JASON MATTHEW WARD
Sediment Trapping within Streamside Management Zones on Two Clearcut Sites in the Georgia Piedmont
(Under the Direction of DR. C. RHETT JACKSON)

A study was conducted to evaluate the effectiveness of streamside management zones (SMZs) for reducing sediment transport from concentrated flow swales draining two clearcut timber harvesting sites in the Georgia Piedmont. Both clearcuts had undergone mechanical and chemical site preparation as well as planting. Silt fences were used to trap sediment transport from zero-order ephemeral swales at the edge of SMZs. Five control swales and nine treatment swales were studied, but one control swale was removed from the analysis. A double mass curve approach was used to graphically compare sediment accumulation rates at the edge of SMZs to accumulation rates within the SMZs at a distance consistent with current recommendations for SMZ width in Georgia. SMZ efficiencies ranged from 27% to 99%. No statistical model was found to explain SMZ efficiencies based on SMZ and contributing area characteristics. The Revised Universal Soil Loss Equation (RUSLE) was used to predict sheet and rill erosion for specific rain events on the study sites and a delivery ratio of 0.25 was calculated. SMZs had a quantifiable ameliorating effect on sediment transport from concentrated flow swales on our clearcut study sites.

INDEX WORDS: Streamside Management Zone, Best Management Practices, BMP Effectiveness, Sediment Transport, Erosion, Forest Hydrology

SEDIMENT TRAPPING WITHIN STREAMSIDE MANAGEMENT ZONES ON TWO CLEARCUT SITES IN THE GEORGIA PIEDMONT

by

JASON MATTHEW WARD

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DEDICATION

This thesis is dedicated to the memory of my grandfather, John D. Ward, who showed me at a very young age that adversity is no reason to give up.

ACKNOWLEDGEMENTS

I thank my major professor, Rhett Jackson, for his straightforwardness and encouragement on this project. I am also very grateful to the other members of my committee, Todd Rasmussen and Larry Morris for their advice and guidance. For help with fieldwork, I want to thank Herwig Goldemund, Stephanie Hyder, Kirk Martin, Kevin Mullinax, Lane Rivenbark, and Jim White. I thank Amy Parker for her encouragement and her bluegrass music in the lab. I also thank Martha Campbell and others working in the Phillips Lab for help with the particle size distribution analysis. For supporting me and assuring me that I can accomplish anything that I put my mind to, I would like to thank my parents, Donna Davenport and Gary Ward, my sister and brother, Christy and Mark, and my grandmother, Myrtle (Nanna) Ward. Lastly, I thank the Lord for providing the rainfall that allowed me to complete this project.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Nonpoint source (NPS) pollution from rural and urban areas is considered one of the most significant water quality problems facing the world today. NPS pollution, including sediment, nutrients, and pathogens, originates and is transported in a diffuse manner from hillslopes by overland flow (Dillaha and Inamdar, 1997). The U.S. Environmental Protection Agency (USEPA) has reported that approximately 40% of U.S. rivers, lakes and estuaries do not meet minimum water quality requirements. Nationally, silvicultural activities account for 1% of the severely impaired and 9% of the overall impaired river and stream miles (USEPA, 1995). Agriculture and other landuses account for the balance of the NPS pollution problem in the nation. Sediment is the most important water quality problem and the largest contributor by volume to NPS pollution in the U.S. (Neary et al., 1988). The process of sedimentation occurs when interstitial spaces in the gravel and cobble substrates of streams are filled by sediment deposition. Sedimentation reduces the quality of available habitat for benthic macroinvertebrates and fish species and can result in a loss of bio-diversity and biomass in aquatic ecosystems (Waters, 1995).

Sediment is also the primary pollutant of concern from silvicultural operations. Historically, cotton farming in the Georgia Piedmont caused a large amount of erosion and sediment loading to streams from the 1830s to the 1930s (Trimble, 1974). USEPA and the forest industry have adopted the concept of best management practices (BMPs) to reduce NPS pollution from silvicultural activities. BMPs are defined as methods, measures, practices, and techniques designed to maintain water quality within forested watersheds (Aust et al., 1996). Riparian forest buffers or streamside management zones (SMZs) are specific BMPs for reducing nonpoint source pollution from silvicultural activities (Georgia Forestry Commission, 1999).

Increasing concern over NPS pollution has generated a need for assessments of the relative impact of silvicultural activities when compared to agriculture and urban NPS pollutant loadings (Ice et al., 1997). Previous studies have not adequately quantified the effectiveness of SMZs for ameliorating the water quality impacts of silvicultural operations. The main objective of this study was to assess the effectiveness SMZs in reducing hillslope sediment transport from silvicultural activities in the Georgia Piedmont. Our approach was to quantify the amount of hillslope sediment transport occurring on a typical and severe clearcut in the Piedmont and to quantify the sediment removal efficiencies of the SMZ. We also wanted to develop a model that predicted SMZ efficiency on our study sites. Lastly, we wanted to compare measured sediment transport data to predicted erosion rates using the Revised Universal Soil Loss Equation (RUSLE) and develop a delivery ratio for RUSLE predictions.

Commercial forestland comprises sixty-four percent of the total land use in Georgia (Georgia Forestry Commission, 1999). Despite evidence showing that forestry has relatively minor contributions to nonpoint source pollution (EPA 1995), the widespread scale of forestry operations in Georgia makes even minor contributions substantial in calculations of cumulative nonpoint source loadings. Historically, the Georgia Piedmont has shown high levels of NPS pollution from poor agricultural practices (Trimble, 1974). The erodibility of Piedmont soils has contributed to the development of extensive rill and gully networks (Van Lear et al., 1985). When intense site preparation techniques are used in the Piedmont physiographic region, sediment production rates can reach levels as high 99 Mg/ha/yr (44 tons/acre/yr) (Dissmeyer and Stump, 1978). When slash is left dispersed on site and exposure of mineral soil is minimized, sediment flux can be reduced to 0.15 Mg/ha/yr (0.07 tons/ac/yr) (Van Lear et al., 1985). This example illustrates how varying management practices can substantially affect the level of nonpoint source pollution from silvicultural operations.

Public awareness of the potential impacts of silvicultural activities on water quality and the upgrading of water quality standards by state regulatory agencies have contributed to the widespread use of BMPs as a means of reducing NPS pollution from silvicultural activities. The primary silvicultural operations that potentially affect water quality are timber harvesting, site preparation, and reforestation. These operations can expose mineral soil and provide preferential pathways for overland flow and sediment transport. Excessive erosion due to silvicultural activities can alter forest productivity, contribute to stream eutrophication, affect aquatic biota and cause deterioration of drinking water supplies (Lynch et al., 1985). As a result, NPS pollution has become a primary concern for forest managers in recent years.

Section 303(d) of the Clean Water Act (CWA) (40 CFR 130.7) requires states to determine what NPS pollution sources are preventing stream segments from meeting water quality standards for their established beneficial uses (Ice et al., 1997). In Georgia, lawsuits by public interest groups have resulted in court orders that require the development of total maximum daily loads (TMDLs) for watersheds in the Piedmont (Sierra Club vs. John Hankinson, 1996). TMDLs are attempts to quantify the maximum amount of pollutant that can be assimilated by a receiving stream without impairing the beneficial use of the stream. The CWA defines beneficial uses as drinking, swimming, and fishing. The TMDL development process has generated a need for assessments of the relative impact of silvicultural activities when compared to agriculture and urban NPS pollutant loadings (Ice et al., 1997). Sediment is the primary pollutant of concern resulting from silvicultural activities. Previous studies have not adequately quantified the effectiveness of SMZs for ameliorating the water quality impacts of silvicultural operations. The filtering efficiency of SMZs must be quantified to estimate overall NPS loading from forestry. Forestry practices may become more closely regulated if studies are not done that provide quantifiable verification that current BMPs are adequate to maintain water quality.

BMPs have been developed to minimize the potential for concentrated overland flow and sediment transport from silvicultural operations. Upland BMPs include contour plowing and water diversion structures along timber harvesting roads that disperse runoff more evenly on hillslopes and prevent channelization of overland flow. Streamside management zones, a specific type of BMP, are buffer strips of planted or indigenous vegetation adjacent to perennial streams, intermittent streams, or lakes that are managed to protect water quality. Vegetation in SMZs provide: 1) shading that buffers water temperature, 2) woody debris that is important for aquatic ecosystems, 3) natural filtration of sediment and other pollutants, 4) denitrification of shallow groundwater, 5) travel corridors and habitat for wildlife, 6) stream bank stability, and 7) some dissipation of flow velocities during flooding periods (Georgia Forestry Commission, 1999). The process of sediment removal in the SMZ is poorly understood and there is no standard or accepted method for buffer zone design (O'Laughlin and Belt, 1995). Consequently, SMZ requirements, such as width and stocking densities, are typically established by political acceptability rather than scientific merit (Dillaha and Inamdar, 1997). Several factors that influence SMZ effectiveness include size and slope of the buffer, resistance to flow, infiltration capacity, and the ability of the soil to hold moisture (Phillips, 1989). SMZs slow delivery of runoff from storms by maintaining an intact litter layer, which provides a slower and more tortuous path for flow than does exposed mineral soil (Hewlett, 1982). In Georgia, SMZ width recommendations vary with the type of stream and the slope of the stream bank. Special consideration should be used on unstable or erosive soils and when litter cover is minimal. SMZs have a limited sediment filtering capacity and cannot correct severe erosion problems caused by poor upslope practices (Georgia Forestry Commission, 1999). Upslope BMPs are designed to minimize the channelization of overland flow prior to entry into the SMZ. SMZs are not effective at trapping sediment from channelized flow because the flow path is shortened through the

SMZ as rills are formed, and there is less time for deposition of sediment (O'Laughlin and Belt, 1995).

Studies of BMP effectiveness have generally used a paired or multiple watershed approach to allow for treatment in one or more experimental watersheds and a control watershed with no treatment (Lynch and Corbett, 1990; Keim and Schoenholtz, 1999, Arthur et al., 1998, Ruhlman, 1999). Lynch and Corbett (1990), after collecting 15 years of water quality and quantity data for a clearcut and an uncut control watershed in the Ridge and Valley province of Pennsylvania, concluded that BMPs were effective at controlling in-stream turbidity and stream temperature increases following a clearcut timber harvest. They attributed much of the turbidity increase in the clearcut watershed to exposure of mineral soil by windthrow of trees near an unbuffered intermittent stream. Buffering intermittent stream channels would have further reduced sediment production from the clearcut watershed (Lynch and Corbett, 1990). A similar study, conducted in the Cumberland Plateau province of eastern Kentucky, found no significant increase in stream temperature following a clearcut when BMPs were used (Arthur et al., 1998). Suspended sediment flux was 14-fold and 30-fold greater on the BMP and Non-BMP watersheds, respectively, than on the uncut watershed. This difference in sediment flux was reduced to 4-fold and 6.5-fold greater than the uncut watershed 17 months after harvest. Sediment fluxes in the clearcut watersheds were driven by a small number of high flow events, suggesting discrete rather than continuous sources of sediment. The SMZ was effective at reducing the temporary effects of clearcutting on sediment flux (Arthur et al., 1998). The paired watershed approach used in this study, however, did not allow for direct measurement of sediment transport attenuation within the SMZ. The paired watershed approach generally employs in-stream monitoring of bedload and suspended sediment load which can be affected by in-channel sediment storage and scour.

Keim and Schoenholtz (1999) conducted a multiple watershed study in the highly erodible Deep Loess region of Mississippi. In this study, SMZs were not effective in filtering sediment from overland flow, but they did reduce in-stream total suspended solids (TSS) due to exclusion of disturbance to the forest floor near streams. Mechanized skidder traffic in the watersheds without SMZs increased exposure of mineral soil by 140% to 200% of the exposure in watersheds with intact, undisturbed SMZs. Understory herbaceous vegetation grew rapidly after clearcutting and actually reduced mineral soil exposure to levels lower than that of the undisturbed control watershed within three years (Keim and Schoenholtz, 1999). This rapid regeneration of understory herbaceous vegetation creates a more tortuous path for overland flow, stabilizes the soil within the SMZ, and reduces the availability of source material for erosion. Channelization of overland flow through the SMZ significantly reduces the filtering effects of riparian vegetation (Keim and Schoenholtz, 1999). This study highlights the importance of preserving an intact litter layer within riparian forest buffers to reduce sediment inputs to receiving streams.

Few studies have looked at BMP effectiveness in the Piedmont physiographic region of the southeastern U.S. Some forest managers in the Piedmont use mechanical site preparation techniques such as bedding and subsoiling that increase the exposure of mineral soil. Ruhlman (1999) conducted a paired watershed BMP effectiveness study near the Coastal Plain/Piedmont interface in Georgia. The study consisted of a 315.7–hectare (780-acre) treatment watershed and a 142-hectare (351-acre) uncut reference watershed. In the treatment watershed, a 24.4-meter (80-foot) SMZ was retained along perennial and intermittent streams and mechanical site preparation techniques were used. Sediment delivery to streams was minimized by applying a system of BMPs that included road and stream-crossing stabilization, plowing on the contour, and exclusion of mechanical operations within ephemeral areas and SMZs. Monthly chemical monitoring for sediment and nutrients yielded no significant difference between the treatment and reference watersheds for most water quality parameters. Suspended sediment and turbidity remained low for the treatment stream and the reference stream. The study concluded that SMZs used in association with intensive forest management activities provided adequate control of NPS pollution from silvicultural activities (Ruhlman, 1999). This study involved monthly monitoring of total suspended solids in the water column, which is not adequate to quantify total sediment transport due to the sporadic nature of storm events and overland flow in the Piedmont. Sediment transport is often driven by a small number of high flow events (Arthur et al., 1998), therefore, storm sampling is a more effective method of estimating overall sediment transport in the Piedmont. Hillslope methods, such as the ones used by Dissmeyer (1982), offer clear advantages for direct measurement of sediment attenuation within SMZs.

Most BMP effectiveness studies have focused on in-stream sediment loads, bedload and TSS. The literature contains little data quantifying the rates of sediment transport and delivery between the erosional and depositional parts of managed forest landscapes. Sediment availability is often restricted to loose material that remains on the ground surface after disturbance. The magnitude of sediment storage in erosion control structures and on adjacent hillslopes has important implications for determining the rates of overland sediment transport and for the evaluation of forest harvesting practices on in-stream water quality (Croke et al., 1999). Research suggests that the sediment filtering capacity of SMZs depends on the extent to which an intact litter layer is left adjacent to steams (Keim and Schoenholtz, 1999). The major sediment removal mechanisms associated with SMZs include changes in flow hydraulics which enhance the opportunity for infiltration of runoff, and filtration and deposition of sediment by vegetation. For these mechanisms to be effective, surface runoff must pass slowly through the SMZ, allowing sufficient contact time for the removal mechanisms to function properly (Dillaha and Inamdar, 1997).

Previous studies of riparian buffer effectiveness have shown relatively high trapping efficiencies for sediment transport. During rainfall simulations in Iowa, Lee et al. (2000) found that a riparian buffers with herbaceous and woody vegetation trapped 93% of sand and silt particles and 52% of clay-sized particles. In Australia, Lacey (2000) found that 10-meter undisturbed buffers frequently reduced runoff by at least 90% and sediment yield was reduced usually between 98% and 99%. Undisturbed riparian buffers reduced sediment yields from approximately 100 Mg/ha/yr to less than 0.5 Mg/ha/yr (Lacey, 2000). Thus, most studies conclude that high sediment trapping efficiencies are possible if channelized flow is prevented within the riparian areas (NCASI, 2000).

Several models have been used to predict erosion in agricultural and silvicultural settings including WEPP (Loch et al., 1999; Nearing et al., 1989), CREAMS (Flanagan et al., 1989), and the Universal Soil Loss Equation (USLE) (Dissmeyer and Stump, 1978). The USLE, developed by Wischmeier and Smith (1978), quantifies soil erosion as the product of six factors which represent rainfall and runoff erosivity, soil erodibility, slope length, slope steepness, cover-management practices, and support conservation practices (Renard et. al., 1997). The USLE was originally developed for agricultural applications, but it has been modified to better predict sheet and rill erosion on forestland. Dissmeyer and Foster (1980) modified the C factor with a series of subfactors that are appropriate for forestland management scenarios. The revised version of the USLE, RUSLE, includes unit energy equations that allow calculation of rainfall erosivity for individual rain events (Renard et. al., 1997). USLE and RUSLE are more accurate at predicting long-term erosion rates because the R factor can vary considerably for different rain events, but cover factors can also vary more on timber harvesting sites as regeneration occurs (Dissmeyer and Foster, 1980).

For RUSLE modeling, erosion is defined as the amount of soil delivered to the point on a hillslope where either deposition begins or where overland flow becomes concentrated (Renard et. al., 1997). Not all of the sediment that is moved during and following a rain event by sheet and interill erosion reaches the toe of a hillslope. Some sediment is stored on hillslope in depressional areas. The delivery ratio is the ratio between the amount of sediment that is moved on a hillslope by sheet and rill erosion to the total amount of sediment that is delivered to the toe of the hillslope. Sun and McNulty (1998) calculated delivery ratios of 0.15 and 0.36 for silvicultural areas with well managed logging roads and poorly managed roads, respectively. Delivery ratios in forestry environments remain poorly quantified (Croke et al., 1999).

CHAPTER 2

SEDIMENT TRAPPING WITHIN STREAMSIDE MANAGEMENT ZONES ON TWO CLEARCUT SITES IN THE GEORGIA PIEDMONT [1]

[1] Ward, J. M. and C. R. Jackson. To be submitted to the Southern Journal of Applied Forestry

Abstract. A study was conducted to evaluate the effectiveness of streamside management zones (SMZs) for reducing sediment transport from concentrated flow swales draining two clearcut timber harvesting sites in the Georgia Piedmont. Both clearcuts had undergone mechanical and chemical site preparation as well as planting. Silt fences were used to trap sediment transport from zero-order ephemeral swales at the edge of SMZs. Five control swales and nine treatment swales were studied, but one control swale was removed from the analysis. A double mass curve approach was used to graphically compare sediment accumulation rates at the edge of SMZs to accumulation rates within the SMZs at a distance consistent with current recommendations for SMZ width in Georgia. SMZ efficiencies ranged from 27% to 99%. No statistical model was found to explain SMZ efficiencies based on SMZ and contributing area characteristics. The Revised Universal Soil Loss Equation (RUSLE) was used to predict sheet and rill erosion for specific rain events on the study sites and a delivery ratio of 0.25 was calculated. SMZs had a quantifiable ameliorating effect on sediment transport from concentrated flow swales on our clearcut study sites.

KEY TERMS: Streamside Management Zone, Best Management Practices, BMP Effectiveness, Sediment Transport, Erosion, Forest Hydrology

INTRODUCTION

Nonpoint source (NPS) pollution from rural and urban areas is considered one of the most significant water quality problems facing the world today. NPS pollution, including sediment, nutrients, and pathogens, originates and is transported in a diffuse manner from hillslopes by overland flow (Dillaha and Inamdar, 1997). The U.S. Environmental Protection Agency (USEPA) has reported that approximately 40% of U.S. rivers, lakes and estuaries do not meet minimum water quality requirements (USEPA, 1995). Silvicultural activities account for only 1% of the severely impaired and 9% of the overall impaired river and stream miles across the nation (USEPA, 1995). Agriculture and other landuses account for the balance of the NPS pollution problem in the nation (USEPA, 1995). Sediment is the most important water quality problem and the largest contributor by volume to NPS pollution in the U.S. (Neary et al., 1988). USEPA and the forest industry have adopted a system of best management practices (BMPs) to reduce NPS pollution from silvicultural activities. BMPs are defined as methods, measures, practices, and techniques designed to maintain water quality within forested watersheds (Aust et al., 1996). Streamside management zones, a specific type of BMP, are buffer strips of planted or indigenous vegetation adjacent to perennial streams, intermittent streams, or lakes that are managed to protect water quality. The sediment filtering efficiency of SMZs must be quantified to estimate overall NPS loading from forestry. Forestry practices may become more closely regulated if studies are not done that provide quantifiable verification that current BMPs are adequate to maintain water quality.

The main objective of this study was to assess the effectiveness SMZs in reducing hillslope sediment transport from silvicultural activities in the Georgia Piedmont. Our approach was to quantify the amount of hillslope sediment transport occurring on a typical and severe clearcut in the Piedmont and to quantify the sediment removal efficiencies of the SMZ. We also wanted to develop a model that predicted the sediment filtering efficiencies of the SMZs on our study sites. Lastly, we wanted to compare measured sediment transport data to predicted erosion rates using the Revised Universal Soil Loss Equation (RUSLE) and develop a delivery ratio for RUSLE predictions.

The Georgia Piedmont has shown historically high levels of NPS pollution from poor agricultural practices (Trimble, 1974). The erodibility of Piedmont soils has contributed to the development of extensive rill and gully networks which can serve as sources and pathways for sediment transport following land disturbance (Van Lear et al., 1985). When intense site preparation techniques are used in the Piedmont physiographic region, sediment production rates can reach levels as high 99 Mg/ha/yr (44 tons/acre/yr) (Dissmeyer and Stump, 1978). When slash is left dispersed on site and exposure of mineral soil is minimized, sediment flux can be reduced to 0.15 Mg/ha/yr (0.07 tons/ac/yr) (Van Lear et al., 1985). This example illustrates how varying management practices can substantially affect the level of nonpoint source pollution from silvicultural operations.

In addition to filtering sediment and other pollutants, SMZs have other beneficial functions. Vegetation in SMZs provide: 1) shading that buffers water temperature, 2) woody debris that is important for aquatic ecosystems, 3) travel corridors and habitat for wildlife, 4) stream bank stability, and 5) some dissipation of water velocities during flooding periods (Georgia Forestry Commission, 1999). The process of sediment removal in the SMZ is poorly understood and there is no standard or accepted method for buffer zone design (O'Laughlin and Belt, 1995). Consequently, SMZ requirements, such as width and stocking densities, are typically established by political acceptability rather than scientific merit (Dillaha and Inamdar, 1997). Several factors are known to influence SMZ effectiveness including size and slope of the buffer, resistance to flow, infiltration capacity, and the ability of the soil to hold moisture (Phillips, 1989). SMZs slow delivery of runoff from storms by maintaining the forest floor litter layer, which provides a slower and more tortuous path for flow than does exposed mineral soil (Hewlett, 1982). SMZs are not extremely effective at trapping sediment from channelized flow because the flow path is shortened through the SMZ as rills are formed, and there is less time for deposition of sediment (O'Laughlin and Belt, 1995). In Georgia, SMZ width recommendations vary with the type of stream and the slope of the stream bank. SMZs have a limited sediment filtering capacity and cannot correct severe erosion problems caused by poor upslope practices (Georgia Forestry Commission, 1999).

Previous studies of riparian buffer effectiveness have shown relatively high trapping efficiencies for sediment transport. During rainfall simulations in Iowa, Lee et al. (2000) found that a riparian buffers with herbaceous and woody vegetation trapped 93% of sand and silt particles and 52% of clay size particles. In Australia, Lacey (2000) found that 10-meter undisturbed buffers frequently reduced runoff by at least 90% and sediment yield was reduced usually between 98% and 99%. Undisturbed riparian buffers reduced sediment yields from approximately 100 Mg/ha to less than 0.5 Mg/ha (Lacey, 2000). Most studies conclude that high sediment trapping efficiencies are possible if channelized flow is prevented within the riparian areas (NCASI, 2000).

Erosion modeling can be an important tool for land managers to plan BMP systems prior to timber harvests. The Universal Soil Loss Equation (USLE) was originally developed for agricultural applications (Wischmeier and Smith, 1978), but it has been modified to better predict sheet and rill erosion on forestland. Dissmeyer and Foster (1980) modified the C factor with a series of subfactors that are appropriate for forestland management scenarios. The revised version of the USLE, RUSLE, includes unit energy equations that allow calculation of rainfall erosivity for individual rain events (Renard et. al., 1997). Delivery ratios relate the total predicted rill and interill erosion on a hillslope to the amount delivered to the toe of the slope. Sun and McNulty (1998) calculated delivery ratios of 0.15 and 0.36 for scenarios with well managed logging roads and poorly managed roads, respectively. Delivery ratios in forestry environments remain poorly quantified (Croke et al., 1999).

MATERIALS AND METHODS

Study Design

This study involved measuring hillslope sediment transport from zero-order swales on clearcut industrial timberland in the Georgia Piedmont. Zero-order swales are unchanneled ephemeral areas or gullies that only generate overland flow during and immediately following rain events. We used a passive sediment trapping technique, specifically silt fencing, to measure hillslope sediment transport (Dissmeyer, 1982). We placed the sediment traps at points where sediment was entering the SMZ from upslope contributing areas. There were two distinct phases in the experimental period of observation. During Phase I, the sediment trap was inset into the SMZ a distance consistent with the current BMP guidelines for SMZ width in Georgia (Figure 1). Therefore, Phase I constitutes a treatment representing the filtering capacity of the SMZ. In the control swales, we placed the sediment traps at the upper edge of the SMZ. During Phase II, we moved the treatment silt fences to the upper edge of the SMZ where there was no SMZ treatment effect. The sediment traps in the control swales remained in place (Figure 2). In essence, we compared sediment production, with and without SMZ treatment, to sediment production in control swales.

Site Selection

This study was conducted on two recently harvested industrial timberland tracts in the Georgia Piedmont. Our study sites did not represent a statistically significant sample of all clearcut timber harvesting sites in the Georgia Piedmont. Instead, the sites represented severe and average levels of sediment transport on clearcut timber harvests as determined by a reconnaissance of 30 clearcut timber harvests in the Piedmont. A student in the Warnell School of Forest Resources at the University of Georgia conducted the reconnaissance project which characterized the perimeter of all SMZs on 30 clearcut timber harvesting sites in the Georgia Piedmont and classified instances of sediment transport into the SMZs. Each study site was then classified based on the average slope of the swales on the site, the frequency of sediment transport through the SMZ, and site preparation techniques employed. "Break through" points were frequently associated with areas of up slope convergence. These areas of convergence are often the initial sediment sources for nonpoint source pollution that originates on silvicultural lands (Bren, 2000).

We selected swales with contributing area sizes of 2.02-hectares (5-acres) or less because larger areas would have produced too much overland flow and sediment for us to accurately measure with the silt fence technique. For the moderate site, average slopes are slightly less than on the severe case, and plowing down the contour was avoided in all swales. For the severe case, intense site preparation techniques were used, including sub-soiling and plowing off the contour, in some locations.

The first study site, the OD-Moore tract, was a 99.5-hectare (246-acre) industrial timberland tract in Taliaferro County, near Sharon, Georgia (Figure 3). The soils on the site are in the Cataula, Helena, and Sedgefield series which are found in the lower Piedmont of Georgia. One control swale and three treatment swales were located at the OD-Moore site. The study swale slopes ranged from 8 to 20%. Litter coverage averaged 65%. Clearcut timber harvesting was completed in April 1999. The SMZs were 21.5-hectares (53.1-acres) in total size and the SMZ perimeter was 6.6 km (4.1-miles). All SMZs along perennial streams were at least as wide as what is recommended by the Georgia Forestry Commission. Following harvest, the site lay fallow for a year until chemical site preparation was done in April 2000 with 5.6 kg/ha (5 lbs./acre) of Velpar®ULW. Site preparation was completed in July 2000 with a Savannah Forestry Equipment 3-in-1 plow®. All plowing was done along the contour in accordance with Georgia BMP recommendations. The site was hand planted in February 2001 at a 1.83 m x 1.83 m (6 ft. x 10 ft.) spacing resulting in 294 trees/hectare (726 trees/acre). A banded herbicide application was done in May 2001 with 47.9 mL/ha (4 oz./acre) of Arsenal® and 24 mL/ha (2 oz./acre) of Oust®.

The second study site, the BMC Ruark tract, was a 118.2-hectare (292-acre) industrial timberland tract in Greene County, near Woodville, Georgia (Figure 4). The soils on the site consist of sandy loams and sandy clay loams in the Cecil series, which is typical of soils in the central Piedmont of Georgia. There were four control swales and six treatment swales at the BMC Ruark site. The study swale slopes ranged from 6 to 18%. Litter coverage averaged 67%. Clearcut timber harvesting was completed in September 1998. The SMZs were 25.6-hectares (63.2-acres) in total size and the SMZ perimeter was 8.21 km (5.89-miles). All residual SMZ widths were equal to, or exceeded, those recommended by the Georgia Forestry Commission. Chemical site preparation was done in April 1999 with 6.73 kg/ha (6 lbs./acre) of Velpar®ULW. In July 1999, site preparation was completed when the site was raked and then ripped with a Savannah Forestry Equipment 3-in-1 plow®. Plowing was done along the contour is most areas, but some plowing off the contour occurred in the contributing area for RT1. The site was hand planted in January 2000 at a 1.83 m x 1.83 m (6 ft. x 10 ft.) spacing resulting in 294 trees/ha (726 trees/acre). In March 2000, 35.9 mL/ha (3oz./acre) of Oust® was applied for herbaceous weed control.

Field measurements

To capture sediment transport from the study swales, we installed Georgia Department of Transportation (GADOT) approved silt fencing in an arc shaped pattern. The silt fence fabric had a pore size of 0.5 mm. Each sediment trap was wide enough to capture and filter all of the overland flow entering the SMZ at the base of the swale. We then installed a 0.5-meter grid system of erosion/deposition yellow poplar dowels in the upslope settling area that resulted from the backwatering effects of the fence. Initially, we measured the height from the mineral soil to the top of each dowel. After each subsequent rain event exceeding 1.27-centimeters (0.5 in.) of cumulative precipitation, we measured the height above the ground surface to the top of the dowels in millimeters.

Given a consistent grid spacing, we then physically integrated the accumulation depth across the grid area to give a volume of sediment accumulation for each rain event.

The control swales were instrumented with a sediment trap at the upslope edge of the SMZ to capture sediment as it enters from the swale (Figure 1). This sediment trap remained stationary for the duration of the experiment. This control allowed us to account for trends in the background sediment transport rates of the site due to factors such as natural regeneration and depletion of the sediment source. For the treatment swales, we first installed the sediment trap within the existing SMZ a distance from the SMZ edge that was consistent with the current BMP guidelines for Georgia (Figure 1). For example, if the slope entering the SMZ was 7%, the BMP guidelines recommend that a 40-foot wide SMZ should be used (Georgia Forestry Commission, 1999). A silt fence would then be placed 12.2-meters (40 feet) into the existing SMZ to simulate a receiving stream. We then allowed 2 rain events to occur prior to monitoring to allow time for settling of backfill material within the grid area. Next, we measured sediment accumulation at all treatment and control swales for four rain events exceeding 1.27 cm (0.5 in.) of cumulative precipitation. Then, we installed new sediment traps at the edge of the SMZ in all treatment swales (Figure 2). The control sediment traps remained in their original location. After another initial settling period, we measured sediment accumulation for four more rain events exceeding 1.27 cm (0.5 in.) of cumulative precipitation.

To assist in the grid system of measurement of sediment accumulation, we applied a layer of feldspar powder in the grid area to serve as a marker horizon in a manner similar to Cohoon and Turner (1989). This would allow us to take cores of the sediment accumulation in the grid area to verify our measurements of total sediment accumulation. We installed an Onset® RG2 tipping-bucket rain gage at each site to record rainfall intensity and duration data. In addition, we used traditional rain gages as a backup for cumulative precipitation measurements following rain events.

Bulk density and particle size distribution was measured within each swale to quantify the weight of sediment transported by overland flow. We collected three random soil cores with a 59.5 cm^3 ring from the accumulated sediment in each swale to measure bulk density using the core method (Blake and Hartge, 1986). The results from the bulk density analysis are summarized in Table 1. The mesh size of the silt fence material was larger than the clay size fraction, so we needed to estimate the amount of clay associated with the sand and silt trapped by the silt fences. In order to characterize the particle size distribution, we collected 30 randomly distributed composite samples with a probe soil sampler from the top 7.5 cm (3 in.) of soil within each swale. Separate composite samples were taken from concentrated flow areas and from bare areas that had not been actively eroded. All samples were analyzed for particle size distribution using the hydrometer method (Day, 1965), and the results are summarized in Table 2 and Table 3.

At the points where overland flow entered the SMZ from the study swales, we measured several vegetative and physical parameters. The slope and width of the SMZs were measured with a Suunto® clinometer and Keason® fiberglass tape and are summarized in Table 4. To give a measure of the degree of overland flow channelization, we also measured the active width where overland flow entered into the grid area (Table 4). Where the flow was channelized within the SMZ, we measured vegetation parameters in the flow areas. When sheet flow occurred within the SMZ, we sampled at a random lateral distance within the width of the silt fence. We categorized ground cover and woody stem density at ¼, ½, and ¾ depths into the SMZ. To classify ground cover, we used a rigid 1-m^2 aluminum frame with criss-crossing aluminum wire that was spaced in 10 cm increments (Alberty, 1993). This provided 100 ground cover sampling points for each frame, which we then classified as bare soil, leaf litter, vegetation, or sticks. We measured woody stem density in a 3 m by 3 m area and included every woody stem greater than 0.318 cm (1/8 in.) in diameter. Halfway into the

SMZ, we also measured basal area (m^2/ha) and canopy cover percentage. Basal area was measured using a 10-factor prism point sample and percent canopy cover was measured with a concave spherical densiometer (Table 5).

We also measured physical characteristics of the contributing areas for the study swales. We measured the contributing area slopes using a Suunto® clinometer. A Trimble GeoExplorer® 3 GPS unit was used to delineate and map the contributing area swales and points of entry into the SMZ. We delineated the hydrologic contributing areas based on field observations of preferential flow paths on the hillslope. We also delineated the areas within each swale that were actively eroding to the base of the swale. Bedding from site preparation activities changed the microtopography on the contributing areas, altered the flow paths for rill and interill erosion, and made delineation difficult in some areas. Table 6 summarizes the physical characteristics of the contributing areas at OD-Moore and BMC Ruark.

Erosion Modeling

The Revised Universal Soil Loss Equation (RUSLE) was used to estimate hillslope sediment transport from each contributing area on the two study sites. The model uses a rainfall erosivity factor (R), soil erodibility factor (K), slope length and steepness factor (LS), cover management factor (C), and a support practices factor (P) to calculate average annual soil loss (A, Mg/ha/yr (tons/ac/yr)). The RUSLE equation is:

$$A = R*K*LS*C*P \qquad \textbf{(1)}$$

The RUSLE factors were evaluated for each study swale. We calculated R using tipping bucket rain gage data following the methods used by Renard et. al. (1997). The maximum thirty-minute intensity (cm/hr) for each rain event was determined graphically from tipping bucket rain gage data and multiplied by the total energy for each rain event to give EI. The unit energy equation for RUSLE was updated by McGregor et. al. (1995) for northern Mississippi, and we used this equation because it is appropriate for the Georgia Piedmont as well (G. Foster pers. comm., 2001). The tipping bucket rain gage was not launched properly during Phase II of experimentation, so no rainfall intensity or duration data were recorded. Therefore, we could only complete RUSLE modeling for Phase I. We obtained K factors for the contributing areas from Natural Resource Conservation Service (NRCS) soil maps for Greene and Taliaferro counties in Georgia (NRCS, 1983 and NRCS, In prog.). We calculated the LS and C factors using the approach suggested by Renard et. al. (1997). The P factor was one for the study sites because the contour plowing during site preparation activities was accounted for in the contour tillage subfactor of C (Renard et al., 1997).

Data Analysis

Sediment transport following each rain event was calculated by measuring the height from mineral soil to the top of each dowel and then subtracting that value from the previous reading on the dowel. This depth of accumulation or scour was then multiplied by the 50 cm x 50 cm area that the dowel represented in the measurement grid to calculate a volume of accumulation. We then summed all the volumes for each dowel within the grid area to give a total volume of sand and silt transported for the rain event. Finally, we multiplied the total volume by the mean bulk density of the accumulated sediment to calculate a total mass. Next, we divided the total mass by the percent of sand plus silt from the particle size distribution analysis in the contributing area. This corrected for clay that was not trapped by the silt fence. We then divided the total mass (Mg) by the hydrologic contributing area of the swale (ha). This gave a measurement of the total amount of eroded sediment for the rain event in Mg/ha.

A double mass curve approach was used to compare the relative sediment accumulation rates during Phase I and Phase II. This approach is commonly used in hydrology to correct precipitation data when a rain gage is moved or when there are gaps in precipitation data (McCuen, 1998). For each treatment swale, the sediment accumulation for each rain event was added to all previous events and then plotted against a running sum of accumulations in the control swales on the study site.

Occasionally, measurements were not recorded in some swales because scour from overland flow had undercut the silt fences and reduced trapping efficiency. We calculated double mass curves for each treatment swale on the two study sites. We also calculated cumulative double mass curves for each study site during the period of observation. These plots reflect the total sediment accumulation at all the treatment swales verses the total accumulation within the control swales at OD-Moore and BMC Ruark for each rain event.

We calculated ratios of treatment swale accumulations to control swale average accumulations for all rain events during Phase I and Phase II. We grouped the ratios together for both study sites to form Phase I and Phase II ratio groups. We then used a t-test and a Mann-Whitney rank sum test to compare the two populations (Phase I and Phase II). We also graphed a vertical scatter plots of the ratios during Phase I and Phase II and compared the means and standard deviations of the two populations.

No measurements were taken in some treatment swales due to scour or filling of the silt fence with sediment after rain events. When this occurred, we used an average of the remaining swale accumulations to add into the double mass curve calculations. The differences in sediment accumulation rates during Phase I and Phase II can be attributed to attenuation within the SMZ during the period of observation. The controls accounted for the magnitude of background changes in sediment inputs compared to the change due to the attenuation within the SMZ.

SMZ trapping efficiency for each treatment swale was calculated using the following equation:

$$SMZ_{efficiency} = \frac{\frac{PhaseII}{Control_2} - \frac{PhaseI}{Control_1}}{\frac{PhaseII}{Control_2}} \qquad \textbf{(2)}$$

Where :

Phase I = sediment accumulation with the SMZ buffer effect

Phase II = sediment accumulation without the SMZ buffer effect

Control $_1$ = total sediment accumulation at control swales during Phase I

Control $_2$ = total sediment accumulation at control swales during Phase II

We used forward stepwise multiple regression to determine if a combination of SMZ and contributing area characteristics adequately predicted SMZ efficiency. The following parameters were evaluated for use in the model:

1. Basal Area
2. Percent canopy cover
3. SMZ slope
4. Contributing area slope
5. Mean woody stem density within the SMZ
6. % Bare ground within SMZ
7. Residual (left after harvest) SMZ width
8. Flow width within the SMZ
9. Flow width entering into SMZ
10. Contributing area slope / SMZ slope
11. Contributing area size
12. Contributing area size / mean active flow width

Parameters with the highest F-statistic were retained in the model and those that did not contribute to the model were removed.

RUSLE model predictions for sediment production for each storm event were compared to measured sediment delivery at the toe slope of the study swales. Since RUSLE modeling was only completed for Phase I of the experiment, the measured accumulations in the treatment swales were not used for model comparison because they included the buffering effects of the SMZs. We plotted measured sediment delivery against predicted sheet and rill erosion for each control swale and rain event during Phase I. Then, we used simple linear regression and the corresponding correlation coefficient to evaluate the effectiveness of RUSLE for predicting sediment transport on the study sites. To calculate a sediment delivery ratio, we summed the total measured sediment accumulation for all the study control swales during Phase I and divided by the total predicted sheet and rill erosion for all rain events during Phase I.

RESULTS AND DISCUSSION

In December 2000, we installed prototype sediment traps on a treatment and control swale to evaluate the strengths and weaknesses of our methods. The silt fence trapping technique was very successful. The dowels remained in place and vertical despite overland flow and sediment washing into the grid areas. It was important to provide time for the backfill material to settle after installation of the silt fences to measure sediment accumulation reliably. The feldspar powder was washed to the edge of the silt fence by overland flow after the first rain event and did not maintain a noticeable horizon in the grid area. Therefore, we discontinued use of the feldspar powder in our experimentation.

Phase I began on January 18, 2001 at OD-Moore and on January 5, 2001 at BMC Ruark. Table 7 and Table 8 summarize the rain events during Phase I and the corresponding sediment accumulations that were measured in each swale. Phase I concluded on March 16, 2001. Then, we installed new silt fences at the edge of the SMZ on the treatment swales and Phase II began on April 1, 2001. Table 9 and Table 10 list the rain events during Phase II and the corresponding sediment accumulations measured at each swale.

The double mass curve approach worked well for comparing the sediment accumulation rates in the treatment swales to the control swales during Phase I and Phase II. Most treatment swales showed an upward shift in sediment production from Phase I to Phase II (Fig 5 – Figure 13). These shifts in accumulation rates in the double mass curves illustrate the buffering effect of the SMZ for trapping sediment transport in the treatment swales. At the OD-Moore site, ODT1 and ODT3 had linear patterns of sediment accumulation relative to the control swale during Phase I and Phase II and showed significant increases in sediment production during Phase II. The contributing area for ODT2 was a small planar slope and there was no significant sediment transport in the contributing area during this study. The cumulative double mass curve for the OD-Moore site shows a clear upward shift in sediment production between Phase I and Phase II (Figure 14). For BMC Ruark, RT1, RT2, RT3 and RT6 don't show distinctive upward shifts in sediment production between Phase I and Phase II and the calculated SMZ efficiencies are all less than 60% (Table 11). RT1 delivered the most sediment of any study swale during the experiment at 26.4 Mg/ha (11.76 tons/ac), and the SMZ had a 57% removal efficiency (Table 11). Site preparation plowing was downslope in a portion of the contributing area at RT1, and this led to preferential flow paths down slope and the formation of deeply incised rills and gullies on the hillslope. RT4 showed no measured sediment transport during Phase I and significantly more accumulation during Phase II resulting in a 99% trapping efficiency. This is because the SMZ was effectively filtering all sediment during Phase I. RT6 showed no shift between Phase I and Phase II. RT6 also had one of the largest contributing areas (Table 6) and the silt fence was topped with flow and sediment for at least one rain event during Phase I and Phase II. There was a large amount of scour in RC2 on 6/9/01 (Table 10). This scour outweighed the accumulations in the other control swales and lead to a negative contribution in the double mass curve for Phase II. We decided to eliminate RC2 from our analysis for both Phase I and Phase II. The cumulative double mass curve at BMC Ruark does not show a distinctive shift in sediment production between Phase I and Phase II (Figure 15).

The ratios between sediment accumulations in the treatment swales and average control accumulations failed to have a normal distribution, so a t-test proved to be inappropriate for our analysis. A nonparametric Mann-Whitney rank sum test yielded a p-value of 0.657, which does not suggest a statistically significant difference between the ratios during Phase I and Phase II. Figure 16 shows an increase in standard deviation between Phase I and Phase II. There is also seems to be a slight increase in the mean of the ratios, but the standard deviations of Phase I and Phase II are too large to provide statistical significance.

SMZ efficiencies ranged from 27% to 99% for the treatment swales (Table 11). RT4 had the highest efficiency at 99%. During Phase I, all of the measurable sediment transport at RT4 was captured by the SMZ. Phase II measurements showed significant amounts of sediment entering into the SMZ from the contributing area at RT4. RT2 had the lowest efficiency at 27%. Site preparation bedding was done along the contour in accordance with Georgia BMP recommendations, but the contributing area for RT2 included a logging road that added enough channelized overland flow to break through the bedding and form deep rills and gullies. RT6 had a low SMZ efficiency as well due to a large convergent slope in the contributing area and high levels of total sediment transport.

Forward stepwise multiple regression yielded no significant results in our attempts to build a model that predicted SMZ efficiency. No single variable or combination of variables provided a statistically significant explanation of the variance in SMZ efficiency. Our analysis was hampered due to multicollinearity between independent variables and a small data set. The logistical constraints of sampling hillslope sediment transport after natural rain events in the field prevented us from increasing the sampling size for this study. If we had used automated data collection techniques, we would have been able to increase our sample size.

RUSLE modeling was used on both sites during Phase I. The tipping bucket rain gages collected data at BMC Ruark and OD-Moore from February 18, 2001 top April 18, 2001 (Figures 17 and Figure 18). The R factors for each rain event are listed in Table 12 and Table 13 for OD Moore and BMC Ruark, respectively. The other RUSLE parameters (K, LS, and C) for each swale are summarized in Table 14. Predicted erosion amounts during Phase I for OD-Moore and BMC Ruark are summarized in Table 15 and Table 16.

A plot of predicted sheet and rill erosion verses measured sediment accumulation (Figure 19) shows a correlation coefficient of 0.24 and a p-value equal to 0.001. We conclude from this that RUSLE predictions and measured accumulations were positively correlated. The delivery ratio for Phase I was 0.25.

CONCLUSIONS

Using the double mass curve analysis, most treatment swales demonstrated an upward shift in sediment transport during Phase II of our experiment. The SMZs had a quantifiable ameliorating effect on sediment transport following timber harvest on our study sites. SMZ efficiencies ranged from 27% to 99% for the treatment swales (Table 11). The average SMZ efficiency at OD-Moore was 94% and the average SMZ efficiency at BMC Ruark was 59%. Given the degree of channelization that we observed in the contributing areas, the SMZs worked well to filter and trap sediment from overland flow. We were unable to generate a model that explained the variation in SMZ efficiencies. RUSLE modeling showed that a positive correlation existed between predicted and measured sediment flux within the study swales. The correlation coefficient for the period of observation, 0.24, is relatively low. This suggests that RUSLE was not accurate at predicting sediment transport rates for individual rain events at our study sites. More field scale experimentation is needed to better assess the predictive abilities of RUSLE for forestry operations in the Georgia Piedmont.

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Table 1. Bulk density of accumulated sediment in the grid area of the study swales at OD-Moore and BMC-Ruark.

Swale	Bulk Density	
	Mean	Standard deviation
	(g/cm^3)	
ODC	1.43	0.04
ODT1	1.29	0.14
ODT2	1.43	0.09
ODT3	1.51	0.06
RC1	1.55	0.13
RC2	1.45	0.12
RC4	1.50	0.06
RC5	1.28	0.12
RT1	1.60	0.08
RT2	1.49	0.18
RT3	1.67	0.25
RT4	1.65	0.11
RT5	1.33	0.10
RT6	1.39	0.07

Table 2. Particle size distribution in the bare ground portions of the contributing areas at OD-Moore and BMC Ruark.

Swale	sand	silt	clay
		(%)	
ODC	46.4	25	28.6
ODT1	61.4	17.5	21.1
ODT2	68.9	15	16.1
ODT3	61.4	20	18.6
RC1	58.9	17.5	23.6
RC2	53.9	17.5	28.6
RC4	53.9	20	26.1
RC5	53.9	22.5	23.6
RT1	48.9	22.5	28.6
RT2	68.9	12.5	18.6
RT3	66.4	17.5	16.1
RT4	61.4	20	18.6
RT5	71.4	15	13.6
RT6	63.9	20	16.1

Table 3. Particle size distribution of the overland flow areas within the contributing areas at OD-Moore and BMC Ruark.

Swale	Sand	Silt	Clay
		(%)	
ODC	56.4	22.5	21.1
ODT1	53.9	22.5	23.6
ODT2	58.9	22.5	18.6
ODT3	71.4	15	13.6
RC1	61.4	17.5	21.1
RC2	43.9	17.5	38.6
RC4	66.4	17.5	16.1
RC5	58.9	20	21.1
RT1	66.4	15	18.6
RT2	48.9	17.5	33.6
RT3	66.4	15	18.6
RT4	66.4	15	18.6
RT5	58.9	20	21.1
RT6	58.9	20	21.1

Table 4. Physical characteristics of the SMZ at OD-Moore and BMC Ruark.

Swale	Active flow width Phase I	Active flow width Phase II	SMZ Width	SMZ Slope
		(meters)		(%)
ODC	n/a	2.3	28.1	4
ODT1	1.3	0.8	29.0	8
ODT2	0.7	0.5	30.5	8
ODT3	1.5	0.5	29.6	16
RC1	n/a	2.5	25.5	8
RC2	n/a	1.4	27.0	22
RC4	n/a	2.9	23.3	8
RC5	n/a	1.1	34.9	14
RT1	5.8	4.3	36.6	4
RT2	0.7	0.5	37.0	19
RT3	0.8	0.6	40.3	11
RT4	0.5	3.9	23.8	4
RT5	3.5	2.4	23.2	7
RT6	2.6	1.7	38.7	10

Table 5. Characteristics of SMZ Vegetation at OD-Moore and BMC Ruark.

Swale	Canopy Cover	Basal Area	Mean WSD	Mean Litter Cover Classifications Bare	Leaf Litter	Vegetation	Sticks
	(%)	(m^2/ha)	(#)	(%)			
ODC	93	21	26	18	62	13	6
ODT1	97	16	30	29	56	11	6
ODT2	88	28	16	13	43	7	8
ODT3	95	5	23	10	59	7	6
RC1	94	30	7	2	59	10	6
RC2	80	25	4	8	66	15	5
RC4	98	7	26	14	63	15	9
RC5	26	7	10	7	72	7	13
RT1	83	5	9	11	69	8	13
RT2	97	16	21	0	62	19	9
RT3	95	30	14	16	53	38	4
RT4	99	18	47	18	37	59	3
RT5	94	14	23	19	16	79	4
RT6	100	18	13	27	28	58	6

Table 6. Physical characteristics of the study swale contributing areas at OD-Moore and BMC Ruark.

Swale	Contributing Area, (CA) Hydrologic	Eroding	CA Slope
	(hectares)		(%)
ODC	2.0	0.9	8
ODT1	1.1	0.1	14
ODT2	0.3	0.2	8
ODT3	0.3	0.1	20
RC1	0.5	0.5	6
RC2	0.1	0.1	18
RC4	0.6	0.3	10
RC5	0.2	0.2	14
RT1	0.8	0.7	12
RT2	0.1	0.1	15
RT3	0.9	0.4	9
RT4	2.0	0.8	15
RT5	0.5	0.4	12
RT6	2.0	2.0	6

Table 7. Measured sediment transport at OD-Moore during Phase I.

Date	Cumulative Precipitation	Swale sediment accumulation			
		ODC	ODT1	ODT2	ODT3
	(cm)	(Mg/ha)			
2/20/01	3.40	-0.002	0.016	0.083	0.090
2/24/01	3.30	0.002	-0.014	-0.067	0.054
3/6/01	4.70	0.038	0.020	0.062	0.193
3/13/01	2.92	0.016	-0.005	0.003	0.103
3/15/01	5.33	0.086	0.215	-0.024	0.304
Total	19.66	0.138	0.232	0.056	0.743

Table 8. Measured sediment transport at BMC Ruark during Phase I.

Date	Cumulative Precipitation	Swale sediment accumulation									
		RC1	RC2	RC4	RC5	RT1	RT2	RT3	RT4	RT5	RT6
	(cm)	(Mg/ha)									
2/20/01	3.18	0.347	3.249	0.194	0.056	1.010	0.644	0.409	0.017	0.067	0.065
2/23/01	3.30	0.555	3.530	0.002	-0.006	2.038	3.010	0.296	-0.006	0.033	0.210
3/5/01	5.21	0.347	1.173	0.136	0.010	1.990	0.986	0.583	0.004	0.024	0.324
3/13/01	3.94	0.170	0.263	0.054	0.021	0.846	0.333	0.391	-	0.085	-
3/16/01	5.33	0.570	0.935	1.001	0.570	3.275	0.386	1.226	-	-	-
Total	20.96	1.989	9.150	1.386	0.651	9.159	5.357	2.906	0.014	0.210	0.598

Table 9. Measured sediment transport at OD-Moore during Phase II.

Date	Cumulative Precipitation	Swale sediment accumulation ODC	ODT1	ODT2	ODT3
	(cm)	(Mg/ha)			
4/18/01	0.86	0.001	0.000	0.022	0.045
5/23/01	1.02	-0.005	-0.009	-0.007	0.010
6/9/01	8.00	0.017	0.052	-0.004	2.537
6/14/01	13.72	0.070	1.389	0.016	9.515
Total	23.60	0.082	1.433	0.026	12.107

Table 10. Measured sediment transport at BMC Ruark during Phase II.

Date	Cumulative Precipitation	Swale sediment accumulation RC1	RC2	RC4	RC5	RT1	RT2	RT3	RT4	RT5	RT6
	(cm)	(Mg/ha)									
4/18/01	1.57	-0.025	-0.037	0.016	0.010	0.193	0.037	0.029	0.024	0.017	0.043
5/22/01	1.88	0.319	-0.385	-0.024	-	0.492	-0.081	0.041	-0.017	-	-
5/23/01	2.03	-0.004	0.104	0.021	0.006	0.528	0.519	0.066	0.014	0.047	0.087
5/30/01	10.92	0.027	-0.073	0.339	0.027	7.988	2.798	2.207	0.334	0.239	-
6/9/01	5.59	0.040	-1.395	-0.019	0.089	6.626	1.377	1.360	0.467	0.089	0.700
6/14/01	12.32	0.006	0.189	2.381	0.033	1.379	1.244	1.312	0.486	0.351	-0.006
Total	34.32	0.363	-1.597	2.714	0.166	17.206	5.894	5.016	1.307	0.743	0.824

Table 11. Measured sediment accumulation during Phase I and Phase II and calculated SMZ efficiencies for the treatment swales at OD-Moore and BMC Ruark.

Swale	Phase I	Phase II	Total	Efficiency
		(Mg/ha)		
ODT1	0.228	1.433	1.661	0.907
ODT2	0.064	0.026	0.090	-0.421
ODT3	0.739	12.107	12.846	0.964
ODC	0.140	0.082	0.222	n/a
RT1	9.159	17.206	26.365	0.571
RT2	5.357	5.894	11.251	0.268
RT3	2.906	5.016	7.921	0.533
RT4	0.014	1.307	1.322	0.991
RT5	0.210	0.743	0.952	0.773
RT6	0.598	0.824	1.423	0.415
RC1	1.989	0.363	2.352	
RC4	1.386	2.714	4.100	n/a
RC5	0.651	0.166	0.817	

Table 12. Total rainfall energy (E), the maximum 30 minute intensity (I_{30}), and the R factor for each rain event at OD-Moore during Phase I.

Date	E	I_{30}	R
	$\left(\frac{ft\cdot ton}{100\cdot acre\cdot in}\right)$	(in/hr)	$\left(\frac{ft\cdot ton}{100\cdot acre\cdot hr}\right)$
2/24/01	8.79	0.64	5.62
3/6/01	10.01	0.38	3.80
3/13/01	6.60	0.64	4.22
3/15/01	11.67	0.50	5.84

Table 13. Total rainfall energy (E), the maximum 30 minute intensity (I_{30}), and the R factor for each rain event at BMC Ruark during Phase I.

Date	E	I_{30}	R
	$\left(\frac{ft \cdot ton}{100 \cdot acre \cdot in}\right)$	(in/hr)	$\left(\frac{ft \cdot ton}{100 \cdot acre \cdot hr}\right)$
2/23/01	10.79	0.92	9.93
3/5/01	12.75	0.46	5.86
3/13/01	10.95	0.68	7.45
3/16/01	15.54	0.68	10.56

Table 14. Soil Erodibility factor (K), slope steepness factor (LS), and the cover management factor (C) for OD-Moore and BMC Ruark.

Swale	K	LS	C
ODC	0.28	2.89	0.124
ODT1	0.28	7.00	0.139
ODT2	0.28	1.73	0.124
ODT3	0.28	8.90	0.154
RC1	0.28	1.51	0.127
RC2	0.28	4.47	0.139
RC4	0.28	2.89	0.123
RC5	0.28	3.69	0.139
RT1	0.28	4.31	0.154
RT2	0.28	3.85	0.139
RT3	0.28	2.83	0.123
RT4	0.28	6.79	0.139
RT5	0.28	3.78	0.123
RT6	0.28	1.85	0.108

Table 15. RUSLE predictions of erosion at the OD-Moore site during Phase I.

Date	Cumulative Precipitation	Predicted Swale Erosion ODC	ODT1	ODT2	ODT3
	(cm)	(Mg/ha)			
2/24/01	3.30	1.261	3.433	0.753	4.850
3/6/01	4.70	0.853	2.322	0.510	3.280
3/13/01	2.92	0.947	2.578	0.566	3.642
3/15/01	5.33	1.309	3.563	0.782	5.032

Table 16. RUSLE predictions of erosion at the BMC Ruark site during Phase I.

Date	Cumulative Precipitation	Predicted Swale Erosion									
		RC1	RC2	RC4	RC5	RT1	RT2	RT3	RT4	RT5	RT6
	(cm)	(Mg/ha)									
2/23/01	3.30	1.192	3.867	2.226	3.198	4.151	3.331	2.181	5.881	2.909	1.247
3/5/01	5.21	0.704	2.283	1.315	1.888	2.451	1.967	1.288	3.473	1.718	0.736
3/13/01	3.94	0.894	2.900	1.670	2.399	3.114	2.498	1.636	4.411	2.182	0.935
3/16/01	5.33	1.268	4.114	2.368	3.402	4.417	3.543	2.320	6.257	3.095	1.327

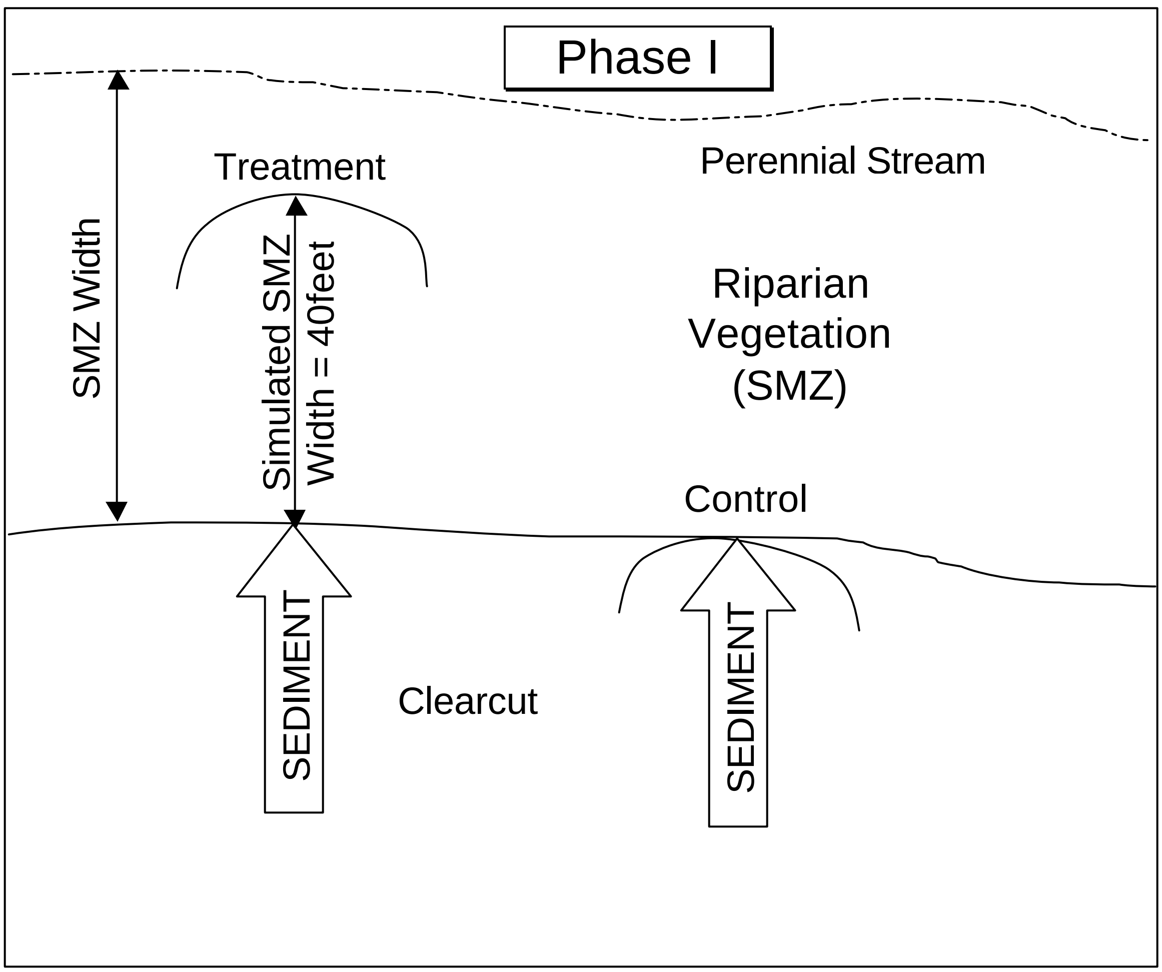

Figure 1. Schematic of Phase I with the treatment silt fence set into the SMZ a distance consistent with current Georgia BMPs.

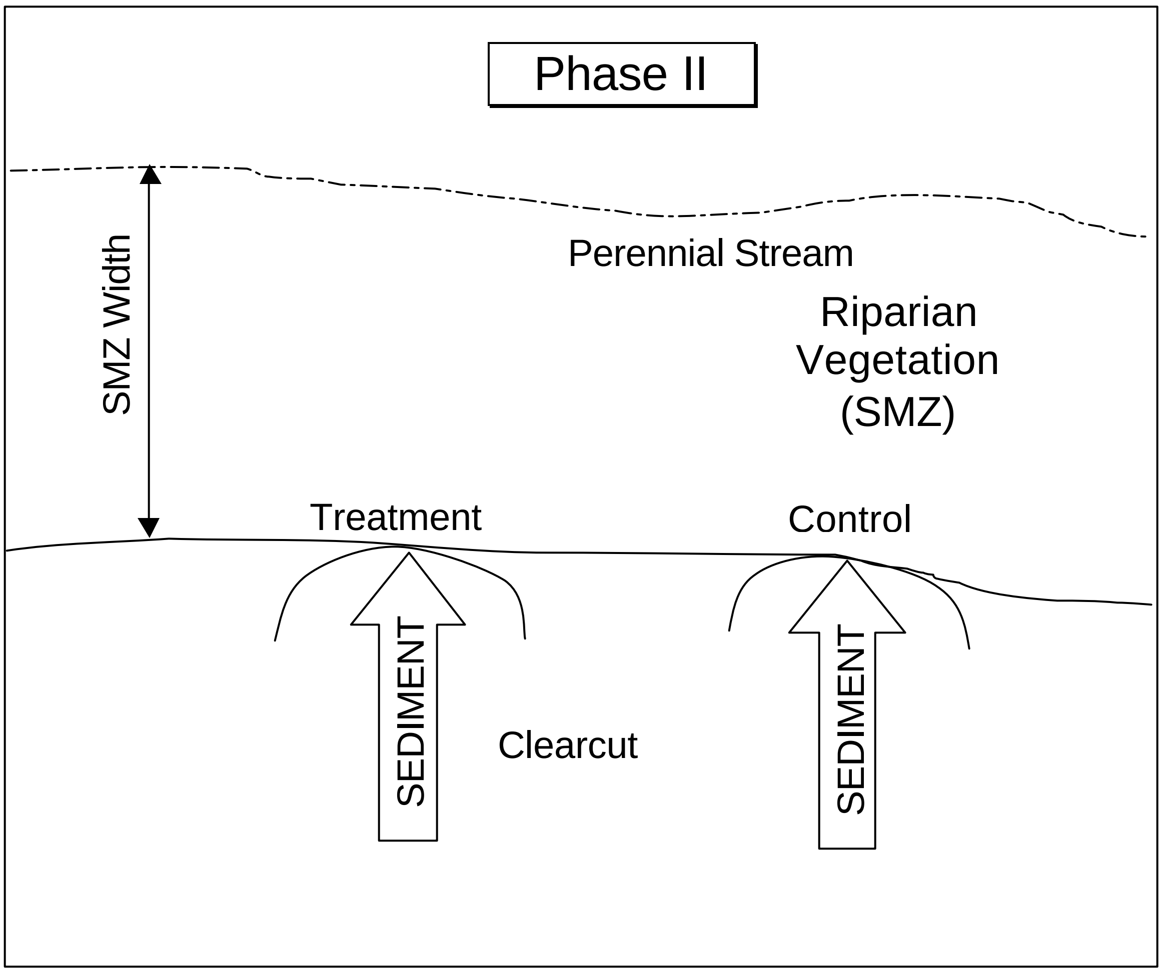

Figure 2. Schematic of Phase II with the treatment silt fence moved to the edge of the SMZ and the control silt fence still in its original location.

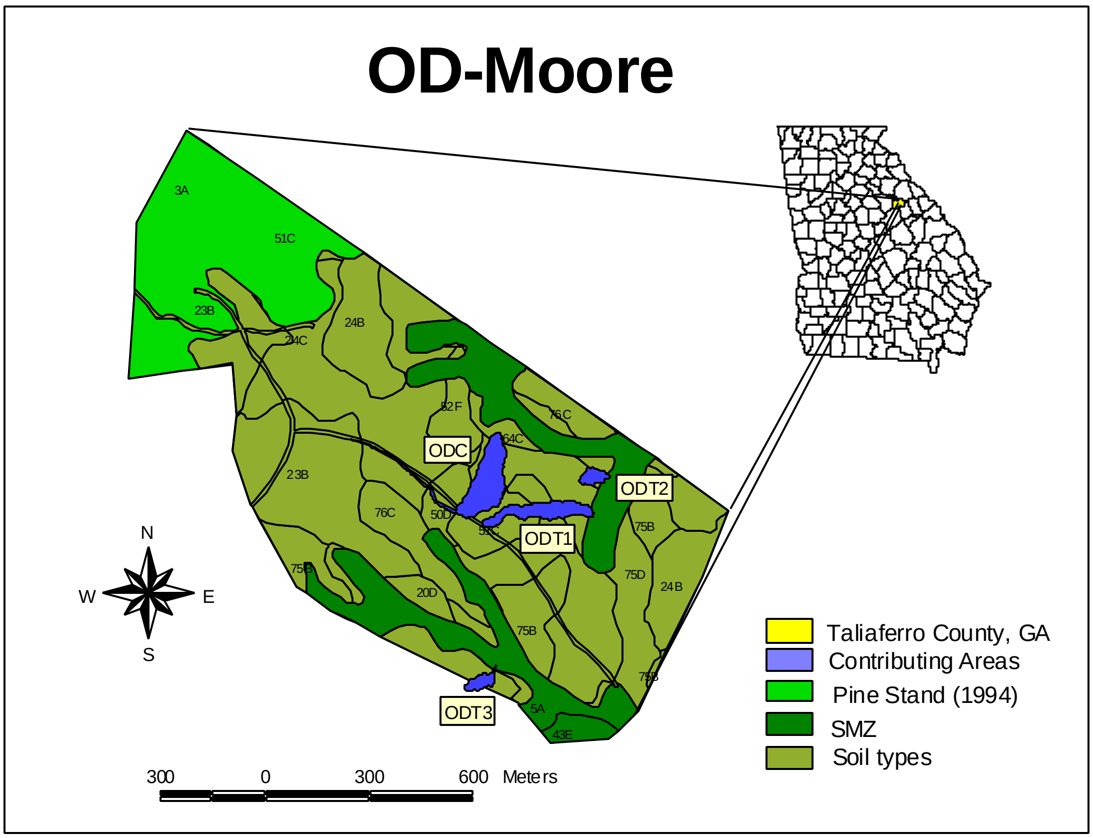

Figure 3. Map of the OD-Moore tract near Sharon, Georgia.

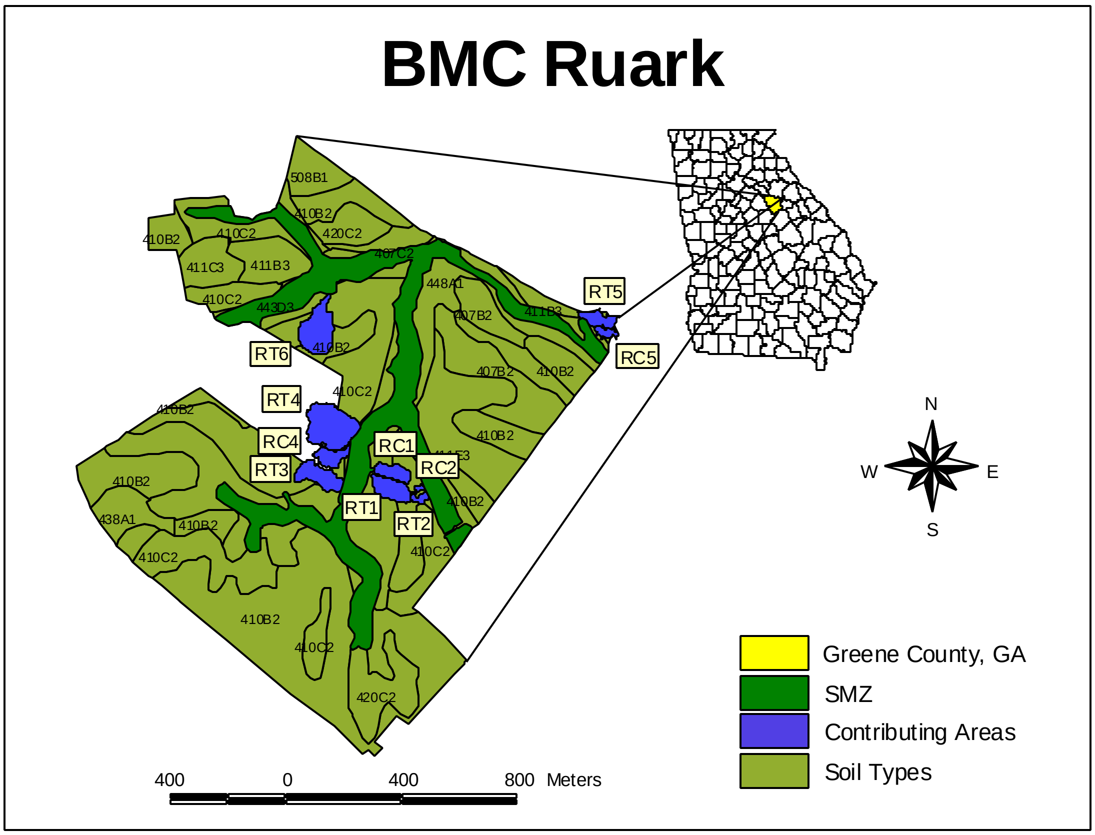

Figure 4. Map of the BMC Ruark tract near Woodville, Georgia.

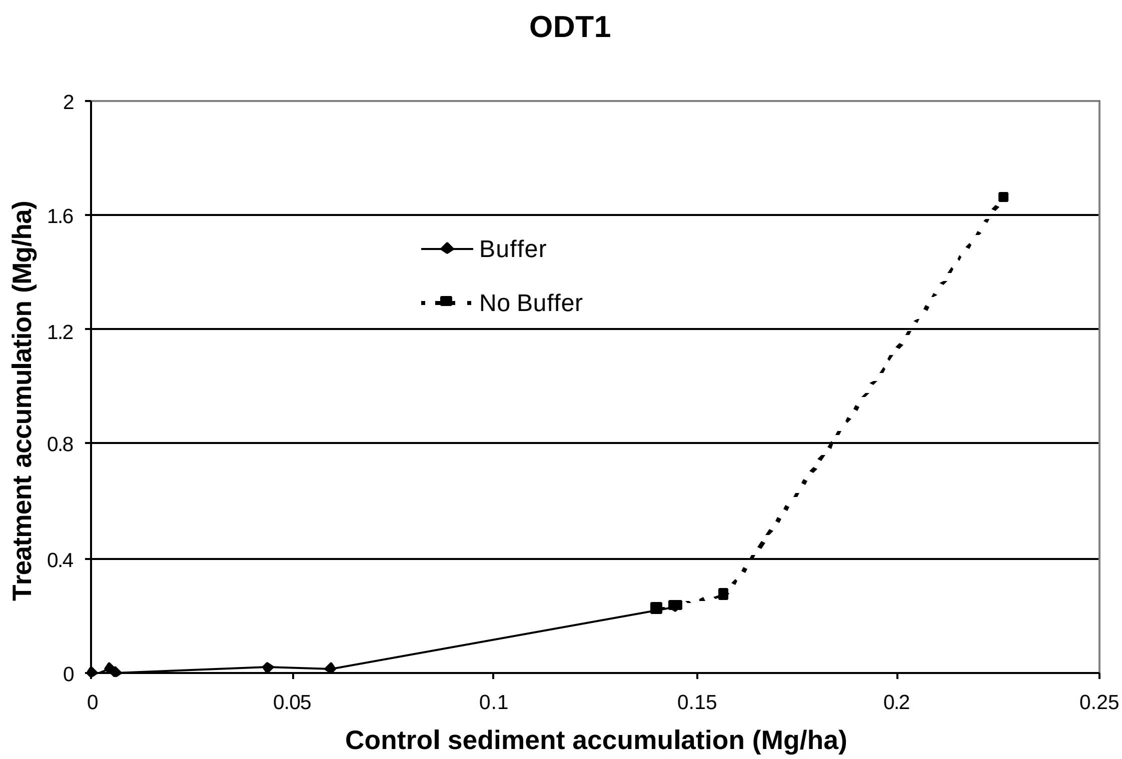

Figure 5. Double mass curve for ODT1 at the OD-Moore tract.

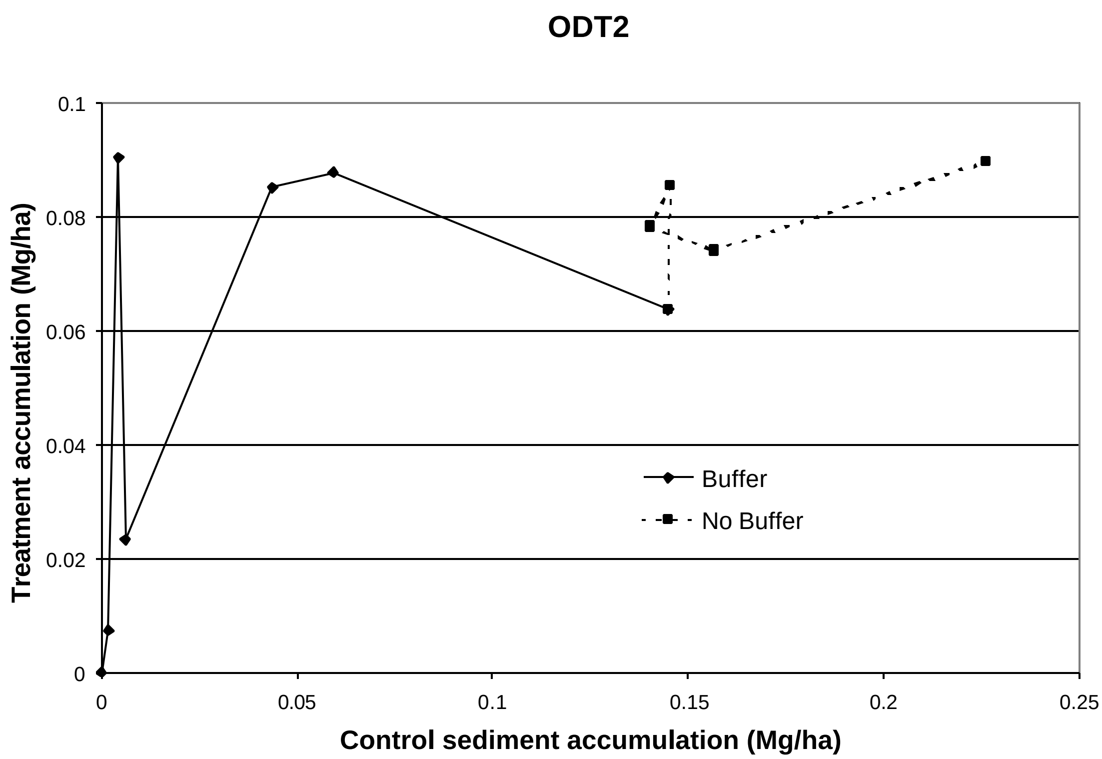

Figure 6. Double mass curve for ODT2 at the OD-Moore tract.

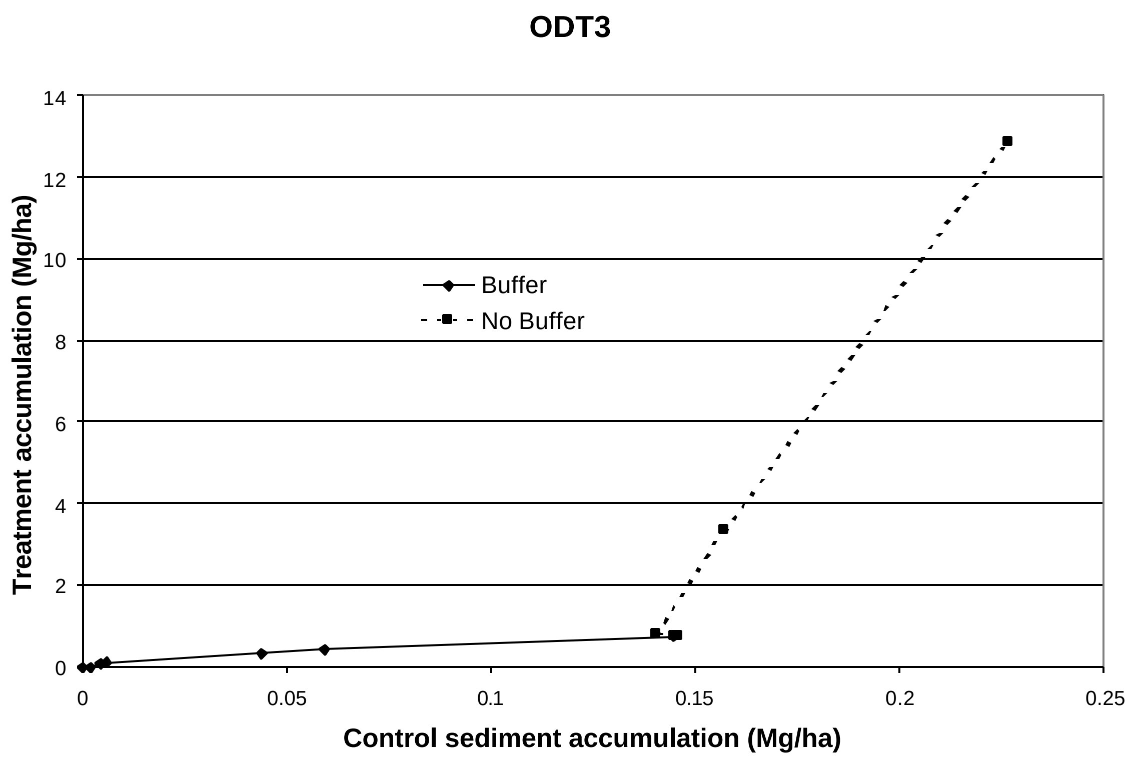

Figure 7. Double mass curve for ODT3 at the OD-Moore tract.

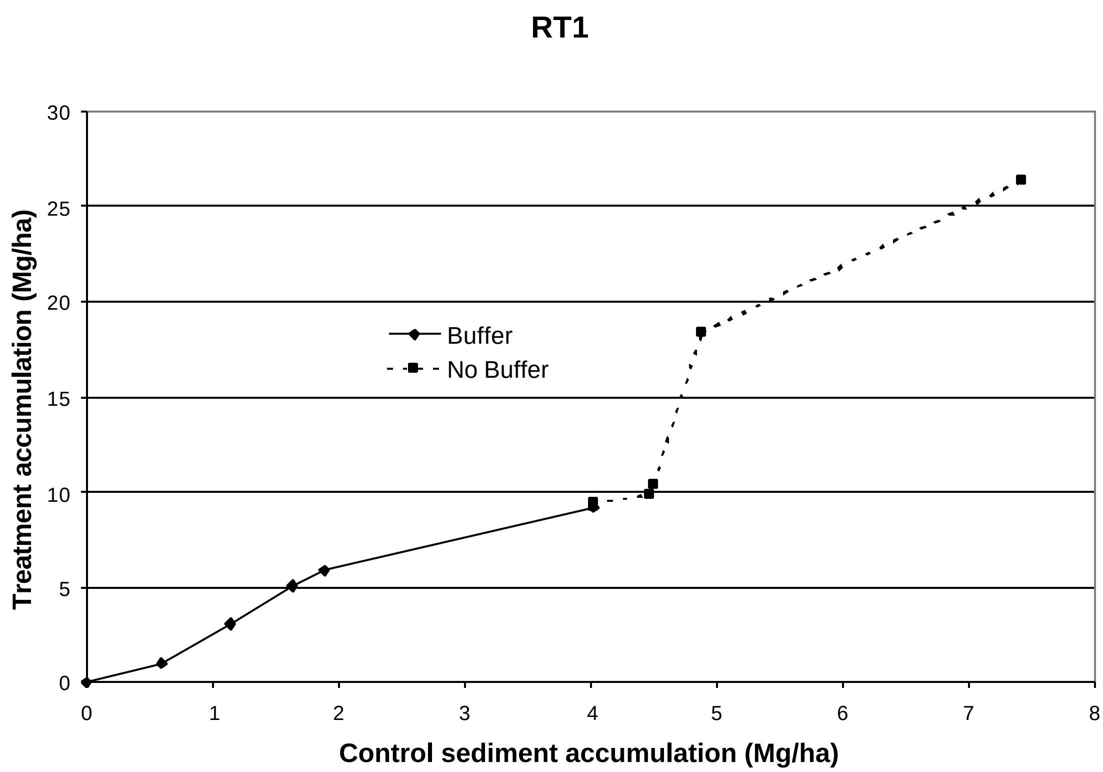

Figure 8. Double mass curve for RT1 at the BMC Ruark tract.

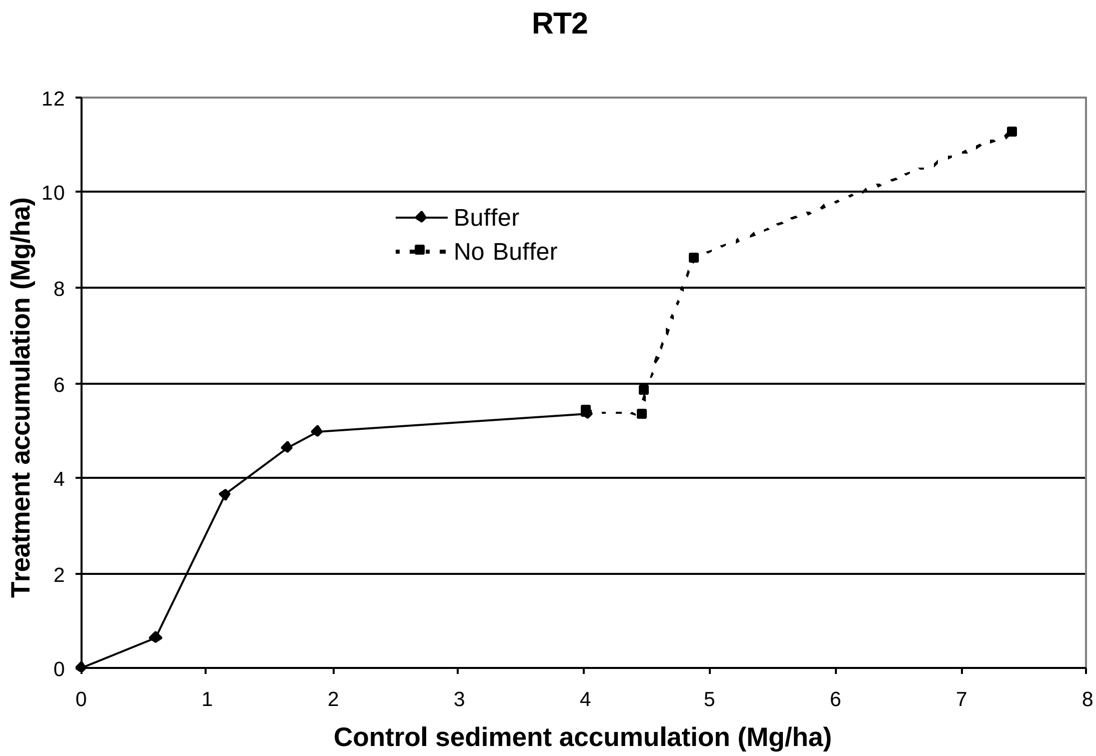

Figure 9. Double mass curve for RT2 at the BMC Ruark tract.

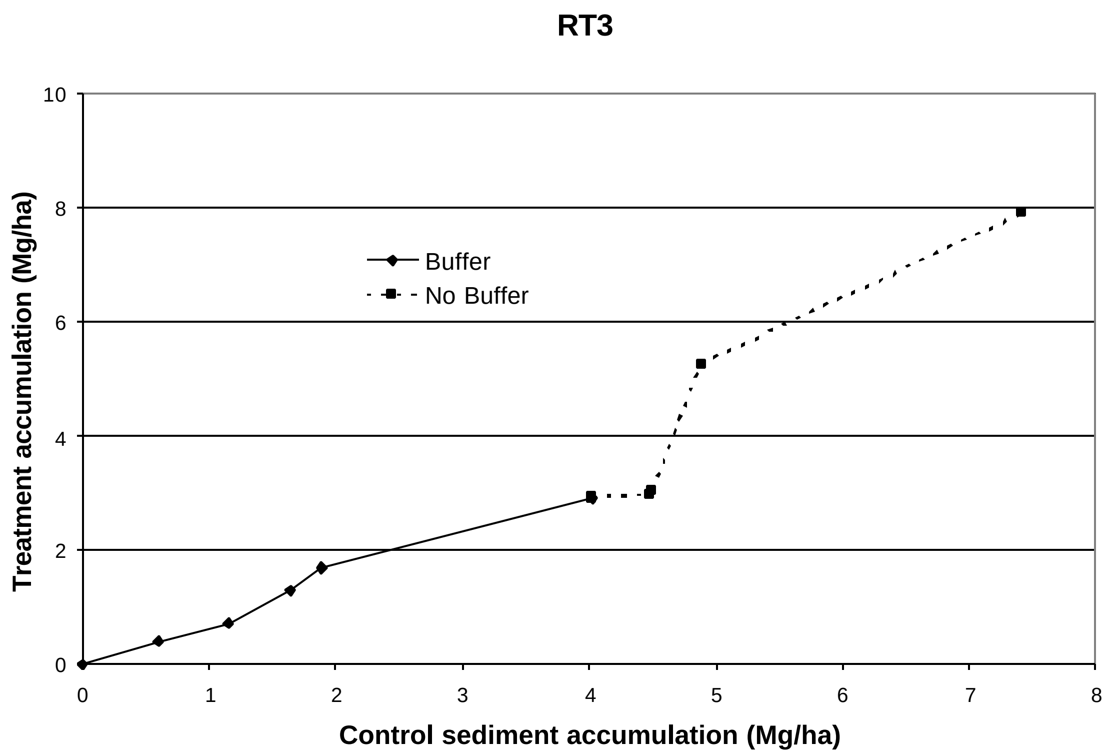

Figure 10. Double mass curve for RT3 at the BMC Ruark tract.

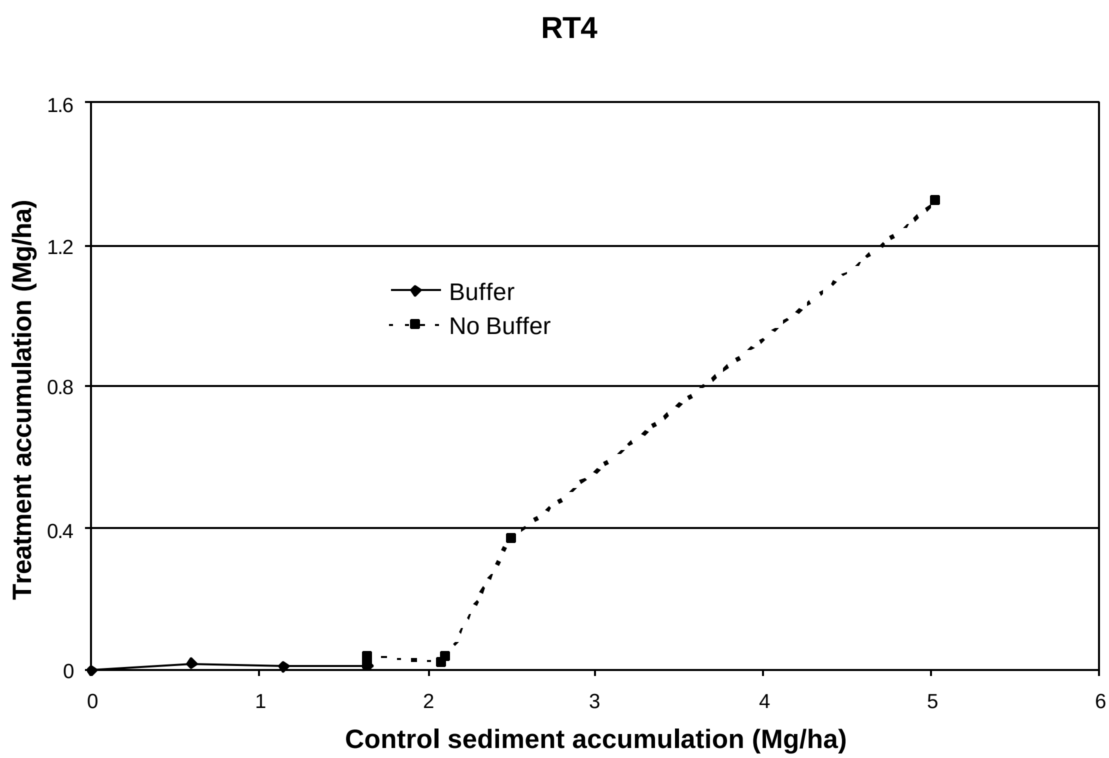

Figure 11. Double mass curve for RT4 at the BMC Ruark tract.

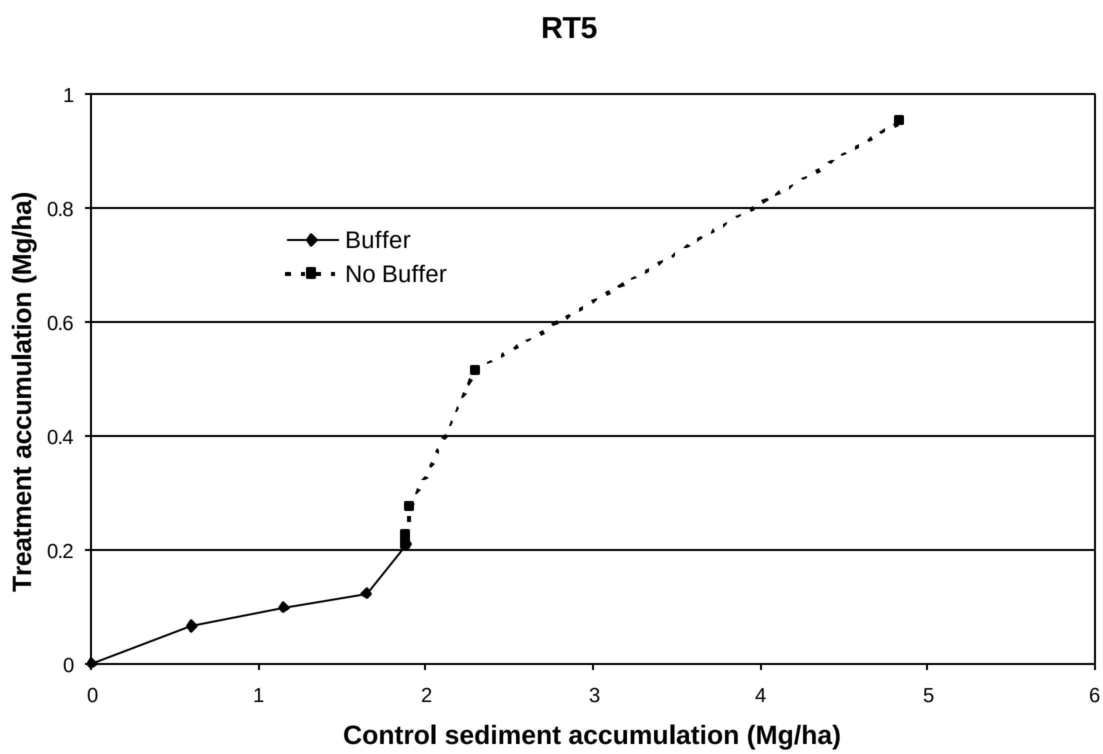

Figure 12. Double mass curve for RT5 at the BMC Ruark tract.

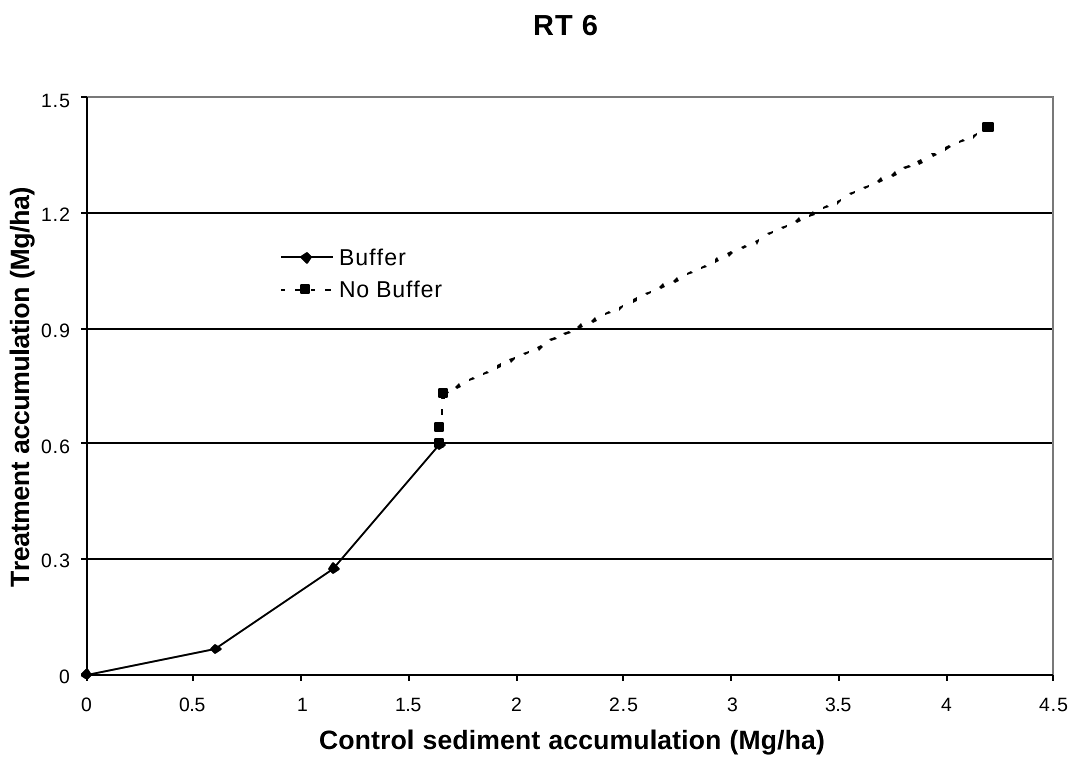

Figure 13. Double mass curve for RT6 at the BMC Ruark tract.

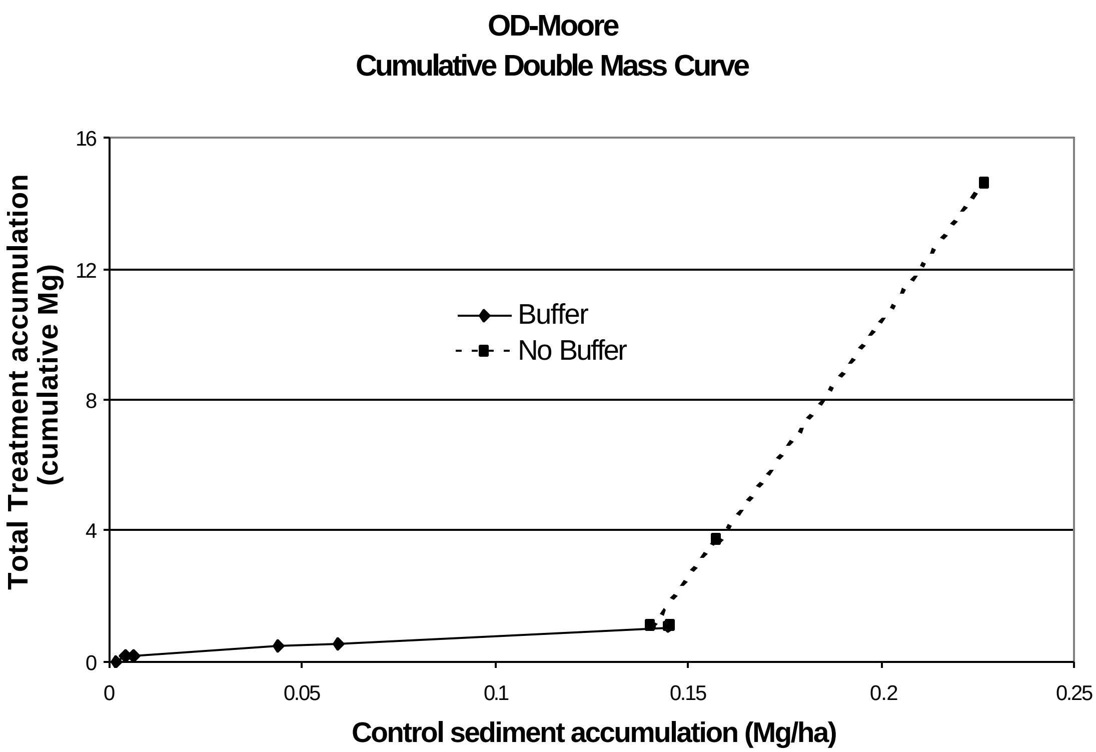

Figure 14. Cumulative double mass curve for the OD-Moore tract.

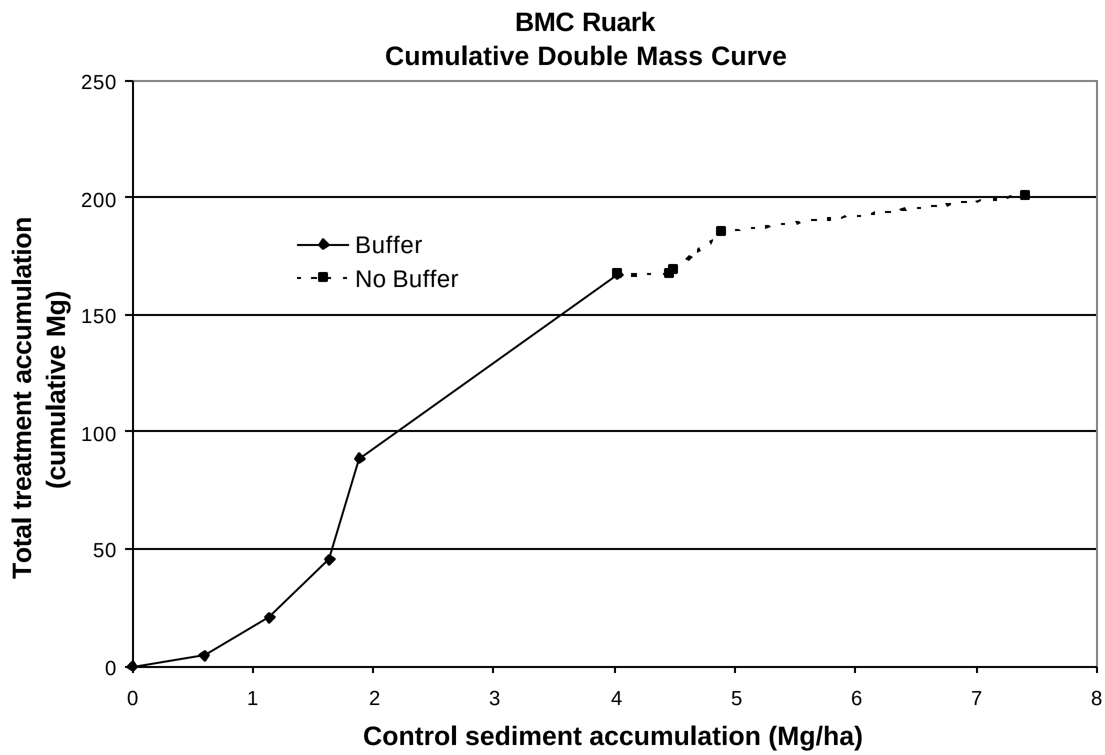

Figure 15. Cumulative double mass curve for the BMC Ruark tract.

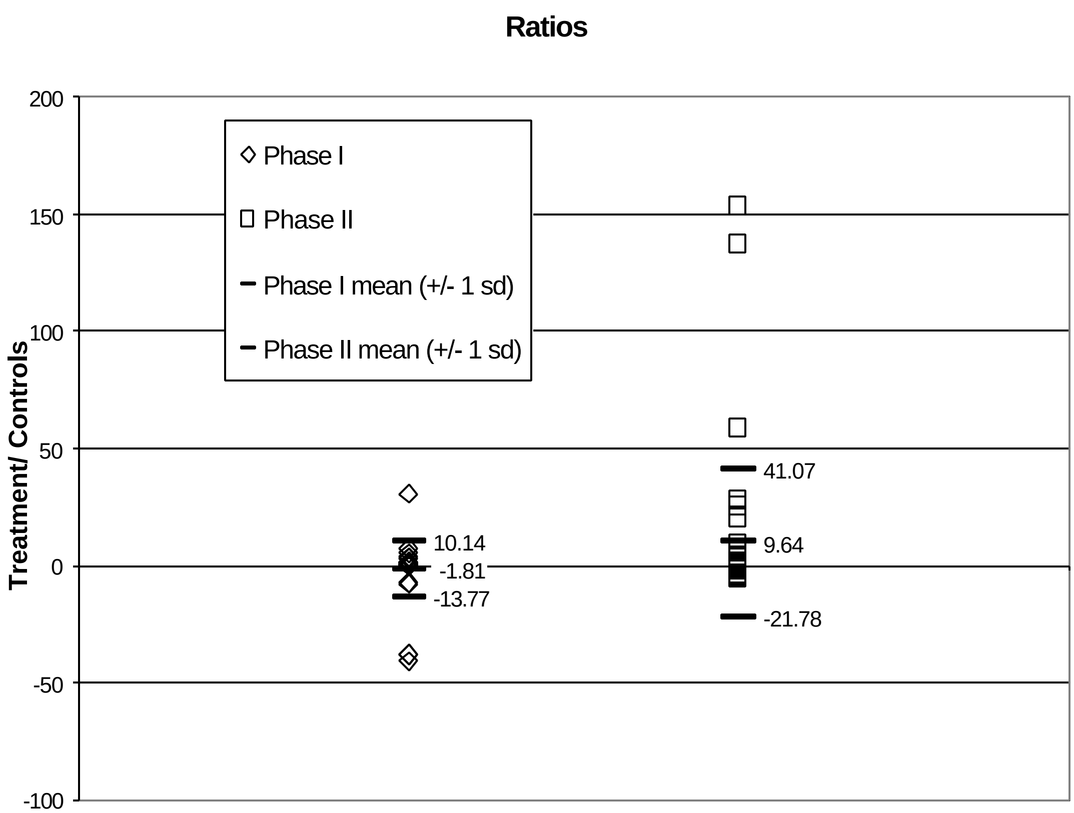

Figure 16. Vertical scatter plot of the sediment production ratios (treatment production/ average control production) for both OD Moore and BMC Ruark during Phase I and Phase II.

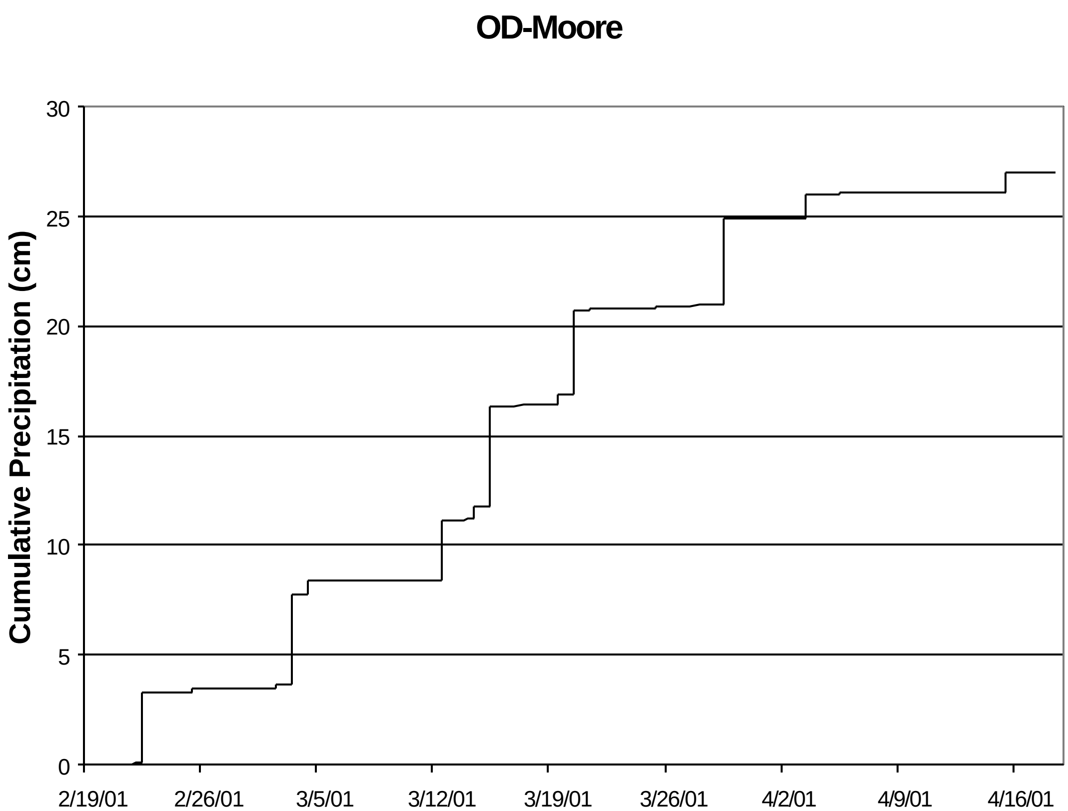

Figure 17. Tipping bucket rain gage data at the OD-Moore site during Phase I.

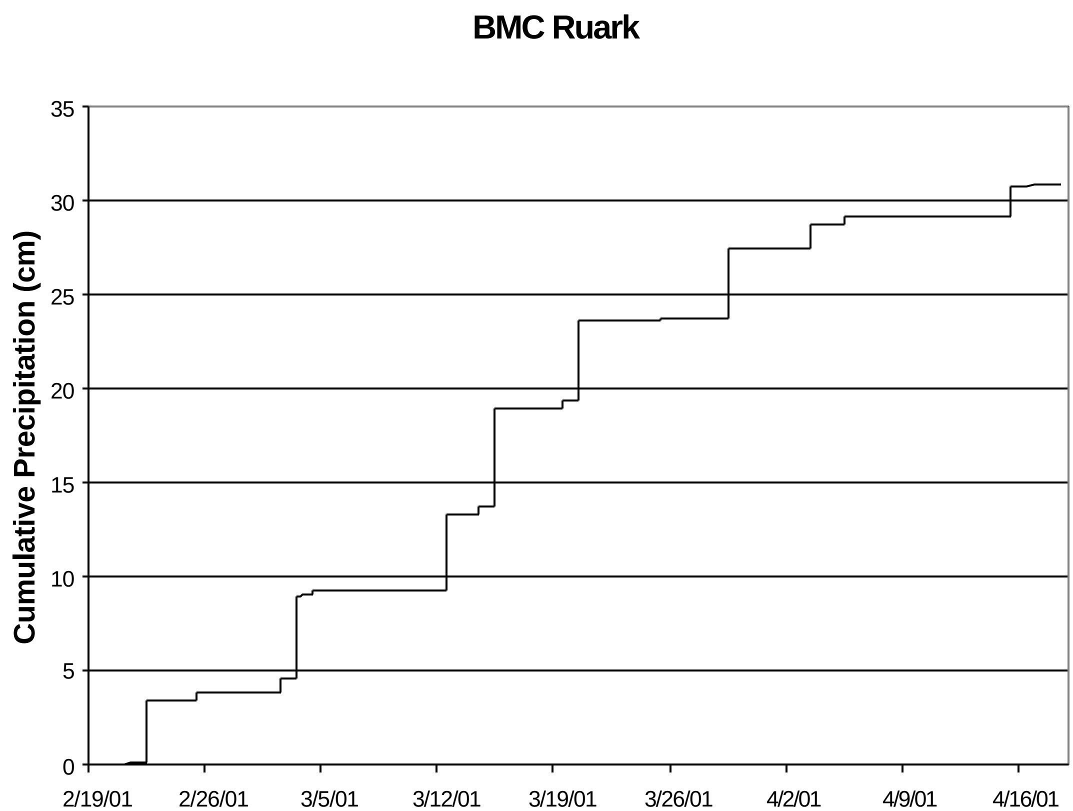

Figure 18. Tipping bucket rain gage data at the BMC Ruark site during Phase I.

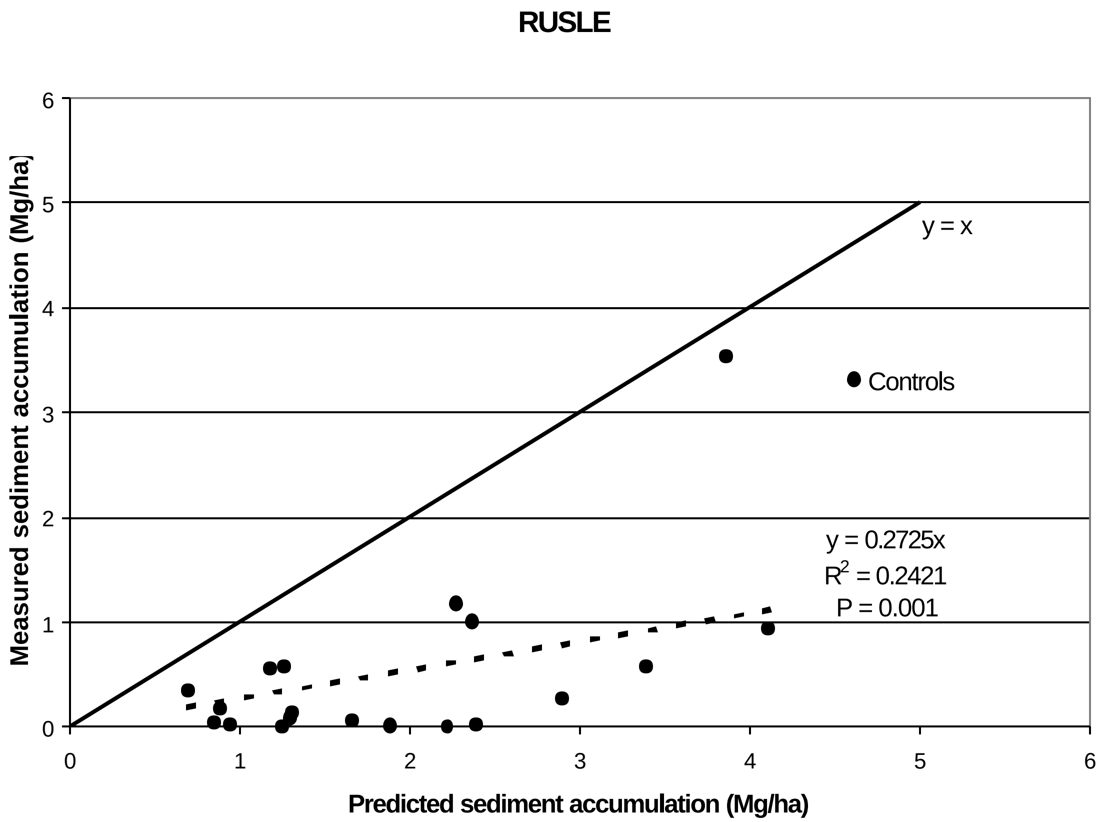

Figure 19. Measured delivered sediment at control swales vs. RUSLE predictions of sheet and rill erosion for rain events during Phase I and Phase II.

CHAPTER 3

CONCLUSIONS

Using the double mass curve analysis, most treatment swales demonstrated an upward shift in sediment transport during Phase II of our experiment (Figure 5- Figure 13). This upward shift was likely due to the lack of the SMZ buffering effect within the treatment swales during Phase II. The erosion rates in Table 11 are within the estimates of previous research on sediment transport in the Piedmont physiographic region (Dissmeyer and Stump, 1978; Van Lear et al., 1985). We successfully quantified riparian buffer effectiveness at our study sites by calculating a range of SMZ efficiencies during our experiment (Table 11). Given the degree of channelization that we observed in the contributing areas, the SMZs worked well to filter and trap sediment from overland flow. Our SMZ effectiveness calculations are comparable to previous research on buffer strip effectiveness in silvicultural settings (Lacey, 2000). However, we were unable to generate a model that explained the variation in SMZ efficiencies.

It is difficult to account for natural variability in hydrologic and soil conditions when doing field scale research of this kind. Experiments that involve rainfall simulations on controlled erosion plots help to eliminate some natural variability, but the results from these experiments are difficult to extrapolate to the field scale. The silt fences worked well for trapping sediment transport, but maintaining and monitoring them after each rain event is vital to collect reliable data. The wooden dowels were slightly prone to rotting and termite activity after several months.

RUSLE modeling showed that a positive correlation existed between predicted and measured sediment flux within the study swales. The correlation coefficient for the period of observation, 0.24, is relatively low. This suggests that RUSLE was not accurate at predicting sediment transport rates for individual rain events at our study sites. More field scale experimentation is needed to better assess the predictive abilities of

RUSLE for forestry operations. An accurate erosion model would be helpful for forest land managers to identify potential problem areas prior to delineating SMZs.

CHAPTER 4

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