Determining Soil Erosion from Roads in the Coastal Plain of Alabama

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ABSTRACT

This paper reports soil losses and observed sediment deposition for 16 randomly selected forest road sections in the National Forests of Alabama. Visible sediment deposition zones were tracked along the stormwater flow path to the most remote location as a means of quantifying soil loss from road sections. Volumes of sediment in deposition zones were determined by depth and deposition area measurements. The Water Erosion Prediction Project (WEPP) was used to predict deposition in buffers and sediment leaving buffers from these forest road sections. WEPP estimates for these Coastal Plain sites were compared to measured sediment deposition from the forest road sections on the National Forests of Alabama. The applicability of WEPP to model these forest roads in the Coastal Plain of Alabama is evaluated with a model efficiency statistic using the observed field experiment data. The study found that of the 16 road segments analyzed, the average road segment length was 45 m, and the average quantity of sediment deposited onto the forest floor from road sections was 2300 kg. The WEPP: Road predictions were not significantly different from the observed sediment deposition. This research effort provides information to quantify the magnitude of soil erosion from typical Coastal Plain forest roads in the southern region of the U.S. The information reported is useful in soil erosion prediction models to validate predictions and create forest road management scenarios.

KEYWORDS: Soil Erosion, Modeling, Forest, Roads, Sediment Deposition

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1.0 INTRODUCTION

Sediment from forest roads is a concern due to its potential delivery to stream systems which can result in degraded water quality (Davies-Colley and Smith, 2001; Van Lear et al., 1997). Numerous studies have been conducted to evaluate factors influencing soil erosion potential of forest roads (Burroughs and King, 1989; Clinton and Vose, 2003; Coker et al., 1993; Grace, 2002a, 2005a, 2005b; Luce and Black, 1999; Luce and Black, 2001; Ketcheson et al., 1999; Packer, 1967; Swift, 1984). Previous forest road erosion research has also recommended the forest floor (buffer strips) as an effective filter of forest road sediments (Swift, 1986; Swift, 1988). Minimum filter strip width criteria have been incorporated into forest road Best Management Practices (BMPs) as a result of this research and recommendations. However, due to the complexity of quantifying sediment movement in the forest setting, the effect of the forest floor filter (and BMPs) on sediment movement downslope of forest roads has not sufficiently been quantified by previous research (Grace, 2005b).

Investigations have identified the need for reliable prediction technology to identify problem areas, and to plan and evaluate forest road operations (Elliot and Foltz, 2001; Elliot, 2004; Grace, 2005b, 2005c; Megahan and Ketcheson, 1996; Swift, 1986). The Water Erosion Prediction Project (WEPP) was developed as a physically-based surface erosion model (Flanagan and Livingston, 1995) and has been presented as a promising tool to predict forest road erosion (Elliot and Hall, 1997; Elliot et al., 1994; Elliot, 2004). The WEPP model has been validated for various road designs and regions (Elliot and Tysdal, 1999; Elliot et al., 1998; Elliot et al., 1995; Elliot and Foltz, 2001; Grace, 2005c, 2007; Morfin et al., 1996). However, little information is available on the validity of WEPP predictions of sediment deposition below roads in general (Elliot and Foltz, 2001), and in the Coastal Plain region in particular. This effort is an attempt to fill a critical information gap by gaining a better understanding of the soil erosion losses from forest roads in the Coastal Plain region of Alabama.

1.1 Objectives

The objectives of this investigation were to quantify soil erosion from 16 road sections in the Coastal Plain region and to validate WEPP predictions of sediment deposition with data from the field experiment. The benefit of this exercise is to assess the applicability of WEPP in predicting sediment deposition from roads in the Coastal Plain of Alabama.

2.0 METHODS

2.1 Study Sites

The study was located at approximately 31^{o} latitude and 86^{o} longitude on the Conecuh National Forest near Andalusia, Alabama in Covington County, Alabama (Figure 1). Slopes, in the study area, range from 0 to 12 percent with the majority of the area having slopes at the lower end of the slope range. Soils on the study roads are primarily mapped as Florala, Orangeburg and Dothan series (SCS, 1989). The three soil series consist of sandy loam surface soils over sandy clay loam subsoil. Dothan series soils are fine-loamy, siliceous, thermic Plinthic Paleudults and consist of deep well drained soils on uplands of the Coastal Plain. Florala series soils are coarse-loamy, siliceous, thermic Plinthaquic Paleudults and consist of deep moderately permeable soils on uplands of the Coastal Plain. Orangeburg series soils are fine-loamy, siliceous, thermic Typic Paleudults and consist of deep well drained soils on uplands of the Coastal Plain. Soils in their original condition are moderate to well drained with permeability ranging from 50 to 150 mm hr^{-1}. Compacted soils, as found on the study roads, are not as permeable with permeability ranging from 1.0 to 50 mm hr^{-1}.

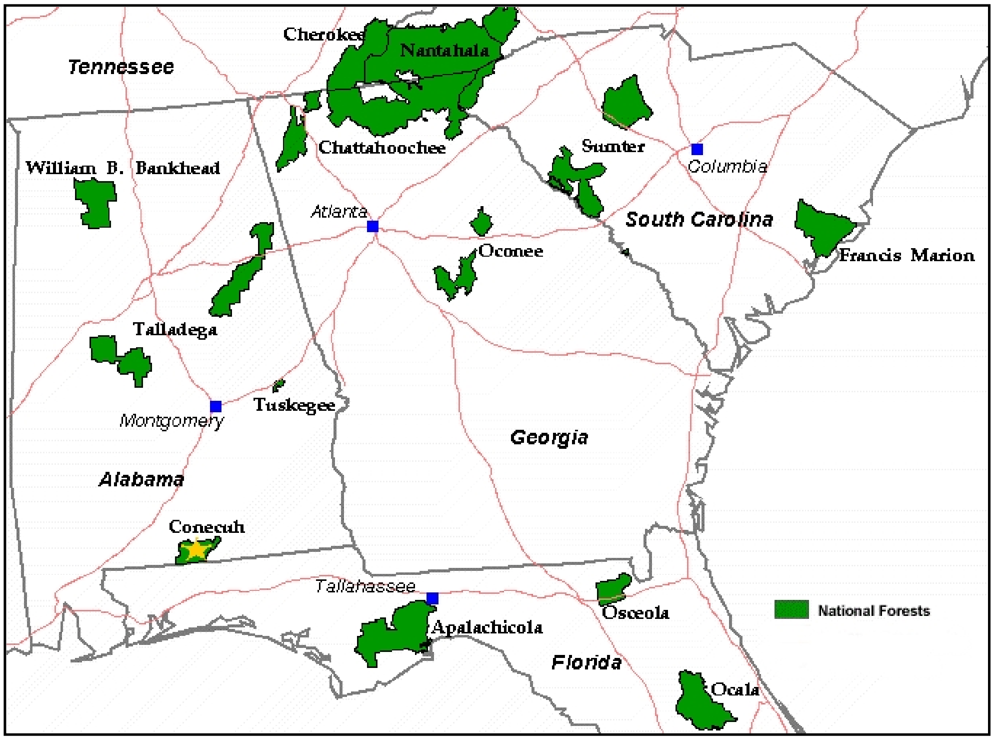

Figure 1. Location of the Conecuh National Forest sites within the Southern Region.

The study consisted of 6 roads randomly located using topographic and administrative maps, in consultation with Forest Service personnel, and reconnaissance. Current traffic intensity ranged from low to moderate with periods of high intensity during management or periods of high recreation pressure. These roads were originally constructed to access stands for management prescriptions i.e. fire management, harvesting, site preparation, planting, and inventories. However, in recent years, roads have evolved to primarily serve recreation (driving for pleasure and hunting).

Study roads are crowned unsurfaced roads drained by lead-off ditch structures (Figure 2). Lead-off ditch structure design and spacing are consistent with specifications recommended by Alabama's Best Management Practices for Forestry (Alabama Forestry Commission, 1993; Grace, 2004, 2005b). These specifications are also consistent with specifications recommended by previous research (Swift, 1986; Trimble and Sartz, 1957) and by most southern state best management practices for forestry (Grace 2002b). Roads in the study traverse managed pine stands consisting primarily of longleaf pine (*Pinus palustris Mill.*) and loblolly pine (*Pinus taeda L.*) of varying age.

Road maintenance consists primarily of maintenance grading twice a year (spring and fall) and annual mowing. Historically, maintenance grading on study roads was greater but grading has decreased in recent years due to changes in management strategy. Maintenance grading is performed consistent with the Road Maintenance Management System (FSH 7709.58, 10) (USDA Forest Service, 1995) for maintenance levels 1- 3. At maintenance levels 1-3, the emphasis is placed on maintaining drainage and preventing damage to adjacent resources. User comfort and convenience are not a priority in maintenance grading. Roads in maintenance levels 1-3 constitute 70 percent of all roads traversing public lands in the Southern Region.

Figure 2. Typical crowned forest road section used in the investigation.

2.2 Field Data Collection

2.2.1 *Deposition Area Measurement*

Based on our field inspection, we determined that we were able to differentiate between the deposition from the past year and previous years by the litter layers that generally cover sediment deposition in the period between late summer and early fall. Deposition above the litter layer can be attributed to the erosion in the previous year, whereas sediment below this upper litter layer was attributed to earlier years. The sediment deposited in this top layer was collected from March 2003 to July 2003. Deposition areas for each of the 16 road sections in this analysis were tracked from the lead-off structure to the most remote visible deposition zone and this length was measured as the deposition length. The deposition zones were overlain with a 1-m grid and deposition depth measurements were taken at each grid location for volume estimation. Three soil cores (51 mm) to be utilized in determining bulk density were taken within the deposition area. Collected bulk density samples were sealed in plastic bags to maintain original moisture content, transported to the laboratory, and refrigerated until analyses were performed.

2.2.2 *Road Characteristics*

Road characteristics vital for contributing area calculations for deposition volume estimation and model development were measured for the 16 road sections. Characteristics measured in the experiment included road section length, width and gradient. Road section length was taken as the slope length of the road section from the upstream runoff divide, or upslope lead-off structure to the lead-off structure draining to the deposition area evaluated. Road section width was taken as the average of three measurements along the road section length. In the crowned roads used in the investigation the contributing width was generally half the total road section width. Road gradient was taken as percent slope along the road section length. Topography adjacent to each road sections was also determined and included downslope gradient, runoff travel path roughness and obstructions to flow.

2.2.3 *Climate*

Average annual precipitation during the study was noted for the Andalusia weather station, located 20 km north of the study site. The long-term average precipitation, based on 70 years of record, for the Andalusia, Alabama area is 1520 mm. These amounts were compared to the average annual precipitation generated stochastically for the WEPP runs.

2.3 Laboratory Analysis and Calculations

Bulk density was determined from the undisturbed soil cores as the oven dried (105^{o}C) mass divided by the core volume. Deposition volume was assumed to be the product of deposition width, length, and depth measurements taken from the 1-m grid in the field data collection. Total sediment deposition mass was the product of deposition volume and the average bulk density from soil cores collected from each deposition area.

2.4 Model Evaluation

WEPP (Road) interface allows input parameters of climate, soil, road gradient, length, width, fill gradient, fill length, buffer gradient, and buffer length. Input parameters are presented for each road section in this application (Table 1). All road sections were modeled as native-surfaced, insloped road sections with 20 percent rock content. The WEPP climate generator (CLIGEN, Version 5.2) was used to generate a 30-year climate input file for the Andalusia, Alabama area.

Table 1. Input parameters for WEPP (Road) predictions of sediment deposition for 16 road sections in the experiment.

Site	Road Gradient (%)	Road Length (m)	Road Width (m)	Fill Gradient (%)	Fill Length (m)	Buffer Gradient (%)	Buffer Length (m)
1	4	73	2.4	3	3.0	3	36
2	5	15	1.5	4	0.9	4	37
3	3	51	2.0	3	3.0	3	21
4	2	22	2.3	5	3.0	5	27
5	1	47	1.8	5	3.0	5	35
6	3	16	2.3	6	3.0	6	51
7	5	42	1.8	5	3.0	5	34
8	3	54	1.7	10	3.0	10	46
9	4	51	1.5	2	3.0	2	25
10	3	94	2.1	1	0.3	3	46
11	6	55	1.8	2	3.0	2	43
12	5	36	1.8	4	3.0	4	30
13	8	70	1.8	2	3.0	2	46
14	6	27	1.7	5	3.0	5	33
15	4	49	1.8	5	0.9	5	31
16	12	19	1.5	6	0.9	6	24

WEPP (Road) predicts sediment deposition within and leaving a defined buffer length. Accuracy of model predictions of sediment deposition in the buffers was evaluated by setting WEPP input buffer length equal to the observed sediment deposition length for each road section. This procedure allowed direct comparison of the observed deposition with WEPP estimates of deposition in the same deposition length. Observed and WEPP-predicted sediment deposition in buffers for each road section were statistically summarized and subjected to analysis. The model's "goodness-of-fit" was determined by procedures defined by Grace (2005c) using the Nash and Sutcliffe (1970) model efficiency (ME) statistic. That is, “goodness-of-fit” provides information on how successful a model is in meeting the objective of accurately describing observed phenomenon. Perfect agreement between predicted and observed soil loss would result in a ME coefficient equal to 1.

3.0 RESULTS AND DISCUSSION

3.1 Climate

The long-term average annual precipitation for Andalusia over a 70-year record is 1520 mm. During the 30 year period in this analysis, the long-term average (LTA) annual precipitation at Andalusia was 1560 mm and ranged from 960 to 2360 mm. During this period there were several tropical storms that occurred. The 30-year climate generated stochastically from the WEPP Run averaged 1450 mm of precipitation. Analysis revealed no difference at the 5 percent significance level between LTA precipitation and WEPP generated precipitation for Andalusia over this 30-year period based on a paired t-test ($P=0.051$). However, the recorded precipitation immediately before the data collection period (2000-2003) was drier than normal for the area. The recorded precipitation for 2000 was only 960 mm which made it the driest year in the 30 year simulation period and the third driest year on record for the area. Precipitation for 2001, 2002, and 2003 were "normal" years in terms of precipitation for this area.

3.2 WEPP Erosion Predictions

WEPP simulations were made for each of the 16 road sections as a native sandy loam surfaced road under both low and high traffic conditions. Observed and predicted sediment deposition for the high traffic condition are presented (Table 2). The average observed deposition length for the 16 road sections was 35 m with an average road section length of 45 m. Observed sediment deposition for the road sections ranged from 450 kg for the shortest road section (site 2, 15 m) to 6100 kg for one of the longer road sections (site 13, 70 m) (Table 2). Predicted sediment deposition in the buffer length (set equal to observed deposition length) exhibited similar trends to those noted for the observed sediment deposition and ranged from 300 to 6100 kg. Predicted sediment deposition based on 30-year simulations for each of the 16 road sections was compared to observed sediment deposition from the field investigation. The predicted mean sediment deposition for the 16 sites of 2000 kg was similar to sediment deposition observed in the field investigation (2300 kg) based on a paired t-test (P=0.32). The 95 percent confidence level for the paired difference was 210 kg.

The road characteristics that had the greatest variation on the 16 road sections in the experiment were road gradient and road section length (slope length). These two factors can greatly influence soil erosion from forest roads (Grace 2004, 2005b; Trimble and Sartz 1957). Grace (2005b) reported that road section length is a primary factor determining the distance sediment moves downslope in a survey of 235 forest road sections throughout the National Forests of Alabama and Georgia. The road section (Site 13) at the upper end of the slope (8%) and road section length (70 m) range yielded the greatest sediment deposition value for both observations and predictions of the 16 sites in the investigation. The road section length of 70 m for Site 13 (Table 1) was greater than the recommended length (spacing) of 50 m for an 8 percent gradient. The extended spacing for Site 13 increased soil erosion from the road section and likely influenced the distance that sediment was transported based on previous reports (Grace 2004, 2005b).

Table 2. Observed and predicted values for sediment deposition in buffer and leaving the buffer for high traffic for each of the 16 road sections in the investigation.

Site	Bulk Density	Observed Deposition	WEPP Estimate Deposition	WEPP Estimate leaving Buffer	% Leaving Buffer	WEPP Estimate Dep + Leaving	% Error Dep	% Error Dep + Leaving
	g cm^{-3}	kg	kg	kg		kg		
1	2.3	4812.4	4523.2	659.1	14.6%	5182.3	6.0%	-7.7%
2	2.1	452.7	307.3	28.4	9.2%	335.7	32.1%	25.8%
3	1.6	483.8	504.5	409.2	81.1%	913.7	-4.3%	-88.9%
4	1.8	1429.1	1655.3	85.4	5.2%	1740.6	-15.8%	-21.8%
5	2.5	1954.5	742.1	231.6	31.2%	973.7	62.0%	50.2%
6	2.3	1222.7	456.5	66.9	14.7%	523.4	62.7%	57.2%
7	2.2	2427.3	1917.7	293.5	15.3%	2211.2	21.0%	8.9%
8	2.3	2305.2	1883.7	589.4	31.3%	2473.1	18.3%	-7.3%
9	2.2	1716.2	1606.9	236.3	14.7%	1843.2	6.4%	-7.4%
10	2.3	3688.2	4062.3	604.0	14.9%	4666.3	-10.1%	-26.5%
11	2.1	3647.6	3139.0	180.8	5.8%	3319.8	13.9%	9.0%
12	2.1	1339.9	1493.6	196.7	13.2%	1690.3	-11.5%	-26.2%
13	2.0	6121.6	6140.4	357.9	5.8%	6498.3	-0.3%	-6.2%
14	1.6	1481.3	1032.0	124.5	12.1%	1156.5	30.3%	21.9%
15	2.3	1978.0	1812.1	372.3	20.5%	2184.4	8.4%	-10.4%
16	2.1	1355.9	891.9	96.9	10.9%	988.8	34.2%	27.1%
Average	2.1						**15.8%**	**-0.1%**

A 15.8 percent error (underprediction) was associated with WEPP predictions of sediment deposition in the buffers i.e. in the distance between the lead-off ditch structure and the observed most remote location of deposition. The percent error associated with sediment deposition in buffers ranged from an overprediction of 15.8 to an underprediction of 62.7 percent. The combination of WEPP predictions of deposition in the buffers and leaving the buffers was similar to observed sediment deposition based on percent error (-0.1 %) and a paired t-test (P=0.49). However, the sediment deposition values and percent errors for the sections had a larger variance.

Observed sediment deposition regressed against WEPP predictions of sediment deposition in buffers and the sum of sediment deposition in the buffers and leaving buffers for the 16 road sections are presented in Figure 3. A highly correlated relationship was found between predicted and observed sediment deposition as illustrated in the regression plot. Similarly, a highly correlated relationship was found between observed sediment deposition and the sum of WEPP predictions of sediment deposition in buffers and sediment leaving buffers. This is indicated by the high R-square values of the regression between observed and predicted sediment deposition (R^2 = 0.94) and observed sediment deposition and the sum of predicted sediment deposition and sediment leaving the buffers (R^2 = 0.93). Analysis also indicated that WEPP slightly underpredicted sediment deposition for 11 of the 16 road sections (Figure 3). However, an underprediction was found for the combination of predicted sediment deposition and sediment leaving the buffers for 7 of 16 road sections. The F-statistic for the hypotheses that the regression slope equals one and the intercept equals zero for sediment deposition predictions (F= 227.4) was significant at the five percent level. Similarly, the F-statistic for the sum of sediment deposition and sediment leaving the buffers (F = 191.8) was significant based on the regression analysis. In addition, regression slopes were not detected as significantly different from 1 with p-values of 0.100 for sediment deposition and 0.347 for the sum of sediment deposition and sediment leaving the buffer.

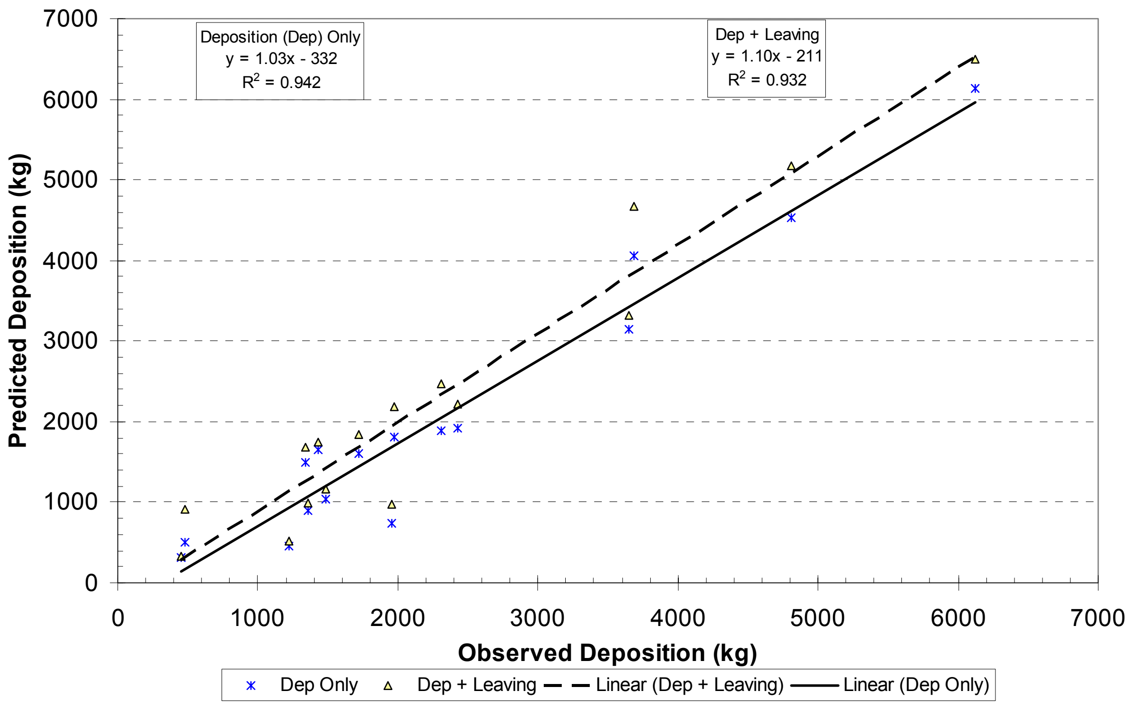

Figure 3. Regression relationships between observed and predicted sediment deposition and the sum of sediment deposition and sediment leaving buffers under high traffic.

The close agreement of predicted and observed values for sediment deposition are indicated by a high ME statistic (approaching 1) which indicates the model's ability to predict sediment deposition in this analysis. The ME statistic for sediment deposition was high at 0.90 indicating that the model was efficient in predicting sediment deposition from the road sections in the investigation. The ME statistic coupled with the regression analysis results clearly indicate that the model adequately predicts sediment deposition from the 16 Coastal Plain road sections.

It is apparent that WEPP may be predicting road erosion rates similar to observed rates, but is underpredicting deposition. There may be several reasons for this. Since the year of data collection was preceded by three dry years, the year of the study could have had higher infiltration rates on these dry soils compared to the LTA conditions predicted by WEPP software. Another possible source of underprediction for deposition is that the hydraulic conductivity for the forest buffer is specified as 30 mm hr-1 for sandy loam conditions. This is a conservative value and may be less than the hydraulic conductivity on this site. The WEPP soil contains 70 percent sand, compared to 76 percent for Dothan, 63 percent for Florela, and 76 percent for Orangeburg. The lower sand content in WEPP for two of the three soils may also have contributed to lower deposition rates. The online WEPP interface used for our predictions does not allow the user to evaluate different textures. Future studies could use the WEPP windows interface to evaluate the effects of soil water content and soil texture on deposition rates, but such an analysis is beyond the scope of this paper.

The road sections in this investigation were modeled as receiving high intensity traffic over the 30-year simulation period which may not have been the case for the entire period. The road sections likely received high traffic during periods of management prescriptions which occurred periodically over the 30 year simulation period. In addition, high intensity traffic is often encountered during the fall (October - January) game hunting season in this region. These periods of high intensity are expected to be periods that would have accelerated erosion losses from the forest roads in the investigation. However, the roads were also modeled as receiving low intensity traffic to provide a range of sediment deposition values predicted by WEPP. The results of the low intensity traffic predictions are provided in Table 3. Predicted sediment deposition ranged from 120 to 1500 kg and was underpredicted for all road sections except Site 3. The percent error associated with predictions averaged nearly 70 percent for the 16 road sections. This is because the low traffic option reduces the erodibility values in the WEPP soil file by 75 percent. The difference was considerably greater than the high intensity traffic scenario presented in Table 2. The R-square values (0.84 and 0.74) of the regression between observed and predicted sediment deposition suggested more scatter than found for predictions of the high traffic condition (Figure 4). This difference in predicted and observed sediment deposition is primarily attributed to the traffic intensity fluctuations discussed above. The observed sediment deposition was likely similar to those predicted for the low traffic situation during low traffic periods however during the high traffic periods accelerated soil erosion and sediment deposition occurred for the road sections.

Table 3. Observed and predicted values for sediment deposition in buffer and leaving buffer for low traffic for each of the 16 road sections in the investigation.

Site	Bulk Density g/cm^{-3}	Observed Deposition kg	WEPP Estimate Deposition kg	WEPP Estimate leaving Buffer kg	% Leaving Buffer	WEPP Estimate Dep + Leaving kg	% Error Dep	% Error Dep + Leaving
1	2.3	4812.4	1280.5	411.0	32.1%	1691.6	73.4%	64.9%
2	2.1	452.7	120.6	19.3	16.0%	139.9	73.4%	69.1%
3	1.6	483.8	586.5	251.9	42.9%	838.4	-21.2%	-73.3%
4	1.8	1429.1	275.4	85.3	31.0%	360.7	80.7%	74.8%
5	2.5	1954.5	457.7	169.9	37.1%	627.6	76.6%	67.9%
6	2.3	1222.7	243.8	45.2	18.6%	289.0	80.1%	76.4%
7	2.2	2427.3	669.2	210.2	31.4%	879.4	72.4%	63.8%
8	2.3	2305.2	920.6	360.9	39.2%	1281.5	60.1%	44.4%
9	2.2	1716.2	427.8	115.0	26.9%	542.8	75.1%	68.4%
10	2.3	3688.2	969.4	216.4	22.3%	1185.9	73.7%	67.8%
11	2.1	3647.6	809.0	108.8	13.5%	917.9	77.8%	74.8%
12	2.1	1339.9	516.4	146.1	28.3%	662.5	61.5%	50.6%
13	2.0	6121.6	1474.2	189.6	12.9%	1663.8	75.9%	72.8%
14	1.6	1481.3	388.9	94.5	24.3%	483.4	73.7%	67.4%
15	2.3	1978.0	551.7	228.4	41.4%	780.1	72.1%	60.6%
16	2.1	1355.9	249.9	61.4	24.6%	311.4	81.6%	77.0%
Average	2.1						67.9%	58.0%

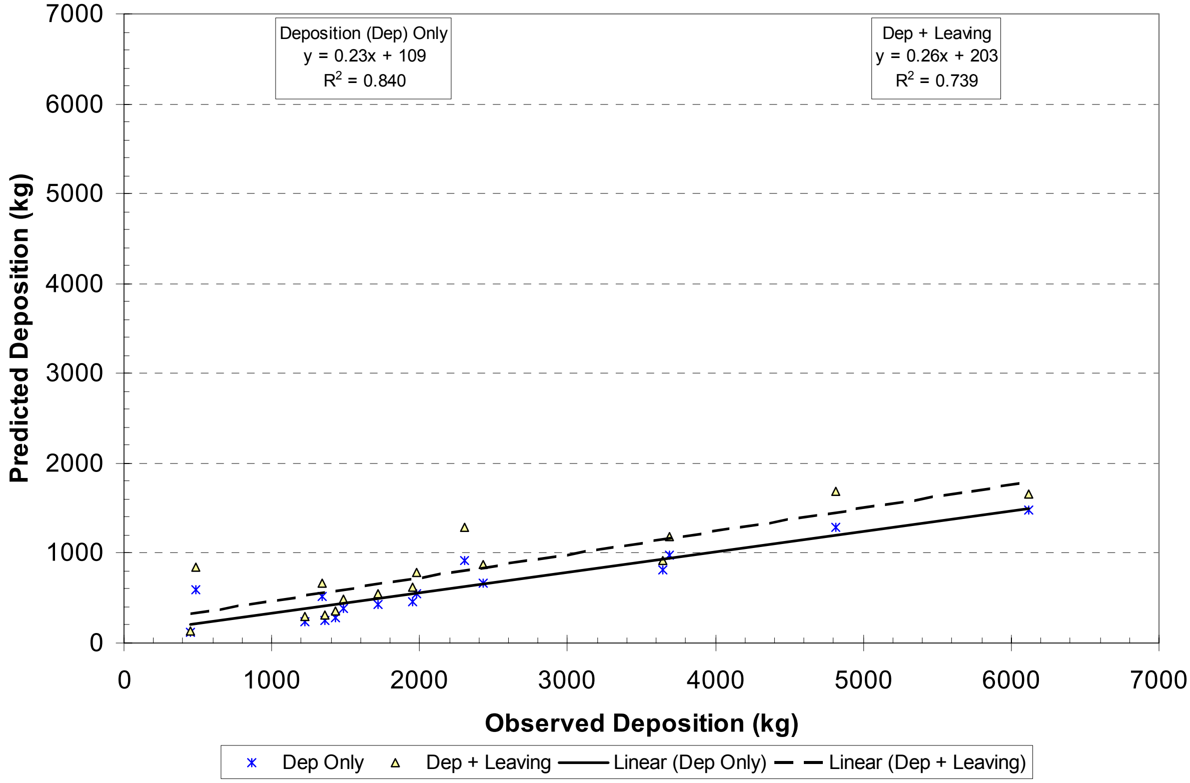

Figure 4. Regression relationships between observed and predicted sediment deposition and the sum of sediment deposition and sediment leaving buffers assuming low traffic.

This investigation of sediment deposition from road sections quantified visible sediment deposition in deposition areas downslope of road sections which likely is a conservative estimate of sediment deposition (and soil erosion). An undetectable (non-measurable) quantity of sediment was likely delivered to the forest floor or in some instances to channel systems. The method utilized to quantify sediment deposition has a disadvantage in quantifying thin layers of sediment or residue remaining on the forest floor or litter. This shortcoming is also compounded by neglecting the smaller fraction (clay fraction) of sediment that remains suspended for further distances downslope and fails to leave a clear deposition zone. In addition, the deposition areas measured were the result of several years of stormwater runoff which may have transported previously deposited sediment further downslope or to channel systems which removed them from the visible deposition zone. This is definitely a possibility in the geographic area where the study was conducted due to several tropical storm systems that passed through the area during the study. Tropical systems typically result in excessive amounts of rainfall at high intensities (greater than 100 year events) which can have a flushing effect on sediment deposition areas below forest roads.

4.0 CONCLUSIONS

Field experimental data were collected on sediment deposition downslope of 16 forest road sections on the Conecuh National Forest in the Coastal Plain region of Alabama. Road characteristic and deposition data were measured and used as input variables for predictions of sediment deposition with the Water Erosion Prediction Project (WEPP: Road). The mean road section length (slope length) was 45 meters and the mean road gradient was 5 percent for the 16 road sections in the investigation. Sediment deposition areas had an average deposition of 2300 kg and deposition length of 35 meters.

Predictions of sediment deposition in buffers averaged 2000 kg for the 16 road sections based on road characteristics measured and a 30-year climate file for Andalusia, AL.

Analysis found a 15.8 percent error in model predictions of sediment deposition and only a 0.1 percent error in the sum of predicted sediment deposition and sediment leaving buffers under high traffic. These WEPP simulations and subsequent analysis revealed that the sum of predicted sediment deposition in buffers and sediment leaving the buffers closely matched the observed sediment deposition for the road sections under high traffic.

Predicted sediment deposition for the high traffic condition was similar to observed values for the 16 road sections based on a paired t-test. The high model efficiency (ME = 0.90) and R^2 value (0.94) for sediment deposition indicated that the model adequately described sediment deposition for the 16 road sections over the 30-year simulation period. Additional work and field studies are required to investigate fraction sediment delivery in buffers and leaving buffers at increasing distance from road sections. This additional work will assist modelers in gaining a better understanding of sediment movement downslope of road sections and to validate model predictions of sediment deposition in buffers and leaving buffers.

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