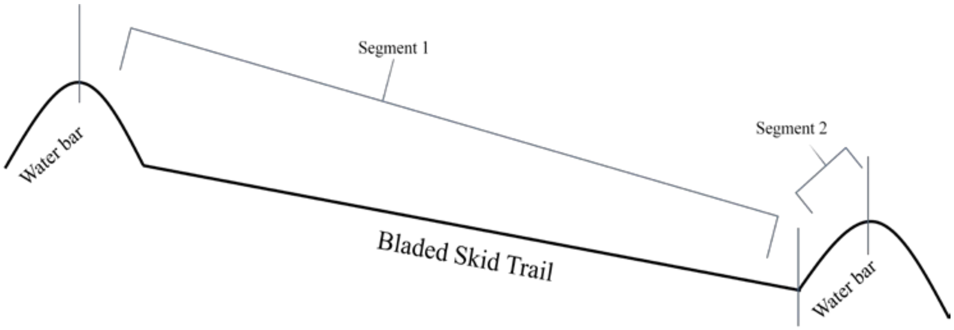

Figure 2. Division of treatments into two separate segments for use in USLE - Forest. Erosion estimates were made for each segment and then a weighted average was taken of the two segments for a total treatment erosion estimate. Slope values for segment 1 were the percent slope from the top of the water bar at the head of the treatment to the base of the water bar at the foot of the treatment and the slope length was the distance between. The slope for segment 2 was the percent slope of the backslope of the water bar at the foot of the treatment and the slope length was the length of the backslope.

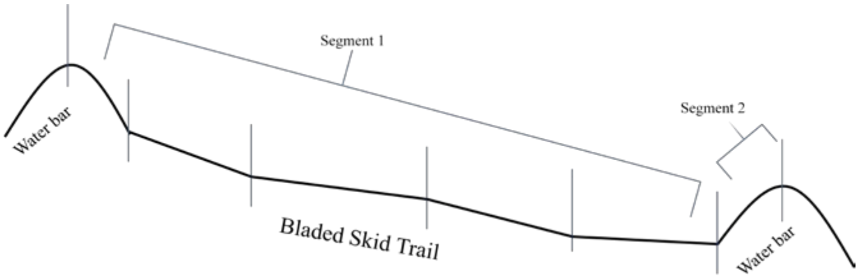

Figure 3. Division of treatments into two separate segments for use in RUSLE2, and WEPP – Forest Roads. Erosion estimates were made for each segment and then a weighted average was taken of the two segments for a total treatment erosion estimate. Segment 1 is more detailed based off of slope and distance data collected at multiple locations. The slope for segment 2 was the percent slope of the backslope of the water bar at the foot of the treatment and the slope length was the length of the backslope.

average of the two segments was used to determine a final predicted erosion rate per treatment. The weights assigned to each segment were based on segment area. Segment 1 included the majority of the treatment area and began and the top of the water bar at the head of the treatment area and continued to the base of the water bar at the foot of the treatment area. One generalized slope value was used for USLE – Forest (Figure 2), while a more detailed profile was possible for use in RUSLE2 and WEPP – Forest Roads (Figure 3). Segment 2 included the area on the back slope of the water bar at the base of the treatment. Treatment areas were divided into separate segments because the slopes of the two segments were very different and the second segment was immediately adjacent to the gutter and sediment trap.

USLE – Forest

The rainfall and runoff factor (R) was derived from the isoerodent map provided in the USLE – Forest manual (Dissmeyer and Foster, 1984). An R value of 175 was determined for the Reynolds Homestead location. A soil erodibility factor (K) of 0.28 was obtained from the Patrick County Soil Survey (NRCS Soil Survey, 2009).

Slope profiles of treatment areas were created by using a total station to measure slope and distance. Values for the LS factor were taken from the USLE – Forest manual (Dissmeyer and Foster, 1984) and were based off of slope and distance values measured in the field. Slope percent and slope length values for segment one were calculated from the top of the upslope water bar of the treatment to the base of the downslope water bar of the treatment. Segment two slope values were the percent slope of the water bar at the foot of the treatment (Figure 2). Slope lengths for segment two were too small to be found in the USLE handbook’s tables, thus the following formula was used to calculate values:

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

Where λ = slope length in feet; θ = angle of slope in degrees; and m = 0.2 for slopes less than 1 percent, 0.3 for slopes between 1 and 3 percent, 0.4 for slopes between 3.5 and 4.5 percent, and 0.5 for slopes of 5 percent or greater (Dissmeyer and Foster, 1984).

The slope of the water bar at the head of the treatment was not separated into a separate segment for several reasons. First, any sediment produced by that water bar would contribute to sediment production in segment one. Also, no cover data was taken explicitly for the upper water bar. Finally, adding a third segment to the analysis would add a degree of complexity that was determined to be unnecessary.

Due to the topsoil disturbance and traffic effects, the bladed skid trails were considered a tilled soil. CP subfactors for a tilled soil include 1) bare soil, residual binding, soil reconsolidation; 2) canopy effect; 3) steps; 4) onsite storage; 5) invading vegetation; and 6) contour tillage. The bare soil, residual binding, soil reconsolidation subfactor was estimated along transects on the treatment slope. Four transects, which were perpendicular to the slope and spaced at 3.7 m (12 ft) intervals along the treatment slope, were established and measurements were collected at 0.3 m (1 ft) intervals along the transects. Three of these transects were in segment one and the fourth transect was in segment two. At each 0.3 m point the ground was classified as either covered or not. Percent bare soil was then calculated for each transect. The remaining CP subfactors were estimated for the entire treatment.

Erosion rates were calculated for each transect, using the percent bare soil estimate and the remaining variables. This provided a total of three erosion rates for segment one and one erosion rate for segment two. The erosion rates of the transects in segment one were averaged together to determine an erosion rate for the segment. The area in each segment was used to provide a weighted average of total erosion rate per treatment.

The USLE – Forest measurements were collected during four seasons (Summer, Fall, Winter, Spring) during the course of the study. A weighted average was used at the end of the study period to determine a final erosion rate per treatment, with each measurement receiving a 0.25 weight coefficient. On the Seed and Mulch treatments where grass became established during the first quarter, both pre and post grass establishment values were collected. For the Seed treatments on Blocks 1 and 2 and for the Mulch treatments on blocks 1 through 5, grass establishment did occur within the first quarter and was assumed to have occurred thirty days after seed application. A weight of 0.08 was used for the pre grass establishment values and a weight of 0.17 was used for the post establishment values. On the Seed and Mulch treatments where grass establishment did not occur until the second quarter, the post grass establishment values were not taken during the first quarterly measurement.

RUSLE2

Erosion estimates using RUSLE2 were conducted in a similar manner as with the USLE – Forest estimates. Treatment plots were divided into two segments and a weighted average of both segments provided a total erosion estimate per treatment, however RUSLE2 allows for a more detailed slope profile, with multiple sections. Elevation data was collected at multiple spots along the treatment slope and this data was used to create profiles in the model where segment one incorporated five sections and segment two had only one (Figure 3). Estimates were made for a one year model run.

First, climate data was accessed from the NRCS and ARS database (NRCS) for Patrick County, Virginia and included average daily and monthly values of rainfall and temperature. Second, a soil file can either be downloaded from the RUSLE2 database or created for site specific conditions. Within the soil file there is information on the texture of the soil, erodibility index, consolidation period, and acceptable soil loss rates. The soils on the study site were mapped as a Fairview sandy clay loam and a soil file pertaining to this classification was downloaded for analysis. Third, slope files were created for each experimental unit based on measured slope and distance. The final component was a management file that described surface conditions. Within the software, there are management files that have already been developed for certain activities. The user can use these files or create new ones for conditions that are not covered in the database. Management files were created in the following way for treatments.

Within the RUSLE2 database there are no files specific to forest roads. To develop a file for the water bar only (Control) treatment, a "highly disturbed land/blade cut" was modified. The "highly disturbed land/blade cut" was used to simulate the cutting and removal of topsoil that occurs when bladed skid trails are constructed. Next a "highly disturbed land/track walking" operation was implemented to mimic the effects that dozer tracks would have on the slope. The date of operation was set to June 1st of year one for both operations. This date coincided with the approximate date of trail installation.

To develop a management file for Seed treatments, the file created for the Control treatment was used as the base template, and a "broadcast seed operation" applying a "southern range grass May 15" was added. This seed application most closely resembled the actual seeding operation. The date of application was set to June 1st of year one.

To develop a management file for the Mulch treatments a mulch addition was made to the Seed treatment management file. The mulching operation was called "highly disturbed land/add mulch". This mulching operation allows the user to choose from a variety of mulching agents. The type of mulch applied in this study was "wheat straw". Within this operation the user is allowed to set the application rate in weight/unit area. Depending on the application rate, RUSLE2 estimates the amount of coverage provided. In the field based portion of the study straw mulch was applied at a rate of 7.9 tonnes/ha (3.5 tons/acre) which gave ≈ 100% coverage initially. To achieve this coverage in RUSLE2 an application rate of 10.1 tonnes/ha (4.5 tons/acre) was required.

The RUSLE2 database does not have management files that are designed for woody slash residue additions. The most similar file is an addition of “wood fiber” as a mulching agent. However, the “wood fiber” is treated as small chip sized pieces that have a relatively short decomposition half life of 35 days. Alterations to this file were made to better represent the slash treatments. The Control treatment management file was used as the template and a mulching operation was performed with “wood fiber” being used as the mulching agent. To mimic the treatments using large woody debris some adjustments to the “wood fiber” were made. The response of the residue was changed from “fragile very small” to “woody large”. For the Hardwood Slash treatments, the decomposition half life was changed to 1800 days. Onega and Eickmeier (1991) examined decomposition rates of woody debris in Southern Appalachian deciduous forests and found litter to have a half life of 3.4 years and tree boles to have a half life of 6.3 years. An average of the two, 4.85 years (1800 days), was taken and used in the model. Barber and Van Lear (1984) examined the decomposition rate of loblolly pine (*Pinus taeda*) debris and estimated that loblolly pine debris would lose 50% of its weight in 10 years. Based on their results, a half life decomposition rate of 10 years (≈3700 days) was used to model the decomposition of pine slash in the Pine Slash treatments. The amount of mulch added was dependent upon the amount of coverage actually achieved in the field. To assess this amount, coverage values taken during the USLE – Forest data collection were used. An average of the cover values from the top 3 transects was taken to get a coverage value for segment one. The 4th transect was used for cover values for segment two.

WEPP – Forest Roads

Similar to RUSLE2, WEPP – Forest Roads requires four types of files to make predictions (slope characteristics, climate, soil characteristics, and cover characteristics - land use). Embedded within the software are generic files for each requirement that the user can utilize or alter to create new site specific files. Erosion estimates were based on model runs of one year.

Slope files were created in WEPP – Forest Roads similarly to the way they were created in RUSLE2. Segment one incorporated five sections, with varying slope and length, and segment two incorporated only one section (Figure 3).

WEPP – Forest Roads has an attached database of CLIGEN parameter files; however there was no parameter file specific to the Reynolds Homestead Forest Research and Extension Center. The nearest weather station with a CLIGEN parameter file is Philpott Dam, Va, approximately 16 km (10 miles) to the northeast. A CLIGEN parameter file was created using the “Add Climate Location” function in WEPP – Forest Roads. This function allows the user to pinpoint the location on a map, then WEPP – Forest Roads searches the surrounding area for any weather stations that have associated CLIGEN files. WEPP – Forest Roads then interpolates data from these stations to produce a unique file for a particular area. Prior to creating the CLIGEN file, WEPP – Forest Roads shows the user the values for average monthly maximum temperature, average monthly minimum temperature, average precipitation on wet days, the probability of a wet day following a wet day, the probability of a wet day following a dry day, solar radiation, maximum 30 minute intensity, time to peak intensity, and the average monthly dew point temperature. The user can either accept these values or replace them with site specific values. Once this is complete, a file is created that can be used in CLIGEN to create climate data.

A total of nineteen weather stations were used to create a CLIGEN parameter file for Reynolds Homestead Forest Research and Extension Center. The closest weather station was approximately 16 km (10 miles) away, and the farthest was approximately 103 km (64 miles) away. Site specific data on average monthly maximum temperature, average monthly minimum temperature, solar radiation, and average monthly dew point temperature was available, therefore this data was used instead of the interpolated data. The resulting CLIGEN parameter file was used in the analysis.

Within the WEPP – Forest Roads database the most similar soil file to a Fairview sandy clay loam was the “Disturbed Skid Clay Loam”, which was used in analysis. WEPP – Forest Roads software comes with management files and some management files were used unaltered while others were changed in the following way to more closely resemble the installed treatments.

Since WEPP – Forest Roads was also designed for erosion estimates on roads, it has a management file for forest roads called “Forest Bladed Road”. This file was used for the Control treatments.

For the Seed treatments, the initial conditions were set to the “Forest Bladed Road” and then “annual ryegrass at a medium fertilization rate” was used. In order to mimic the die off of the grass, the senescence parameters were altered. The percent growing season when leaf area index (LAI) declines was accepted at its default value of 85%, the period over which senescence occurs was accepted at the default of 14 days, the canopy remaining after senescence was changed to 50%, and the biomass remaining was also changed to 50%. The date of grass seed application was set to 5 days after construction.

Mulch treatment management files were created by using the file created for the Seed treatment and then adding a fescue residue as a mulch at a rate of 0.788 kg/m^2. This value equates to roughly 36.3 kg (80 lbs)/treatment which is the amount of straw mulch applied in the field portion of the study.

There are no management files within the WEPP – Forest Roads database that use woody debris as mulch. New files had to be created for both the Hardwood and Pine Slash treatments. Since there were no residue additions that resembled hardwood or pine slash, Slash treatments were modeled by applying fescue mulch. The Control management file was used as the base template and fescue mulch was applied. In RUSLE2 the coverage provided by the mulch could be used for application rate, however WEPP – Forest Roads does not give the user that option. In WEPP – Forest Roads the actual weight per unit area is used. The application rate actually applied to the Slash treatments in the field was used.

Data Analysis

Normal probability plots were examined for each model to see if predictions were normally distributed. Based on results, model predictions were determined not to be normally distributed, thus the data was transformed. A logarithm transformation was used to provide a normal distribution. All statistical analyses performed were based on the transformed data.

Each treatment was replicated six times for a total of thirty erosion model estimates. Treatment effects for each erosion model were determined by analyzing the model predictions in SAS v9.2 statistical software (SAS Institute 2008) as a Completely Randomized Design using the GLM procedure. Treatment effects were determined to be significant based on an alpha level of 0.05. If treatments were determined to be significantly different then a Tukey means separation test was used to examine treatment differences.

Erosion model estimates were also compared to field measured erosion rates to determine model accuracy and applicability. Linear regression analysis was used to compare erosion model estimates to the corresponding field measured erosion rates and model accuracy was determined through the linear regression diagnostic correlation coefficient, and the use of the Nash and Sutcliffe (1970) model efficiency (ME) statistic. Where ME was calculated as follows:

$$ME = 1 - \frac{\sum_{i=1}^{n}(Q_o i - Q_p i)^2}{\sum_{i=1}^{n}(Q_o i - \overline{Q}_o)^2}$$

Where $Q_o i$ = is the actual field measured erosion rate, $Q_p i$ = the erosion rate predicted by the erosion model, $_o$ is the mean of the field measured erosion rates, and n = the number of observations (30). This measure of efficiency is somewhat analogous to the correlation coefficient (r) from the linear regression, however it compares the measured values to the 1:1 line of measured equals predicted rather than to the best fit regression line. Therefore it not only considers the linearity of the data but also the relative differences between the measured and predicted values (Risse et al., 1993). A value of one indicates a perfect model, a value of zero indicates the model results are no better than the mean, and a negative value indicates that using the mean would be better than using model predictions.

Results and Discussion

Treatment Effects

The field based study found the Control treatment was the most erosive, while the Seed, Mulch, and Slash treatments provided significant erosion control (Table 1). Significant

Table 1. Average erosion estimates for each treatment collected by Dirtbags® and predicted by three soil erosion models. Treatment values within a column followed by the same letter are not significantly different at α = 0.05.

Treatment	Actual Sediment Weight Collected with Sediment Traps		USLE - Forest			RUSLE2			WEPP		
			Model estimates of erosion								
	Mg/ha/yr		tonnes/ha/yr	Ratio of Actual:Predicted		tonnes/ha/yr	Ratio of Actual:Predicted		tonnes/ha/yr	Ratio of Actual:Predicted	
Control	137.7	a	63.1	2.2x	a	148.4	0.9x	a	18.3	7.5x	a
Seed	31.5	b	44.9	0.7x	a	15.6	2.0x	b	12.0	2.6x	a
Hardwood Slash	8.9	bc	4.3	2.1x	b	17.5	0.5x	b	2.0	4.3x	b
Pine Slash	5.9	c	1.6	3.6x	c	15.5	0.4x	b	2.6	2.3x	b
Mulch	3.0	c	3.2	0.9x	b	3.8	0.8x	c	0.8	3.7x	c

treatment effects were found by all three erosion models. As expected, each model indicated that treatments that increase ground cover decrease soil erosion. For all models, the most erosive treatment was the Control treatment, followed generally by the Seed treatment, then the Slash and Mulch treatments. Depending on the erosion model, the Slash and Mulch treatments are juxtaposed with regard to effectiveness (Table 1).

USLE – Forest

The USLE – Forest predicted that the least effective treatment was the Control with an average erosion rate of 63.1 tonnes/ha/yr (28.0 tons/acre/yr), followed by the Seed treatment with an erosion rate of 44.9 tonnes/ha/yr (20.0 tons/acre/yr), then by the Hardwood Slash treatment at 4.3 tonnes/ha/yr (1.9 tons/acre/yr), then the Mulch treatment at 3.2 tonnes/ha/yr (1.4 tons/acre/yr), and finally the most effective treatment was the Pine Slash with an erosion rate of 1.6 tonnes/ha/yr (0.7 tons/acre/yr) (Table 1). Treatment differences were found (p value <0.0001) where the Control and Seed treatments were not significantly different; the Mulch treatment was significantly similar to the Hardwood Slash treatment and the Pine Slash treatment was not significantly similar to any other treatment (Table 1).

RUSLE2

RUSLE2 predicted that the least effective treatment was the Control with an average erosion rate of 148.4 tonnes/ha/yr (66.0 tons/acre/yr). The second least effective treatment was the Hardwood Slash with an erosion rate of 17.5 tonnes/ha/yr (7.8 tons/acre/yr). The Seed treatment was ranked next with a rate of 15.6 tonnes/ha/yr (6.9 tons/acre/yr), followed by the Pine Slash treatment with a rate of 15.5 tonnes/ha/yr (6.9 tons/acre/yr). The most effective treatment was the Mulch with an average rate of 3.8 tonnes/ha/yr (1.7 tons/acre/yr) (Table 1). Treatment differences existed (p value <0.0001) where the Hardwood Slash, Pine Slash, and Seed treatments were not significantly different from one another while the Control and Mulch treatments were not significantly similar to any other treatments (Table 1).

WEPP – Forest Roads

WEPP – Forest Roads predicted that the least effective treatment is the Control with an erosion rate of 18.3 tonnes/ha/yr (8.1 tons/acre/yr), followed by the Seed treatment at 12.0 tonnes/ha/yr (5.3 tons/acre/yr). The Pine Slash treatment at 2.6 tonnes/ha/yr (1.2 tons/acre/yr), then the Hardwood Slash treatment at 2.0 tonnes/ha/yr (0.9 tons/acre/yr), and finally the most effective treatment was the Mulch treatment at 0.8 tonnes/ha/yr (0.4 tons/acre/yr) (Table 1). The Pine Slash and Hardwood Slash treatments were not significantly different from one another and the Control and Seed treatments were significantly similar to one another. However, the Mulch treatment was not significantly similar to any other treatment (p value < 0.001) (Table 1).

Model Accuracy and Applicability

Erosion model estimates were transformed by taking the natural logarithm. These transformed data formed a significant linear relationship with the transformed actual erosion data. All three erosion models had correlation coefficients (r) above 0.85. The untransformed data was used to calculate the ME statistic and USLE – Forest, RUSLE2, and WEPP – Forest Roads had ME values of 0.55, 0.86, and -0.10 respectively (Figures 4-6), implying that USLE – Forest and RUSLE2 compared favorably with the actual erosion data and the WEPP – Forest Roads model was not predicting the actual data very well.

USLE – Forest had the weakest linear relationship with the collected sediment data; however, it performed similarly to RUSLE2. The estimated model is Y = 0.85 + (0.81 * X), where Y is the natural log of the actual field measured erosion rates and X is the natural log of the USLE – Forest estimates. This linear relationship had an R^2 of 0.7522 and an r of 0.8673 (Figure 4). RUSLE2 had the second best linear relationship when compared to the log

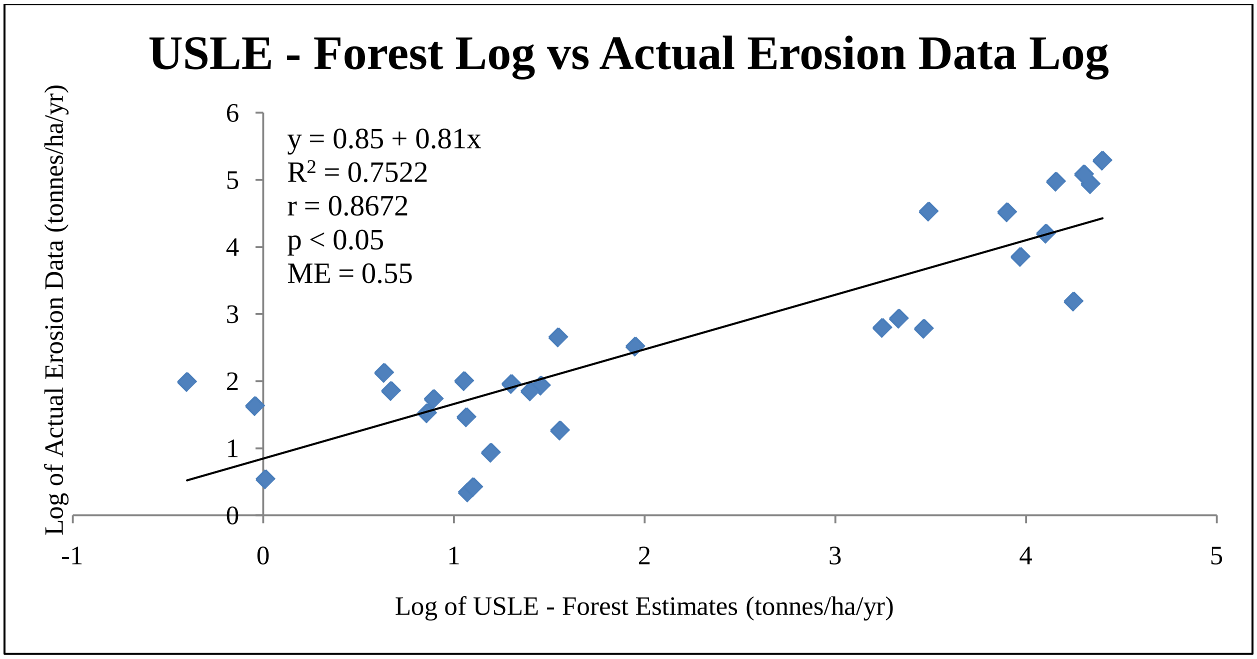

Figure 4. Linear relationship found between USLE – Forest estimates and the field measured erosion rates. In the reported equation Y represents the logarithm transformed field measured results and X represents the logarithm transformed USLE – Forest results.

transformed actual erosion data. The estimated model is Y = -0.53 + (1.07 * X), where Y is the natural log of the actual field measured erosion rates and X is the natural log of the RUSLE2 estimates. This linear relationship had an R^2 of 0.7963 and an r of 0.8924 (Figure 5). Overall

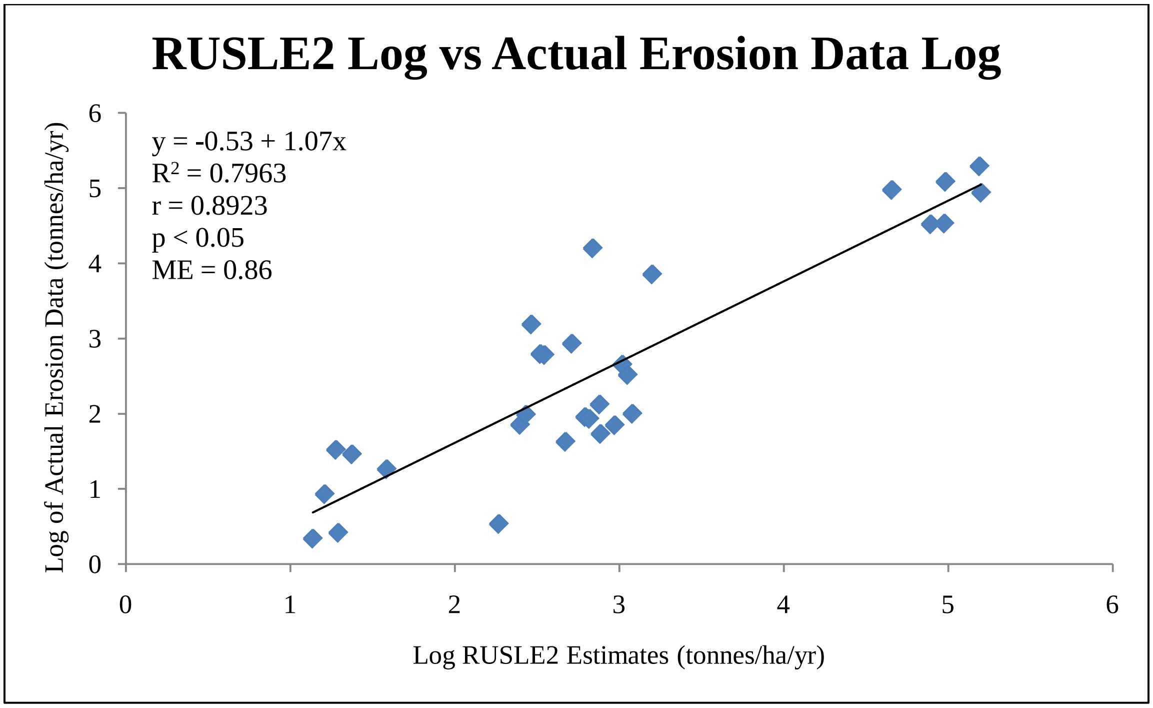

Figure 5. Linear relationship found between RUSLE2 estimates and the field measured erosion rates. In the reported equation Y represents the logarithm transformed field measured results and X represents the logarithm transformed RUSLE2 results.

WEPP – Forest Roads had the best linear relationship with an estimated linear model of Y = 1.12 + (1.10 * X), where Y is the natural log of the actual field measured erosion rates and X is the natural log of the WEPP – Forest Roads estimates. This linear relationship had an R^2 of 0.8342 and an r of 0.9134 (Figure 6).

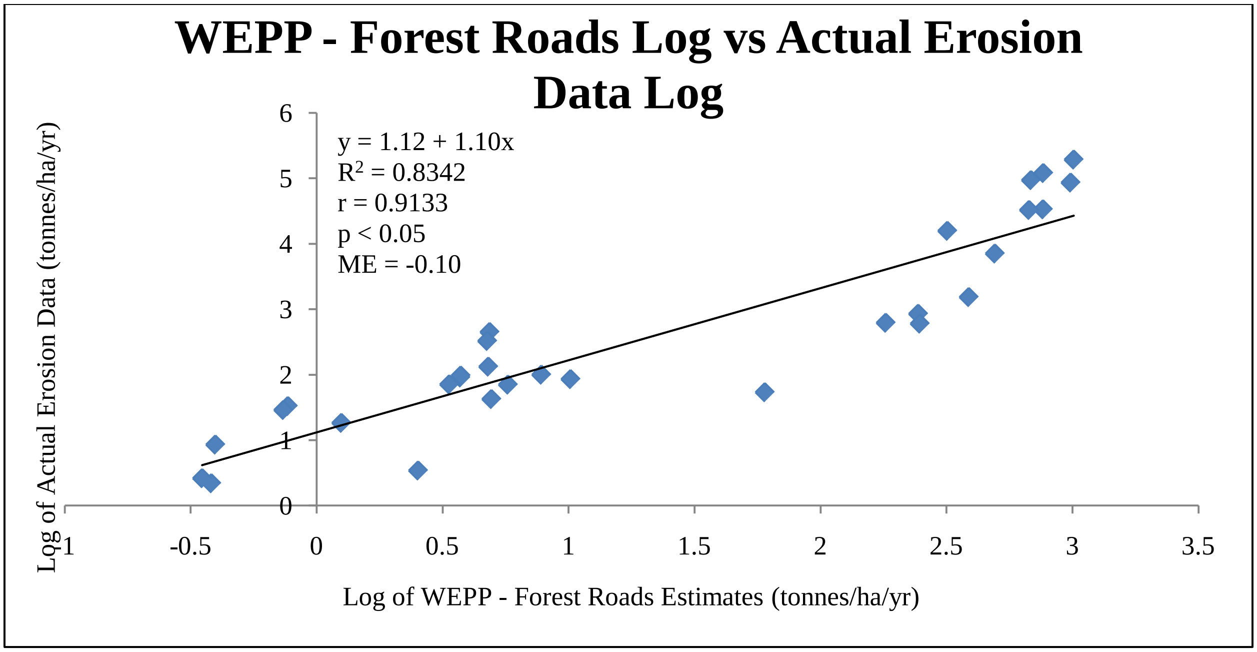

Figure 6. Linear relationship found between WEPP – Forest Roads estimates and the field measured erosion rates. In the reported equation Y represents the logarithm transformed field measured results and X represents the logarithm transformed WEPP – Forest Roads results.

Overall WEPP – Forest Roads had the worst ME statistic (-.10), followed by the USLE – Forest (0.55), and the RUSLE2 (0.86). WEPP – Forest Roads had the highest average magnitude of error at 30.3 tonnes/ha/yr, where magnitude of error is calculated as the absolute value of the difference between model predictions and field measured rates. When field measured erosion rates were high, as in the case of the Control treatments, WEPP – Forest Roads tended to under predict, with the most extreme magnitude of error being 177.6 tonnes/ha/yr (Figure 7). WEPP – Forest Roads was more accurate when field measured erosion rates were less, as in the case of the Slash and Mulch treatments, indicating that it is more suitable for these site conditions. If the ME statistic was calculated with the Control treatment data removed the ME increases to 0.77. Overall the USLE – Forest had an ME value of 0.55. Like WEPP – Forest Roads, the USLE – Forest was more accurate when field measured erosion rates were minimal. The USLE – Forest also tended to under predict when erosion rates where high, such as the case seen on the Control treatments, but not to the extent that WEPP – Forest Roads did (Figure 8). The most extreme difference in the model predictions and field results was 116.2 tonnes/ha/yr and the model had an average magnitude of error of 20.1 tonnes/ha/yr.

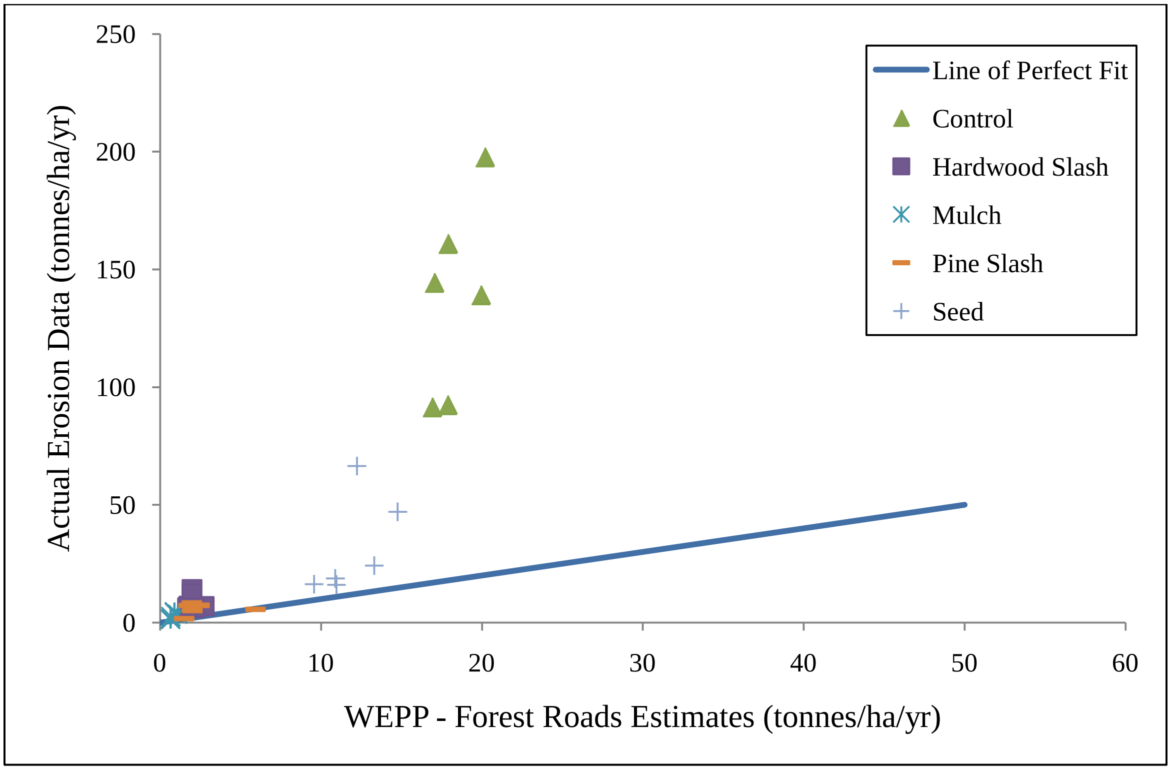

Figure 7. WEPP – Forest Roads estimates plotted against actual field measured erosion data.

RUSLE2 had the highest ME statistic, 0.86, indicating that the model predictions were the closest to the actual measured erosion. Overall RUSLE2 neither over nor under predicted erosion rates consistently. Like the other two models, the largest difference in model predictions compared to field measure rates was seen on the highly erosive treatments, Control, and the smallest difference was seen on treatments with minimal erosion, Slash and Mulch (Figure 9). Overall the average magnitude of error was 14.0 tonnes/ha/yr.

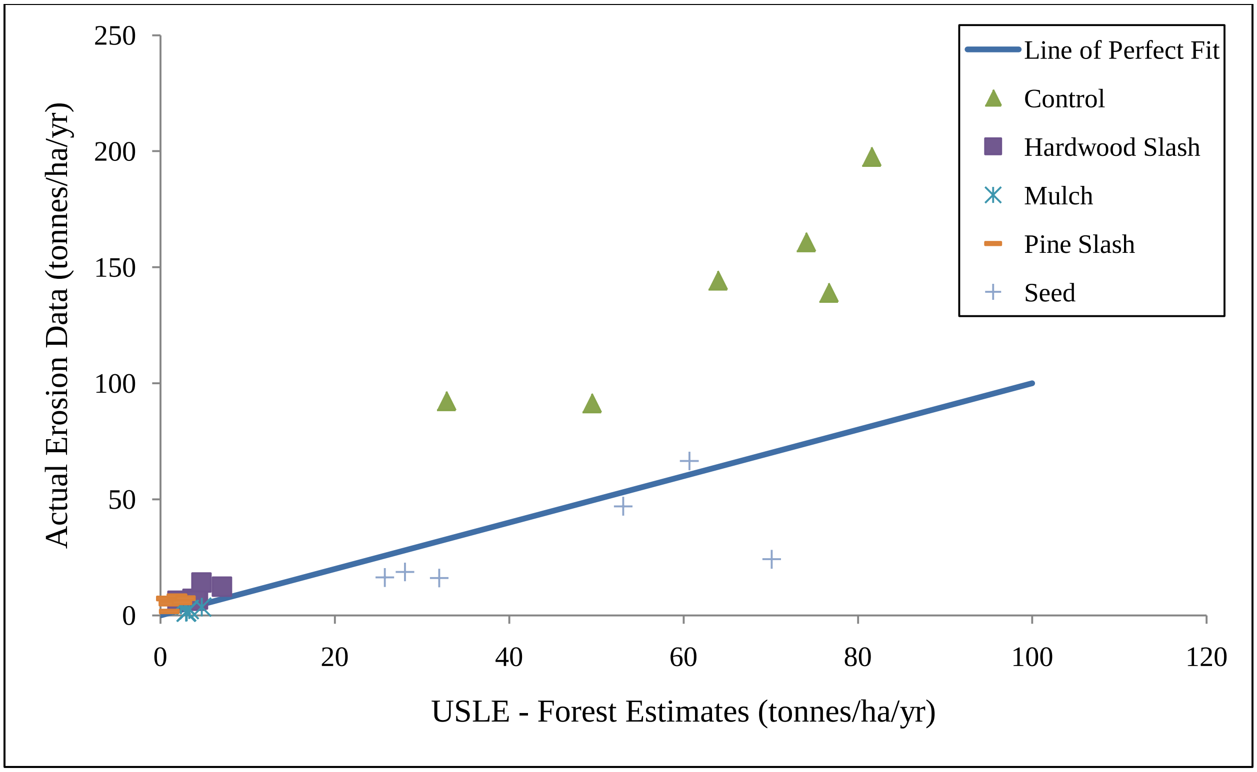

Figure 8. USLE – Forest estimates plotted against actual field measured erosion data.

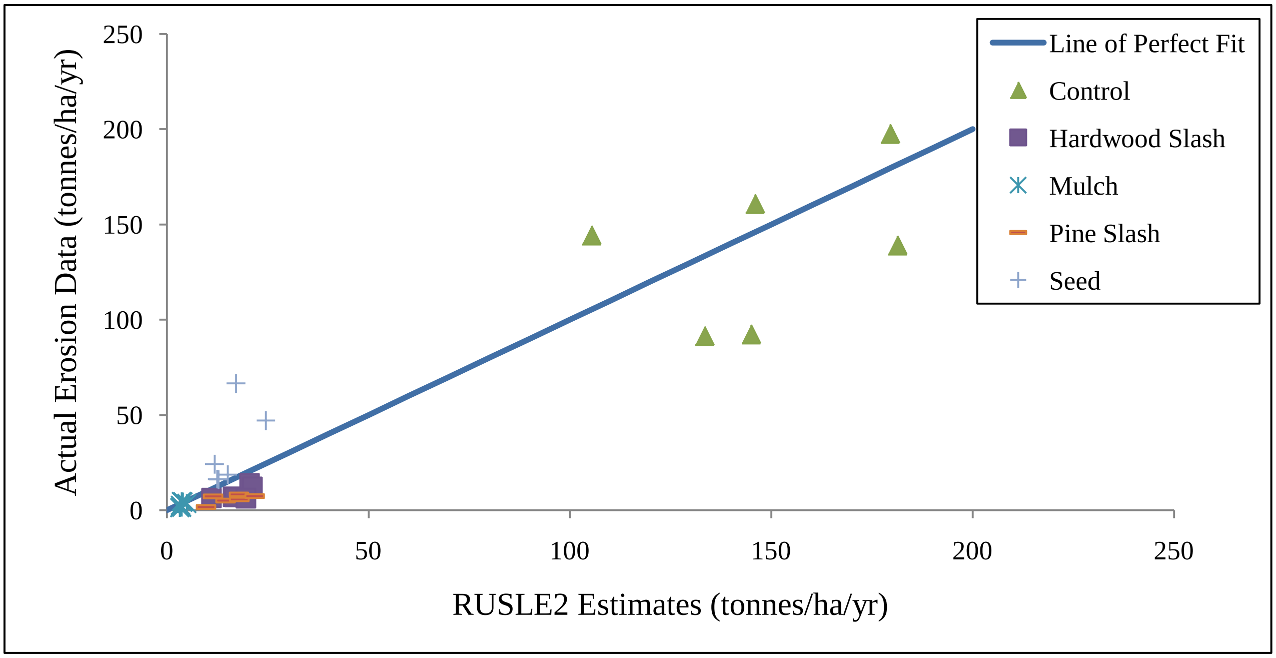

Figure 9. RUSLE2 estimates plotted against actual field measured erosion data.

These results are similar to what Tiwari et al. (2000) found comparing the same models. Models were evaluated based on data from 20 locations and more than 1,600 plot years of data. Results indicated that USLE performed the best, followed by RUSLE, and then WEPP – Forest Roads. WEPP – Forest Roads had an ME statistic of 0.71, which is much higher that what was found in this study, indicating that there was less variability in their dataset. Their dataset, however, was more applicable for use in USLE and RUSLE because these models used locally derived empirical erodibility parameters, while WEPP – Forest Roads calculated parameters based on soil properties. Also, this study evaluated sites that were primarily influenced by agricultural practices and also erosion rates were not as great, with the highest being 89 tonnes/ha. Grace (2005b) evaluated the performance of WEPP – Forest Roads on cut and fillslopes in the Southern Appalachian region. He found that WEPP – Forest Roads adequately described erosion across three levels of control, including a bare soil treatment and two vegetation treatments. Risse et al. (1993) evaluated USLE, using the same dataset used by Tiwari et al. (2000) and concluded that USLE performed adequately. They found that the model tended to over predict small values and under predict larger values, but on a consistent basis the model neither over predicted nor under predicted.

The USLE – Forest is a versatile erosion model, based on many types of sites. The model is simple to learn and apply with a relatively small learning curve. The USLE – Forest is especially useful for field work. Assessments of erosion can be made quickly and easily with little more than the USLE – Forest manual, while in WEPP – Forest Roads and RUSLE2 modeling computations are more easily facilitated by the use of computers. The model provides the contribution of each individual variable and their relative significance to erosion rates. It is easy to understand the importance of the factors for any given site and management.

However, there are some disadvantages to using the USLE – Forest. The model provides long term average annual erosion rates (tonnes/ha/yr or tons/acre/yr) and is not appropriate for shorter time periods nor does the USLE – Forest estimate sediment deposition. For a new user variable selection can seem very subjective with it being difficult to judge a precise disturbance, without taking detailed measurements.

Unlike the USLE – Forest, RUSLE2 does not require field measurements. RUSLE2 comes in a computer package and offers databases that allow the user to download a variety of climate and management files. RUSLE2 was originally developed for use on agricultural land and therefore many of the management files within the model are for cropland. However, the model allows the user to create management files for specific conditions that are not covered within the database. This allows the model to be applicable for a variety of land management regimes. Creating management files can be time consuming and tedious for one site, but a created file can be used easily in the future. There is also a database of climate and soil files for most of the U.S. RUSLE2 allows the use of multiple managements on each hillslope, allowing the land manager to examine the effects of combinations of management regimes, such as an SMZ below a clear cut harvest. Being a complex computer program, RUSLE2 allows the user to create a watershed containing multiple hillslopes. RUSLE2 will model the erosion from each hillslope and predict the erosion from the watershed. RUSLE2 will also estimate sediment deposition on concave slopes at dense vegetation strips, terrace channels, and in sediment basins which is a feature that the USLE – Forest cannot predict. RUSLE2 will also vary the rainfall and runoff factor (R) throughout the year. Monthly values can be viewed to see what times in the year are the most prone to erosion. For the USLE – Forest calculations, only one R value is used throughout the year. There is also less of a learning curve with RUSLE2. Today many land managers are computer literate and can easily learn the new software.

Since RUSLE2 is a computer based erosion model it is not as easy to apply in the field as USLE – Forest. Initially, there can be more time involved in RUSLE2 estimates relative to the USLE – Forest estimates due to the creation of management files, however once files have been created they can quickly and easily be used in the future. Site factor and management influence can be visualized with RUSLE2 through climate, soils, and management file selections but the effects are more obscure than with the USLE – Forest. The USLE – Forest has advantages for those who are learning about processes behind erosion while RUSLE2 assumes an understanding.

WEPP – Forest Roads is a computer based model, so it is more similar to RUSLE2 than to the USLE – Forest in the way that the user interacts with the model. Many of the same beneficial aspects of RUSLE2 are shared with WEPP – Forest Roads. WEPP – Forest Roads offers databases of management files, soil files, and climate files that cover a wide geographic area and encompasses many different management regimes. Since WEPP – Forest Roads was part of a USDA Forest Service collaboration it includes many management files that are specific to forest operations. Like RUSLE2, if a particular situation is not covered by a database management file, a new file can be created or existing files can be altered. Again, creating management files may initially be time consuming but once created, files can be rapidly used in the future. Soil files and climate files can also be altered. The soil file in this study was not altered but the climate file was. WEPP – Forest Roads also allows the use of multiple management conditions per hillslope. Unlike the USLE – Forest or RUSLE2, WEPP – Forest Roads provides monthly estimates of erosion. This is very beneficial from a planning standpoint.

It indicates times of the year when additional measures should be taken to reduce erosion. RUSLE2 also does this, but instead of showing monthly erosion rates it shows monthly rainfall and runoff factor (R) values. Similar to RUSLE2 but unlike the USLE – Forest, WEPP – Forest Roads can also estimate deposition on concave slopes.

Negative aspects of RUSLE2 are shared by WEPP – Forest Roads. Since WEPP – Forest Roads is computer based it is relatively difficult to use in the field. WEPP – Forest Roads may also be more time consuming than the USLE – Forest due to management file creation, however it requires no more time than RUSLE2. Like RUSLE2, the site characteristics that lead to erosion are more obscure in WEPP – Forest Roads than they are in the USLE – Forest.

Model accuracy can be evaluated in two general ways. First, the relationship of the actual erosion value to predicted value can be evaluated. Secondly, models could be evaluated based on how ranking of results would influence management decisions. WEPP – Forest Roads had the best overall linear relationship with field data (r = 0.9133) but the worst ME statistic (-0.10). This low ME was a result of the model drastically under predicting erosion rates on the Control treatment. This could be a result of WEPP – Forest Roads being prone to under estimating high values (Tiwari et al., 2000) or that the management file, “Forest Bladed Road”, used is not appropriate for bladed skid trails. When the data on the Control treatment was removed from the model efficiency calculation the ME statistic rose to 0.77, indicating that it is more accurate when erosion rates are less. USLE – Forest and RUSLE2 performed similarly to one another with RUSLE2 having a slightly better r value and a higher ME statistic. RUSLE2 was better able to predict values on the Control treatment indicating that it may be more suitable for bladed skid trails.

If the models are being used for management decisions, then all three models performed well. All models ranked the Control as the most erosive treatment which would not be suitable for many areas. All three models indicated that as cover increases on the bladed trail, erosion rates decreased. However, no model was able to correctly predict the order of effectiveness of treatments as determined by the field data.

Conclusions

Overall, significant treatment differences were identified by all of the erosion models. Each model showed that the water bar only Control treatment was the least effective erosion control technique and had unacceptably high erosion rates. It is important to note that the erosion rates reported here are not estimates of sediment delivery to waterways; however, high erosion rates increase the likelihood of sediment being transported to waterways. Results indicate that when water quality is a concern, skid trail closure operations should employ a technique that adds cover to bare soil. Water bars alone may not be adequate enough to prevent sediment from entering a waterway. If water bars are used without additional measures they should be spaced at the state BMP recommended spacing and should be designed to route the runoff over non road areas so as to filter out sediment before reaching a waterway.

Depending on the erosion model, the Seed treatment had varying degrees of effectiveness. Both the USLE – Forest and WEPP – Forest Roads had the Seed treatment as being the 4th most effective treatment while RUSLE2 had it as being the 2nd most effective. Overall, the Seed treatments were effective at reducing erosion when compared to the Control.

In general, the Slash and Mulch treatments were the most effective at reducing erosion. These treatments are most suitable in areas where water quality is of great concern and or erosion potential is high. The erosion control provided by the Slash and Mulch is immediate, occurring directly after application. The erosion control is also persistent, lasting several years.

Each erosion model performed well when compared to the erosion rates determined from field measurements. Linear relationships were fit to all erosion models and WEPP – Forest Roads performed the best with an R^2 of 0.8342 and an r of 0.9134, but had the worst ME statistic -0.10. RUSLE2, had an R^2 of 0.7963, an r of 0.8924 and the best ME statistic of 0.86. The USLE – Forest had an R^2 of 0.7522, an r of 0.8673 and a ME statistic of 0.55. Results show that all models over predicted at smaller values and under predicted at larger values, with WEPP – Forest Roads drastically under predicting the Control treatments. On sites with conditions similar to the Control treatment, WEPP – Forest Roads may not be the most suitable model. If it were to be used then the management file “Forest Bladed Road” may not be the most appropriate file to use, and a file more specific to bladed skid trails should be developed. If conditions similar to the Control are present then RUSLE2 would be a more appropriate model. RUSLE2 did not under predict the higher erosion rates as much as the other two models. All models seemed to predict lower erosion rates adequately. If field estimates were needed the USLE – Forest would be a better choice. The USLE – Forest is a very versatile model and works well over a wide geographic area, has been oriented to forest conditions, and it very easy to take into the field. The USLE – Forest had the weakest linear relationship but still had an r of 0.8876. The USLE – Forest is also a good teaching tool, illustrating the site characteristics that are most influential in the erosion process. The three models used to evaluate skid trail erosion appear to be useful for ranking BMP effectiveness, but should not be used for generating erosion estimates if the actual mass is necessary.

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Chapter 4. Conclusion

Study Objectives

The objectives of this study were to evaluate the performance of five closure and cover BMPs on the reduction of erosion on bladed skid trails, and to evaluate the accuracy and applicability of three erosion models by comparing model predictions to field measured erosion rates through linear regression. The BMPs evaluated were: 1) water bar only (Control); 2) water bar, and grass seed (Seed); 3) water bar, grass seed and straw mulch (Mulch); 4) water bar, and piled hardwood slash (Hardwood Slash); and 5) water bar, and piled pine slash (Pine Slash). The erosion models used were: 1) the Universal Soil Loss Equation for Forestry (USLE - Forest) (Dismeyer and Foster, 1984); 2) the Revised Universal Soil Loss Equation version 2 (RUSLE2); and 3) the Water Erosion Prediction Project for Forest Roads (WEPP – Forest Roads).

Objective 1

The field based portion of the study was conducted as a Randomized Complete Block Design with Repeated Measures. The data analyzed was the monthly Dirtbag® weight measurements and the repeated measure was time. The data was analyzed in SAS v9.2 statistical software (SAS Institute 2008) using the Proc GLIMMIX procedure. Treatment differences were determined by using a Tukey means separation test and were considered significant based on an alpha of 0.05.

Dirtbag® weight measurements were collected monthly over a thirteen month period, beginning in June of 2009 and concluding in July of 2010. Overall treatment effects were found as well as period treatment effects. Overall the Control treatment was the most erosive, with an average erosion rate of 137.7 tonnes/ha/yr (61.2 tons/acre/yr). The Seed treatment was the second most erosive, with overall average erosion rate of 31.5 tonnes/ha/yr (14.0 tons/acre/yr).

The Hardwood Slash treatment was the third most erosive treatment and had an overall erosion rate of 8.86 tonnes/ha/yr (3.94 tons/acre/yr). The Pine Slash was the fourth most erosive treatment with an overall erosion rate of 5.90 tonnes/ha/yr (2.62 tons/acre/yr). The Mulch treatment was the most effective and had an overall erosion rate of 2.98 tonnes/ha/yr (1.32 tons/acre/yr). Over the entire study period the Control treatment was found to be significantly different from all other treatments. The Seed treatment was significantly similar to the Hardwood Slash but different from the Control, Pine Slash, and Mulch treatments. The Hardwood Slash treatment was significantly similar to the Seed and Pine Slash but different from the Control, and Mulch treatments. The Pine Slash and Mulch treatments were significantly similar to one another but different from all other treatments.

Period treatment differences were seen during periods 1, 2, 5, 9, 10, 12, and 13. In periods 1 and 2 (May – June 11, 2009) the Control and Seed treatments were different from all others. In period 5 (September 15 – October 8, 2009), the Control and Seed treatments were similar to one another but different from all others. In periods 9 (January 15 – February 27, 2010), 10 (February 27 – March 31, 2010), 12 (April 28 – June 2, 2010), and 13 (June 2 – July 2, 2010) the Control treatment was different from all other treatments. These periods represented the time directly after skid trail installation, and periods that generally experience more intense rain events.

The Control treatment had high initial erosion rates at the onset of the study, with periods 1 and 2 (May – July 14, 2009) having rates of 26.0 tonnes/ha (11.5 tons/acre), and 24.7 tonnes/ha (11.0 tons/acre) respectively. Unconsolidated soil and high amounts of rainfall were the likely causes. From period 3 till period 8 (July 14, 2009 – January 15, 2010), erosion rates decreased and remained low. Over this time period the soil began to armor itself, natural vegetation started to establish on trails, and while rainfall amounts were still high these events likely were low intensity. From period 8 until the conclusion of the study (January 15 – July 2, 2010) erosion rates on the Control treatments began to increase. During the winter months high amounts of snowfall caused the soil to become saturated. In addition to the saturated soils, the soil particles became loosened and uncompacted due to the soil continually freezing and thawing. All these factors combined, resulted in soils that were highly erosive. Erosion rates dropped off in period 11 (March 31 – April 28, 2010) due to low amounts of rainfall, however they increased in periods 12 and 13 (April 28 – July 2, 2010). Periods 12 and 13 experienced more rainfall, 11.1 cm and 9.4 cm, and the rain events during this time of the year were likely more intense than the previous periods.

The Seed treatments were the second most erosive treatment evaluated, with an overall erosion rate of 31.5 tonnes/ha/yr (14.0 tons/acre/yr). They however reduced erosion by 77% when compared to the Control. Erosion rates were high at the beginning of the study but quickly decreased as the grass began to germinate and become established. Once grass became established erosion rates dropped to below 3 tonnes/ha and were less variable.

The Hardwood Slash and Pine Slash treatments acted similarly to one another, providing a 94% and 96% reduction in erosion when compared to the Control, respectively. They provided erosion control by protecting bare soil from the impact of rainfall and also slowing down overland flow causing an increase in the soil’s critical sheer stress as well as causing deposition of any suspended sediment that the overland flow may be transporting. Overall the Pine Slash treatment provided better ground cover than the Hardwood Slash. Pine slash is generally more brittle and can easily be broken down by equipment, giving better coverage. Hardwood slash is more flexible and is not easily broken down, causing gaps where bare soil is exposed. In this study natural vegetation became established in these gaps, reducing the amount of bare soil.

The Mulch treatment was the most effective treatment evaluated, with an average erosion rate of 3.0 tonnes/ha/yr (1.3 tons/acre/yr). Similar to the other treatments the Mulch treatment had a higher rate at the beginning of the study, yet this rate was below 1 tonnes/ha and then rates remained below 1 tonnes/ha for the duration of the study.

The Mulch treatment provided erosion control in two ways. First it helped to promote the establishment of grass by providing cover to the seed and helping increase the soil moisture. Grass on the Mulch treatments became established more quickly and was more persistent throughout the study. The straw mulch also helped reduce the velocity of overland flow decreasing the erosive force and causing deposition of suspended sediment.

Results show that while water bars provide a degree of erosion control, they alone may not be an appropriate closure technique in areas where water quality is of concern, such as stream crossings, or where the site conditions enhance the soils susceptibility to erosion, such as steep grades. The Control treatment was the most variable throughout the year. Rates were highest after skid trail construction and during spring months, and seemed to be highly influenced by climatic factors such as rainfall amount, rainfall intensity, and freeze thaw actions. In areas where water quality is of concern and on sites that are prone to erosion, closure techniques that enhance soil stability should be utilized, especially during the spring months and periods directly after soil disturbance.

Seed was shown to be an effective erosion control technique. However, the beneficial effects of grass seed are only seen once the seed has become established. On bladed skid trails, and other disturbed areas, it is often difficult to get grass to germinate. Soil amendments, such as lime and fertilizer, may be needed to help promote germination.

The erosion control provided by applications of straw mulch and slash are immediate, occurring directly after application. Straw mulch and slash provide erosion control by reducing rainfall impact and reducing the velocity of overland flow. In a silvicultural operation, slash in the form of tree tops is an easily accessible mulching agent. Depending on the type of operation and equipment available, application of slash may be more cost effective than applying straw mulch. Slash also limits vehicular access to closed trails, allowing trails to rehabilitate. On sites where both a supply of hardwood slash and pine slash are available pine slash may be preferable because it provides better coverage, and potentially will be more persistent over multiple years due to its slower decomposition rate, however there was no statistically significant difference seen between Hardwood Slash and Pine Slash treatments.

Slash may also be preferable over applications of grass seed and straw mulch due to the additions of nutrients overtime as the slash begins to decompose. Decomposing slash will also build up an organic A horizon on the trails which will increase infiltration rates and further provide erosion control. Slash is an easily applied mulching agent and will provide immediate cover and surface storage. Slash may also be preferable in areas, such as publicly managed forests, where use of exotic grass mixtures is unwanted due to biodiversity issues.

Objective 2

Model predictions were made for experimental unit for a total of 30 predictions per erosion model. After reviewing the normal probability plots of the model predictions it was determined that they did not fit a normal distribution. A logarithm transformation was applied and the data then better fit the normal distribution and all statistical analysis conducted used the transformed data. Treatment effects for each erosion model were determined by analyzing the model predictions in SAS v9.2 statistical software (SAS Institute 2008) as a Completely Randomized Design using the Proc GLM procedure. Treatment effects were determined to be significant based on an alpha level of 0.05. If treatments were determined to be significantly different then a Tukey means separation test was used to examine treatment differences.

Erosion model estimates were also compared to field measured erosion to determine model accuracy and applicability. Linear regression analysis was used to compare erosion model estimates to the corresponding field measured erosion rates. Model accuracy was based on linear regression diagnostics and a model efficiency (ME) statistic developed by Nash and Sutcliffe (1970).

The USLE – Forest predicted that the least effective treatment was the Control with an average erosion rate of 63.1 tonnes/ha/yr (28.0 tons/acre/yr), followed by the Seed treatment with an erosion rate of 44.9 tonnes/ha/yr (20.0 tons/acre/yr), then by the Hardwood Slash treatment at 4.3 tonnes/ha/yr (1.9 tons/acre/yr), then the Mulch treatment at 3.2 tonnes/ha/yr (1.4 tons/acre/yr), and finally the most effective treatment was the Pine Slash with an erosion rate of 1.6 tonnes/ha/yr (0.7 tons/acre/yr). The Control and Seed treatments were not significantly different; the Mulch treatment was significantly similar to the Hardwood Slash treatment and the Pine Slash treatment was not significantly similar to any other treatment.

RUSLE2 predicted that the least effective treatment was the Control with an average erosion rate of 148.4 tonnes/ha/yr (66.0 tons/acre/yr). The second least effective treatment was the Hardwood Slash with an erosion rate of 17.5 tonnes/ha/yr (7.8 tons/acre/yr), the Seed treatment was next with a rate of 15.6 tonnes/ha/yr (6.9 tons/acre/yr), followed by the Pine Slash treatment with a rate of 15.5 tonnes/ha/yr (6.9 tons/acre/yr) and finally the most effective treatment was the Mulch with an average rate of 3.8 tonnes/ha/yr (6.9 tons/acre/yr). The Hardwood Slash, Pine Slash, and Seed treatments were all significantly similar to one another while the Control and Mulch treatments were not significantly similar to any other treatments.

WEPP – Forest Roads predicted that the least effective treatment was the Control with an erosion rate of 18.3 tonnes/ha/yr (8.1 tons/acre/yr), followed by the Seed treatment at 12.0 tonnes/ha/yr (5.3 tons/acre/yr), then the Pine Slash treatment at 2.6 tonnes/ha/yr (1.2 tons/acre/yr), then the Hardwood Slash treatment at 2.0 tonnes/ha/yr (0.9 tons/acre/yr), and finally the most effective treatment was the Mulch treatment at 0.8 tonnes/ha/yr (0.4 tons/acre/yr). The Pine Slash and Hardwood Slash treatments were significantly similar to one another and the Control and Seed treatments were significantly similar to one another. However, the Mulch treatment was not significantly similar to any other treatment.

Linear regression diagnostics and the ME statistic was used to determine the accuracy of the models. Based on the regression diagnostics WEPP – Forest Roads was determined to have the best linear fit with an estimated model of $Y = 1.12 + (1.10 * X)$, where Y is the natural log of the actual field measured erosion rates and X is the natural log of the WEPP – Forest Roads estimates and an r of 0.9133. RUSLE2 had the second best linear fit with an estimated model of $Y = 0.53 + (1.07 * X)$, where Y is the natural log of the actual field measured erosion rates and X is the natural log of the RUSLE2 estimates, and an r of 0.8923. The USLE – Forest had the weakest linear fit with an estimated model of $Y = 0.85 + (0.81 * X)$, where Y is the natural log of the actual field measured erosion rates and X is the natural log of the USLE – Forest estimates, and an r of 0.8672.

Regression diagnostics indicated that WEPP – Forest Roads performed the best, followed by RUSLE2 which was only slightly better than USLE – Forest. WEPP – Forest Roads had the lowest ME statistic (-0.10) indicating that there were large differences in model predictions and actual erosion rates. RUSLE2 had the highest ME statistic (0.86), indicating that model predictions were closer to actual results. USLE – Forest had an ME statistic of 0.55, indicating that overall, model predictions were closer to actual erosion rates than WEPP – Forest Roads but not as close as RUSLE2.

The USLE – Forest is a widely used model and because it is based on such a large database it is useful over a wide spatial scale. The USLE – Forest is a very useful model to take into the field. Both RUSLE2 and WEPP – Forest Roads are computer programs and are difficult to make field estimates with. With the USLE – Forest, the contribution of each individual variable and their relative significance to erosion rates is easily seen. It is easy to understand the importance of the factors for any given site and management. RUSLE2 and WEPP – Forest Roads also have this capability, by manipulating input parameters, but it is more difficult to decipher. WEPP – Forest Roads and RUSLE2 were both easily learned and offered soil, climate, and management files that fit most sites and conditions. If, however, a site or condition was not covered in the provided databases, files could easily be manipulated to fit the needed site.

Results show that all models over predicted at smaller values and under predicted at larger values, with WEPP – Forest Roads drastically under predicting the Control treatments. On sites with conditions similar to the Control treatment, WEPP – Forest Roads may not be the most suitable model. If it were to be used then the management file "Forest Bladed Road" may not be the most appropriate file to use, and a file more specific to bladed skid trails should be developed. If conditions similar to the Control are present then RUSLE2 would be a more appropriate model. RUSLE2 did not under predict the higher erosion rates as much as the other two models. All models seemed to predict lower erosion rates adequately. If field estimates were needed the USLE – Forest would be a better choice. The USLE – Forest is a very versatile model and works well over a wide geographic area, has been oriented to forest conditions, and it very easy to take into the field. The USLE – Forest had the weakest linear relationship but still had an r of 0.8876. The USLE – Forest is also a good teaching tool, illustrating the site characteristics that are most influential in the erosion process.

Literature Cited

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