CHAPTER 2. ANALYSIS OF FINDINGS

The ATV study was effectively designed to answer three questions.

1. On a continuum from undisturbed to highly disturbed, are the natural resources being affected by ATV use? Is change occurring?

2. To what degree are they affected. Is the disturbance level low, moderate, or high?

3. Do vehicle designs and/or the manner in which the vehicles (sport and utility models) are equipped make a difference?

This chapter explores ATV disturbance levels to soil and vegetation in response to these three questions. Two analytical tools were uses to collect the results from ATV traffic, the trail disturbance class matrix and rainfall simulation. Analyzing information from both sources provided conclusive information about how ATVs affect soil and vegetation.

Another expectation was that dust generated by ATV activity may have an affect on vegetation and the soil migration (through the air) that was occurring contributes to soil erosion.

A dust study was conducted at Land Between the Lakes, Kentucky, to quantify soil loss caused by the effects of ATV trafficking. This study is included in the appendix C.

Disturbance Classes

An expectation was that wheel slip and vehicle weight would produce a continuum of disturbances from none to unacceptable. Rather than attempt to measure each structural characteristic of the natural environment along this continuum, three disturbance classes, low, medium, and high, were proposed. The three determining characteristics were litter and vegetation, trail width, and ATV rut depth.

Removal of litter and vegetation causes visual impacts and increases soil erosion. The low disturbance class had 0- to 30-percent ground cover loss with few exposed roots or rocks. The medium disturbance class was characterized by 30- to 60-percent ground cover loss; small roots exposed; and broken, fractured, and exposed rocks. As roots and rocks were increasingly exposed and litter and vegetation were reduced, the disturbance condition moved toward high. The high disturbance class was characterized by greater than 60-percent ground cover loss and exposed roots and rocks. As noted before the descriptors in table 6 are adapted from McMahon (1995), Page-Dumroese et al. (2000), and Meyer (2002). Generally these

Table 6—Trail disturbance class matrix.

	Low Disturbance	Medium Disturbance	High Disturbance
Litter and vegetation	0- to 30-percent ground cover loss, small roots exposed, rocks no more exposed than natural conditions.	30- to 60-percent ground cover loss, small roots exposed and broken, rocks exposed and fractured.	Greater than 60-percent ground cover loss, large roots exposed and damaged, large rocks worn around or displaced.
Trail width (both tread and displaced material)	54 inches or less.	Between 54 and 72 inches. Some trail braiding. Evidence of width increasing.	72 inches or greater. Braided trails evident. Trail width is growing.
ATV rut depth	Ruts less than 3 inches deep.	Ruts 3 to 6 inches deep.	Ruts greater than 6 inches deep.
TOTALS			

references used either a set of descriptions for unacceptable conditions or had four to six classes of disturbance. The present study chose three classes.

Trail width was a key indicator of trail conditions. A trail width of 54 inches or less was rated as a low disturbance class. As the width increased from 54 to 72 inches, the condition was rated a medium disturbance class, and a width greater than 72 inches was rated a high disturbance class.

ATV rut depth was the final indicator of trail conditions. A low rating was from no ruts up to 3-inch-deep ruts; a medium rating was 3- to 6-inch-deep ruts; and a high rating was greater than 6-inch-deep ruts.

To use the disturbance class matrix, an observer walked along a trail section and made a qualitative judgment, or in a few cases a quantitative measurement, for each entry in the matrix by circling the appropriate description. After all of the descriptors had been rated, the number of circles in each column (disturbance class) was totaled. The disturbance class corresponding to the column with the highest total was deemed the condition of that trail section. Ties between low and medium or between medium and high were rounded down. Any observation of high resulted in a condition classification of at least medium.

Analysis of Disturbance Classes

The experimental design for the ATV traffic was one loop for each combination of vehicle and tire type, for a total of four loops at each site. Each loop had four trail features, and each feature was rated with the condition class matrix after approximately every 40 passes. While this results in a large number of observations, there are no replications in the experimental design. Further, the number of ATV passes was not the same on each loop, and the goal of reaching the high condition was not achieved at all sites.

Frequently, the data say only that riding stopped after 500 passes and the trail condition was medium. From this information one can conclude only that it would have taken more than 500 passes to reach the high condition. There are instances where a similar statement has to be made for the medium class, as well. It is not possible to average an observation of 150 passes and one of greater than 500 passes.

Data that measure lifetime—or the length of time until the occurrence of an event—are called lifetime, failure time, or survival data. Classic examples are the lifetime of diesel engines, the length of time a person stays on a job, or the survival time for heart-transplant patients. An intrinsic characteristic of survival data is the possibility for censoring observations, that is, the actual number of passes until leaving a class was not observed. A large percentage of censored values results in a low statistical validity. In the ATV study, the corresponding variable of interest is the number of passes before leaving the low or medium condition class. There were occasional censored values for leaving the low condition and a large number of censored ones for leaving the medium condition.

The first step in the analysis of survival data is an estimation of the distribution of survival times, which are often called failure times. Uncensored survival times (i.e., times at which the event actually occurs) are called event times. The survival-distribution function (SDF) is used to describe the lifetimes of the population of interest. The SDF evaluated at *t* is the probability that an experimental unit from the population will have a lifetime exceeding *t*, or

$$S(t) = \Pr(T > t)$$

where *S(t)* denotes the SDF and *T* is the lifetime of a randomly selected experimental unit. For the ATV study, times were synonymous with passes.

To make an SDF, two of the three independent variables (i.e., trail feature, vehicle and tire combination, and sites) have to be combined in order to investigate changes in the third variable. The condition-class-matrix results were used to determine the survival distribution function for (1) sites where trail feature and vehicle type were combined, (2) trail feature where sites and vehicle type were combined, and (3) vehicle type where trail feature and sites were combined. There was an insufficient number of uncensored passes to make a statistical analysis of the transition from medium to high condition class, so only the transition from low to medium is presented.

The median number of passes required to transition from low to medium condition class will be considered to be that corresponding to the 0.50 value of the SDF. When comparing one SDF to another, a lower number of passes for the same value of the SDF is indicative of fewer passes to achieve the same disturbance and, hence, a greater sensitivity to ATV traffic.

Rut-Depth Analysis

Each trail feature had three cross sections measured at the end of each driving day, resulting in replicated rut depth data. The wheel rut depth was measured from top of the berm to bottom of the rut. The depth of any initial rills or ruts was subtracted from that caused by ATV traffic. The three replications were averaged to determine a representative rut depth.

Erosion Determination Methods

Rainfall simulation on 1-meter-square bordered plots was used to determine infiltration and raindrop-splash parameters. The rainfall simulator used a Spraying Systems Veejet 80100 nozzle to approximate the raindrop distribution of natural rainfall.

Rainfall-simulation plots consisted of an upper border and two side borders of 16-gauge sheet metal driven into the soil 2 inches deep. The lower border consisted of a runoff apron flush with the soil surface that drained into a collection trough with a centrally located 1-inch opening. The runoff apron was placed on top of a 1/4-inch-thick layer of bentonite to prevent any water from flowing under the apron. Dimensions of the exposed soil inside the plot were 1 meter by 1 meter.

Two rainstorms with an intensity of 4 inches per hour with 30-minute duration were applied to each plot. The two rainstorms were applied 3 hours apart. The 4 inches per hour, 30-minute-duration storm had a return period varying from 5 years at the Louisiana site to 450 years at the Arizona site. This rainfall intensity and duration were chosen not to represent a specific design storm, but to exceed the expected infiltration rate at each site, thus allowing the entire plot to contribute to runoff. Entire-plot contribution to runoff is a requirement when determining infiltration and erosion parameters from simulated rainfall.

Two soil-moisture samples from each side of the plot were taken at a depth of 0 to 1½ inches before and after each simulated storm. These soil samples were oven-dried overnight at 105 degrees Celsius (°C).

Once runoff began on a plot, timed grab-samples in 500-milliliter bottles were taken each minute for the runoff's duration. These runoff samples were oven-dried overnight at 105 °C to determine sediment concentrations. Water-runoff rates, sediment concentrations, and sediment-flux rates were calculated based on these samples. There were three repetitions of each soil-disturbance class at each site.

Ground cover was measured by counting the number of grid points above vegetation, rocks, or duff in simulation-plot photographs. Each plot photograph was counted twice using different grid orientations.

The WEPP model was used to determine the infiltration and erosion characteristics from the ATV study. The WEPP model (Flanagan and Livingston 1995) is a physically based soil erosion model that provides estimates of runoff, infiltration, soil erosion, and sediment yield considering the specific soil, climate, ground cover, and topographic conditions.

The WEPP model uses the Green-Ampt Mein-Larson model for unsteady intermittent rainfall to represent infiltration (Stone et al. 1995). The primary user-defined parameter is hydraulic conductivity. Interpretation of this parameter is straightforward. Higher values indicate a more rapid infiltration rate and hence, less runoff. The parameter also is an indication of the maximum-rainfall rate that a soil can absorb without producing runoff.

Raindrop splash in the WEPP model is characterized by an interrill-erodibility coefficient, which is a function of rainfall intensity and runoff rate (Alberts et al. 1995). Interpretation of the interrill-erodibility coefficient is also straightforward, although the units of $kg \cdot s \cdot m^{-4}$ are not intuitive. Higher values indicate higher raindrop-splash erosion.

From the rainfall-simulation data, the WEPP parameters of hydraulic conductivity and interrill erosion were determined for each run. The resulting six values (first and second rain for each of the three repetitions) were averaged to determine values for each treatment class at each site. Prerain soil saturation, bulk density, and ground cover as well as plot geometry were entered into the WEPP model. Hydraulic conductivity was determined by minimizing the objective function in equation 1. The objective function (Obj_{hc}) gave equal weight to matching the total rainfall-simulation runoff volume and the peak flow and is shown below.

Equation 1.

$$Obj_{hc} = (RO_{meas} - RO_{WEPP})^2 + (Peak_{meas} - Peak_{WEPP})^2$$

where RO_{meas} was the measured runoff, RO_{WEPP} was the WEPP-predicted runoff, $Peak_{meas}$ was the measured-peak runoff, and $Peak_{WEPP}$ was the WEPP-predicted peak flow. When the appropriate value of hydraulic conductivity was determined, the interrill-erosion parameter was found in a similar iterative manner until the WEPP-predicted soil loss matched the measured-sediment loss. Calculated hydraulic conductivity and interrill-erosion parameters were averaged to represent values for each treatment class at each site.

Weather Measurements

Hourly air temperature and breakpoint precipitation were taken during and after traffic. National Weather Service records from nearby stations were used to supplement locally measured values.

Results

Weather Measurements

Table 7 shows the 5-day antecedent precipitation, total rainfall, and average temperatures for both the ATV traffic and the rainfall-simulation periods. The 5-day antecedent precipitation served as an indicator of soil-moisture content. Noteworthy were the precipitation values in Louisiana, where both traffic and simulation were performed during a very wet period. At least 3 days were lost due to natural rainfall during the rainfall-simulation period. None of the other sites had lost days due to natural rainfall.

Table 7—Precipitation and temperatures during ATV traffic and rainfall-simulation activities for all sites.

Site	ATV-traffic period			Rainfall-simulation period		
	5-day antecedent precipitation (in)	Total precipitation (in)	Average temperature (°F)	5-day antecedent precipitation (in)	Total precipitation (in)	Average temperature (°F)
AZ	0	0	91	0	0	86
KY	0.34	0	59	0.4	2.84	76
LA	3.36	0.95	78	2.09	10.59	79
MN	0.10	0.38	56	0	2.98	60
MO	0	0.72	64	no rainfall simulation		
MT	0.34	0	61	0	0.67	63
WA	0	0	64	0	0.28	67

Disturbance Class Results

The number of passes required to leave the low and medium condition for each site and each trail feature is shown in appendix A. The transition from low to medium and from medium to high was not achieved on some loop-treatment combinations. In these cases, the final number of passes is preceded by a "greater than" symbol (e.g., >160).

Question 1 – Are the natural resources being affected by ATV use?

One of the goals of the study was to answer the question "Are the natural resources being affected by ATV use?" An inspection of the disturbance-class results will be used to answer this question. Table 8 contains data showing the minimum number of passes required to remain in both low and medium classes and the range of passes to achieve medium and high condition classes. For table 8, vehicle and tire combinations were combined as were trail features with only the sites displayed separately. For this level of analysis, these combinations are appropriate. On real trails, there would be a mix of vehicle types and tires. No trail could exist without a mix of curves, straights, uphill, and downhill, so this combination is also appropriate. The minimum number of passes to remain in low represents how quickly some portion of the trail transitioned from the low disturbance class to the medium class. Similarly, the minimum number of passes to remain in medium represents how quickly some portion of the trail transitioned from the medium class to the high-disturbance class. The range of passes to remain in low and medium classes is included.

At all seven sites, some portion of the trail transitioned from low to medium disturbance class in 20 to 40 passes. While the number of days required to achieve this number of passes varies from location to location, this level of ATV traffic could be achieved in one weekend from a moderate-sized ATV group. Not all of the trail had left the low disturbance class, but some combination of vehicle and tire and trail feature was no longer in the low class. Similarly, all seven sites had some portion of the trail transition from the medium to high disturbance class in 40 to 120 passes. This level of ATV traffic could be achieved in less than a month, depending upon trail usage.

Our conclusion is that the natural resources are being affected by ATV use as exhibited by the impacts achieved during the study. It is also reasonable to expect that similar impacts would result to similar natural resources on any national forest and grasslands where similar ATV riding occurs.

Table 8—Minimum and range of ATV passes to remain in low and medium condition classes for all trail features and all vehicle and tire combinations.

Site	Minimum number of passes to		Range of passes to	
	Remain in Low	Remain in Medium	Remain in Low	Remain in Medium
AZ	40	60	40 to >160	60 to > 160
KY	40	40	40 to >320	40 to > 800
LA	30	70	30 to >630	70 to > 730
MN	40	120	40 to >600	120 to > 700
MO	40	80	40 to >560	80 to > 560
MT	40	120	40 to >640	120 to >1,000
WA	20	80	20 to >480	80 to > 960

Question 2 – To what degree are the natural resources being impacted?

The second goal of the study was to answer the question “To what degree are the natural resources being impacted?” This study uses the condition-class matrix to quantify the degree of natural resource impacts. The impacts were caused by three independent variables, namely, sites, trail features, and vehicles and tires. Vehicles and tires will be considered separately in question 3. Combinations of the remaining two impacts, sites and trail features, and the causative agents will be discussed by considering the number of passes required to remain in the low disturbance class.

By site: The survival distribution function for number of passes required to remain in the low disturbance class is shown in figure 6. Visual inspection of this figure suggests that there are differences among the sites, and statistics validates this observation. The p-value for a difference among the sites was 0.067, indicating that one can be 93 percent confident that there is a difference among the sites. The range of median values for the remain-in-low condition class was 80 at Kentucky to 270 at Louisiana. Sites in Arizona, Kentucky, and Minnesota were the most susceptible to ATV traffic; Missouri, Montana, and Washington were intermediate; and Louisiana was the least susceptible for remaining in the low condition class.

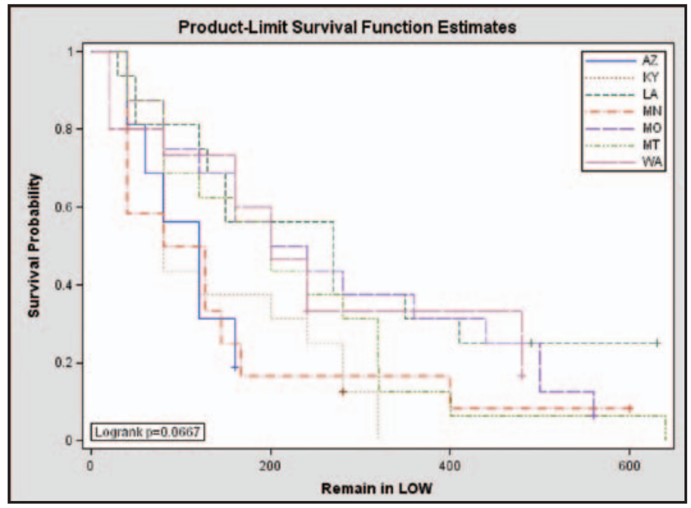

Figure 6—Survival-distribution function for number of passes to remain in low condition class for each site.

Rut depths were measured at three locations in each trail feature at each site, allowing average values to be calculated. ATV passes and average rut depths for each combination of vehicle and tire type as well as each trail feature at each location are shown in figures 7 through 10.

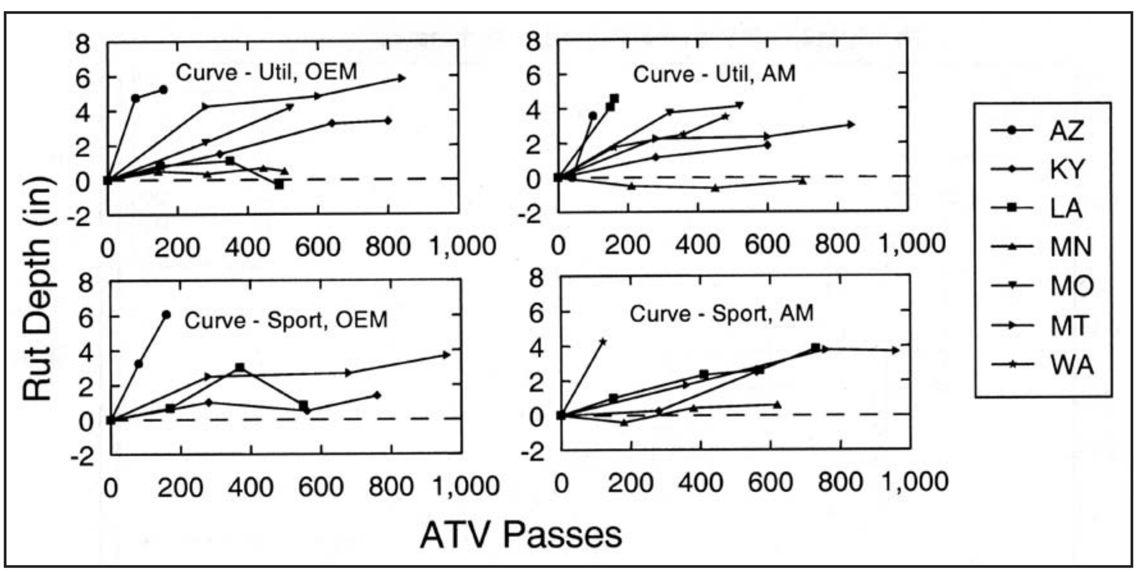

Figure 7—Rut depth and ATV passes for curve trail feature.

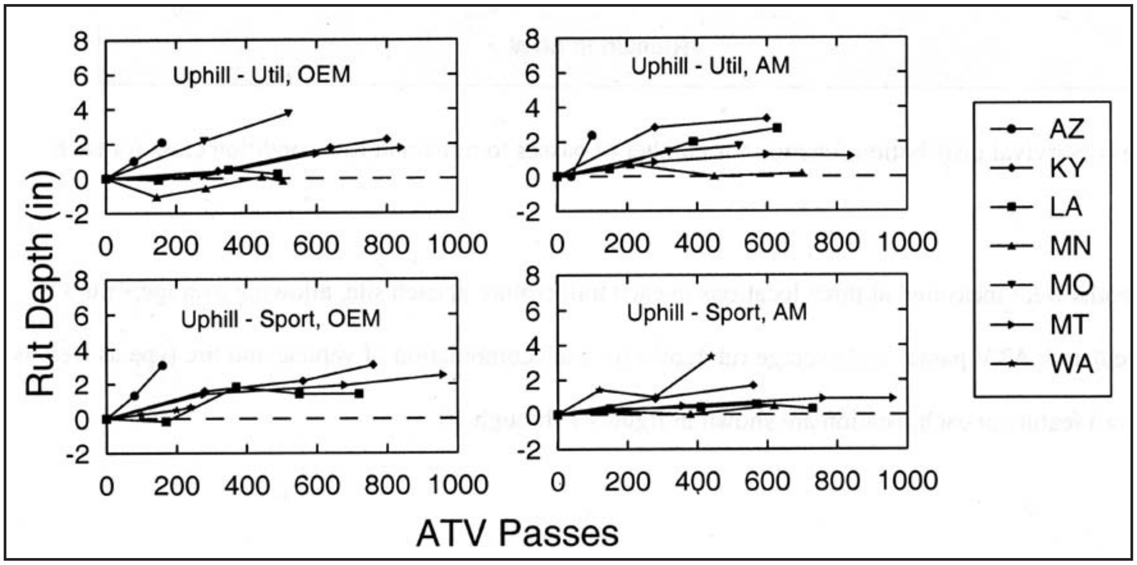

Figure 8—Rut depth and ATV passes for uphill trail feature.

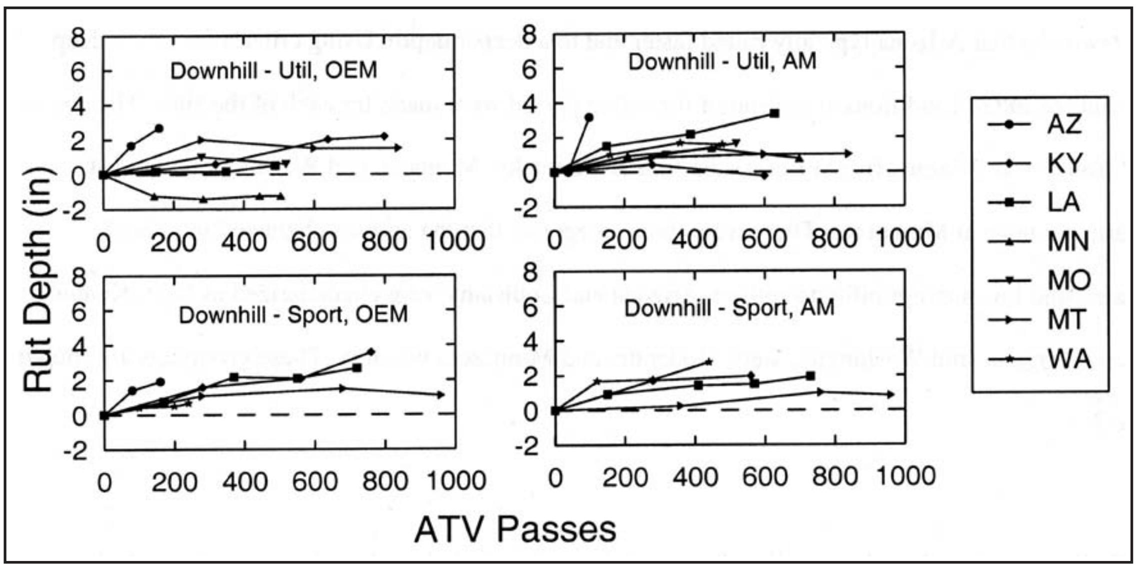

Figure 9—Rut depth and ATV passes for downhill trail feature.

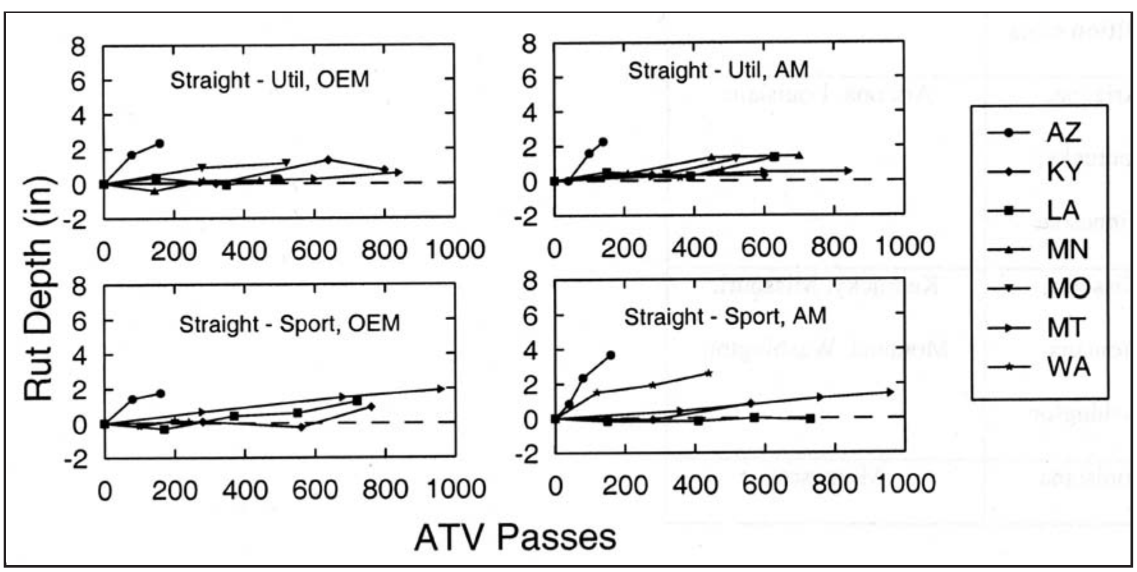

Figure 10—Rut depth and ATV passes for straight trail feature.

It is noteworthy that Arizona typically rutted faster and to a deeper depth. Using criteria of 3-inch-deep ruts, counts of rutted conditions at the end of the riding period were made for each of the sites. The counts ranged from six at Arizona; five at Louisiana; four at Kentucky, Montana, and Washington; three at Missouri; and none at Minnesota. There were three categories that the authors characterize as high-, moderate-, and low-susceptibility to rutting. Arizona and Louisiana were characterized as high; Kentucky, Missouri, Montana, and Washington were moderate; and Minnesota was low. These groupings are shown in table 9.

Table 9—Site groupings based on similar characteristics to remain in low disturbance condition and susceptibility to rutting. Order is highest to lowest.

Remain in low condition class	Susceptibility to rutting
Arizona, Kentucky, Minnesota	Arizona, Louisiana
Missouri, Montana, Washington	Kentucky, Missouri, Montana, Washington
Louisiana	Minnesota

By trail features: The four trail features tested were curves, downhill, straight, and uphill. Figure 11 presents the survival-distribution function for number of passes to remain in the low-condition class. It is clear that the curve feature required fewer passes before it was no longer in the “remain in low condition.” Results of the statistical analysis were that one could be +99 percent confident that there was a difference among the trail features (p-value of >0.0001). The curve was no longer in the low condition in nearly 5 times fewer passes than in the next highest impacted trail feature (40 for the curve compared to 200 for the uphill). The range of median passes to remain in the low-condition class was 40 for the curve to 320 for the straight. Both the uphill and the downhill had median values of 200 passes.

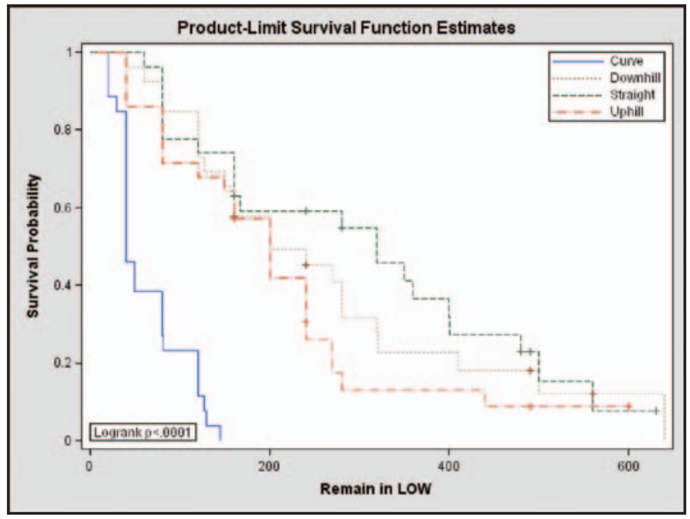

Figure 11—Survival-distribution function for number of passes to remain in low condition for each trail feature.

Using figures 7 through 10, the number of instances of 3-inch-deep or greater ruts was 14 for the curve, 6 for the downhill, 4 for the uphill, and 1 for the straight trail features. The groupings for trail features based on rut depths were (1) curve, (2) downhill and uphill, and (3) straight.

Table 10 displays the rutted condition groups for the overall condition class and the rut depth. The authors conclude that the trail features, in decreasing order of impact, are curves, uphill, downhill, and straight.

Table 10—Trail feature groupings based on similar characteristics to remain in low disturbance condition and susceptibility to rutting. Order is highest to lowest.

Remain in low condition class	Susceptibility to rutting
Curve	Curve
Uphill, Downhill	Uphill, Downhill
Straight	Straight

Question 3 – Do the vehicle and tire combinations tested make a difference in impacts to the natural resources?

The impacts considered are trail condition class and rut generation.

Trail condition class: The survival-distribution function for number of passes to remain in low condition class for combinations of vehicle and tires is shown in figure 12. The range of median passes required to remain in low condition class ranged from 127 for the utility vehicle with aftermarket tires to 200 for the sport vehicle with original equipment manufacturer tire. There was no statistically significant difference between the vehicle and tire combinations tested (p-value = 0.56).

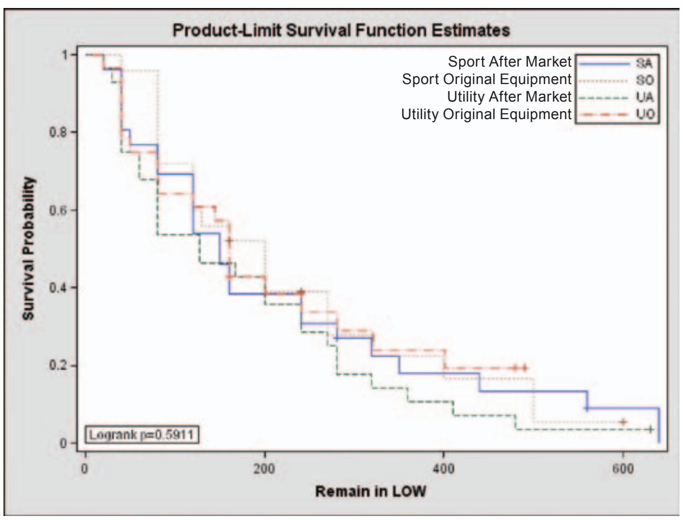

Figure 12—Survival-distribution function for number of passes to remain in low condition class for each ATV and tire combination.

Rut generation: The rut-depth figures are shown in figures 7 through 10. The number of ruts with depths greater than 3 inches—caused by vehicle type and tire combinations—were nine for the utility vehicle with aftermarket tires, six for the sport vehicle with original equipment tires, and five for both the utility and sport vehicles with aftermarket tires. Only two groups resulted from the rut-depth measurements. There does not appear to be a clear order to the vehicle type (see table 11). Therefore, the authors conclude that while ATV traffic does have an impact on the natural resources, we were not able to distinguish differences in impacts among the four vehicle and tire combinations tested.

Table 11—ATV vehicle and tire groupings based on similar characteristics to remain in low disturbance condition and susceptibility to rutting. Order is highest to lowest.

Remain in low condition class	Susceptibility to rutting
SA, SO, UA, UO	UA
	UO, SO, SA

Rainfall Simulations

In order to have each site representative of conditions immediately following traffic, rainfall simulation was intended to immediately follow the ATV traffic. This was achieved at Arizona, Louisiana, and Washington, but not at Kentucky, Minnesota, and Montana due to logistical conflicts between the ATV driving crew and the rainfall simulation crew. At Kentucky, Minnesota, and Montana, the rainfall crew made up to 100 additional ATV passes to reduce natural compaction and remove surface sealing that occurred between the end of traffic and beginning of rainfall simulation.

The study's intent was to attain each condition class at each site and then to perform rainfall simulation on each condition class; however, rainfall simulation on the high-condition class was not always performed. At Minnesota there was no simulation on the high class because it was not achieved by the traffic crew in 1,000 passes. At Montana there was no simulation on the high class because it was achieved only in curves, where it was not possible to install rainfall simulation plots. At Arizona there was no simulation on the medium class because of time constraints. Table 12 summarizes the dates of traffic and rainfall simulation as well as condition classes with rainfall simulation.

The soil texture and grain size measurements for each site are shown in table 13. Textures ranged from loamy sand for Louisiana to gravelly sand for Arizona and Montana. All sites had less than 6-percent clay and, with the exception of Louisiana, had more than 15-percent rock fragments. Mean grain size (d_{50}) ranged from 1.38 millimeters (Arizona) to 0.19 millimeter (Louisiana).

Average ground cover (plants, litter, and rock) for each site and disturbance class for the rainfall simulation plots is shown in table 14. Changes in ground cover with ATV traffic were a major impact. Visually, the reduction of cover distinguishes an ATV trail from the undisturbed forest. Additionally, the ground cover loss increases raindrop-splash erosion because there are fewer plant leaves to absorb the raindrop impacts.

Table 12—Date of traffic, rainfall simulation, and condition classes with simulation.

Site	Traffic Dates	Rainfall Simulation Dates	Und	Low	Med	High
AZ	May 24-26, 2005	May 25-June 7, 2005	✓	✓		✓
KY	Oct. 3-5, 2004	May 21-June 3, 2004	✓	✓	✓	✓
LA	June 4-6, 2004	June 7-July 2, 2004	✓	✓	✓	✓
MN	June 20-23, 2004	July 20-Aug 2, 2004	✓	✓	✓	
MO	Oct. 7-10, 2004	no rainfall simulation				
MT	July 22-24, 2004	Aug 11-21, 2004	✓	✓	✓	
WA	June 14-16, 2005	June 16-July 2, 2005	✓	✓	✓	✓

Table 13—A horizon soil characteristics at rainfall simulation sites sorted by soil texture.

Site	Soil texture	d_{84} (mm)	d_{50} (mm)	d_{16} (mm)
LA	Loamy sand	0.35	0.19	0.05
WA	Gravelly loamy sand	2.86	0.50	0.05
KY	Gravelly sandy loam	3.24	0.48	0.02
MN	Gravelly sandy loam	3.22	0.96	0.02
MT	Gravelly sand	2.40	0.89	0.27
AZ crust	Gravelly sand	2.97	0.95	0.15
AZ	Gravelly sand	3.26	1.38	0.49

Continued ATV use also inhibits plant regrowth in much the same manner as vehicle traffic inhibits plant regrowth on unpaved forest roads. Noteworthy were (1) the decrease in cover from undisturbed to low, (2) the continuing decrease in cover from low through high, and (3) the lower covers at Montana and Washington for all disturbance classes. Montana sites were on a high-elevation forest with less rainfall and, hence, less cover. The Washington site was in a burned area, on a compacted logging road, and at high elevation. Cover at the Arizona site appears unusually high, but was visited in the spring following a wet winter.

Inspection of table 14 suggests that the ground covers for the disturbed classes were not consistent with the definitions of 0- to 30-percent removal, 30- to 60-percent removal, and greater than 60-percent removal. Values in table 13 were taken from the rainfall simulation plots centered on the wheel tracks. These 1-meter-square plots were samples taken from the entire 54- to 72-inch-wide trail where the trail condition assessment was performed. When the area outside the wheel tracks was included, the reduction in cover was consistent with the definitions.

Table 14—Ground cover for rainfall simulations sorted by soil texture.

Class	LA	WA	KY	MN	MT	AZ
Undisturbed	99.9	47.9	99.6	90.8	69.9	96.1
Low	49.5	25.3	42.1	33.5	17.6	42.6
Medium	31.0	6.8	14.7	15.0	3.0	ND
High	32.5	ND	1.3			21.4
ND indicates no data because no rainfall simulation was performed on these plots						

Hydrographs and sediment concentrations for each initial run on the undisturbed, low, medium, and high condition classes are shown in figures 13 through 18. The hydrographs and sediment concentrations represent the average of the three repetitions for each disturbance class.

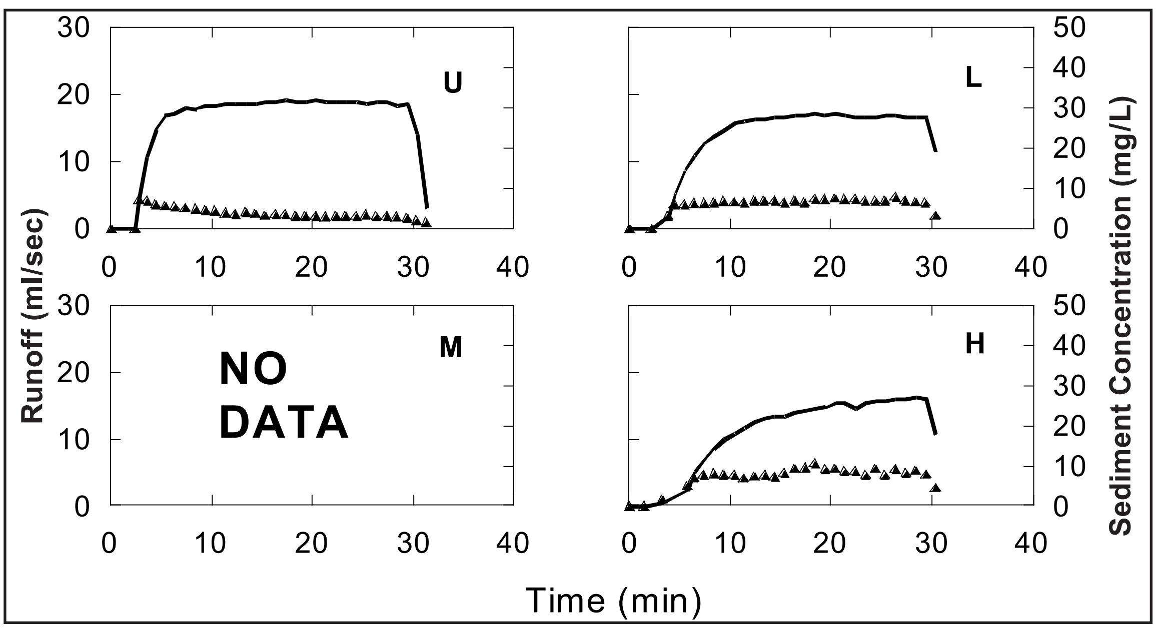

Figure 13—Hydrograph and sediment concentrations for initial run at Arizona.

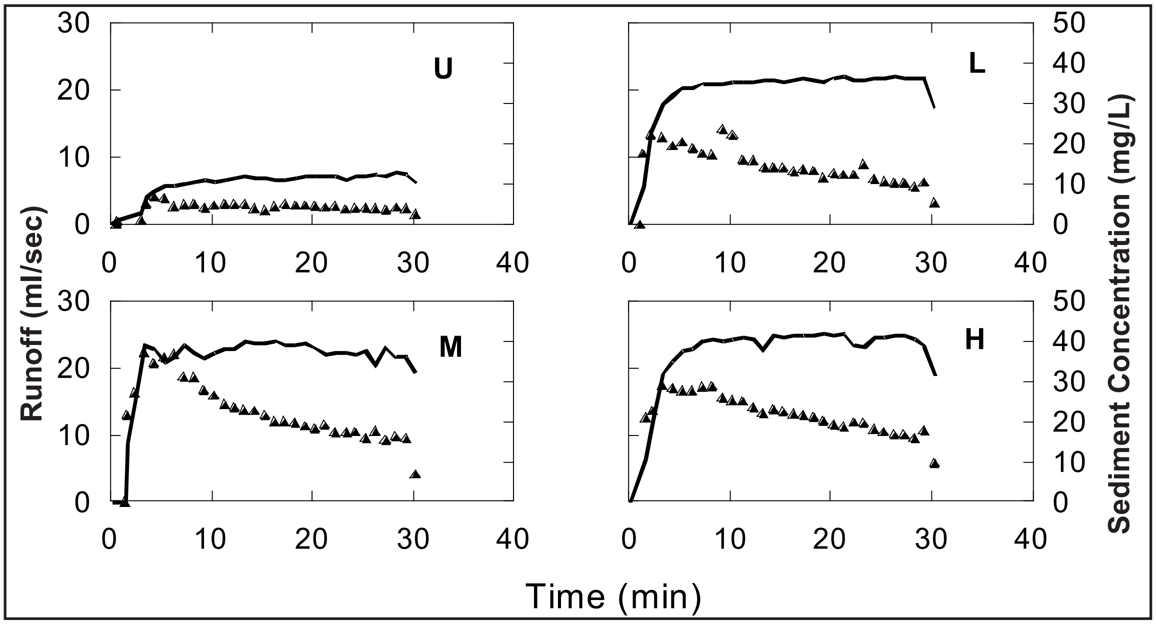

Figure 14—Hydrograph and sediment concentrations for initial runs at Kentucky.

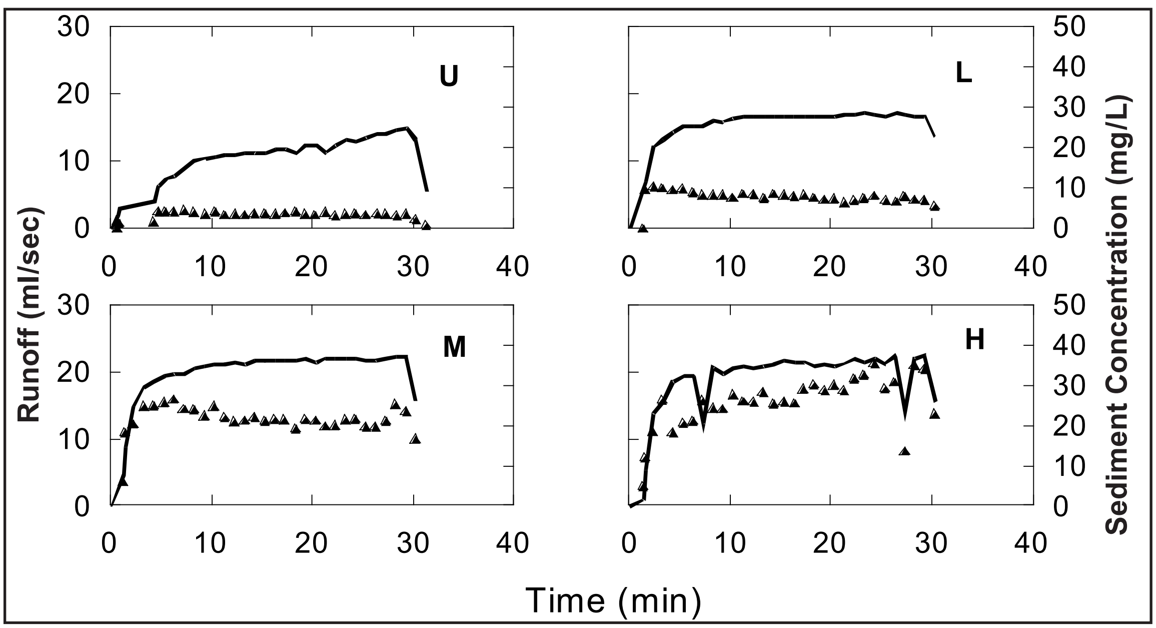

Figure 15—Hydrograph and sediment concentrations for initial runs at Louisiana.

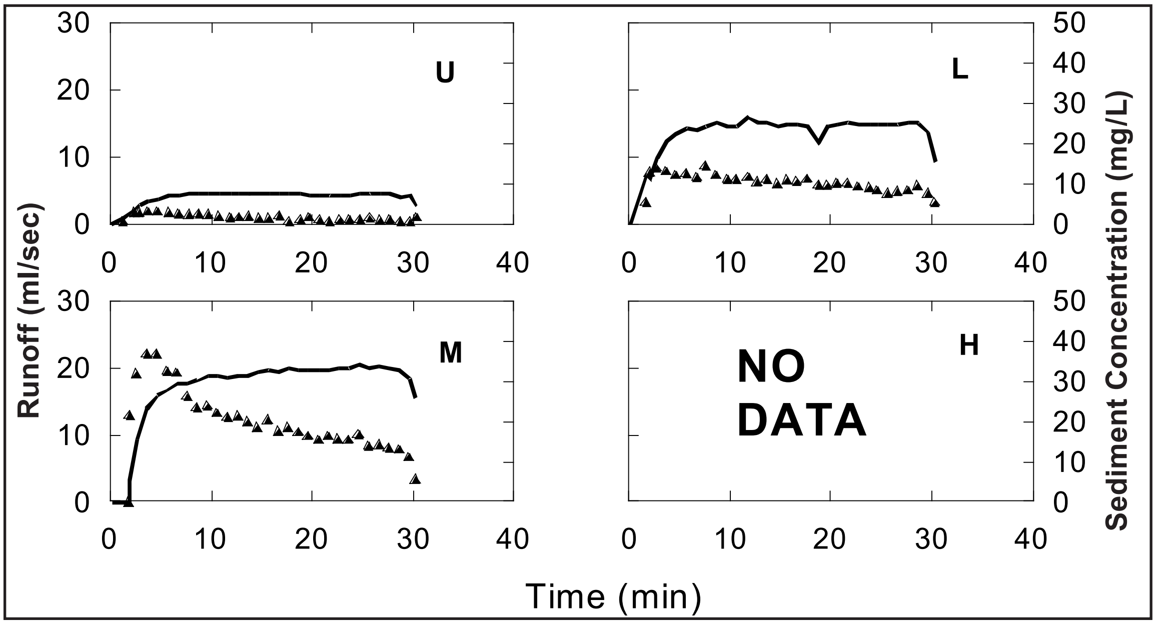

Figure 16—Hydrograph and sediment concentrations for initial runs at Minnesota

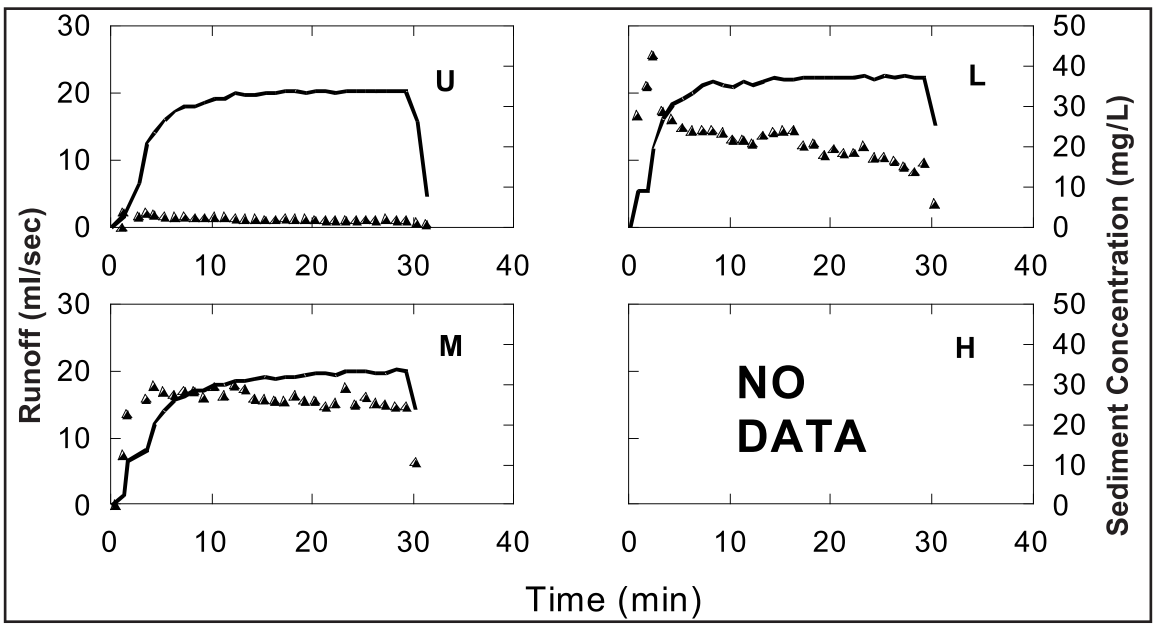

Figure 17—Hydrograph and sediment concentrations for initial runs at Montana.

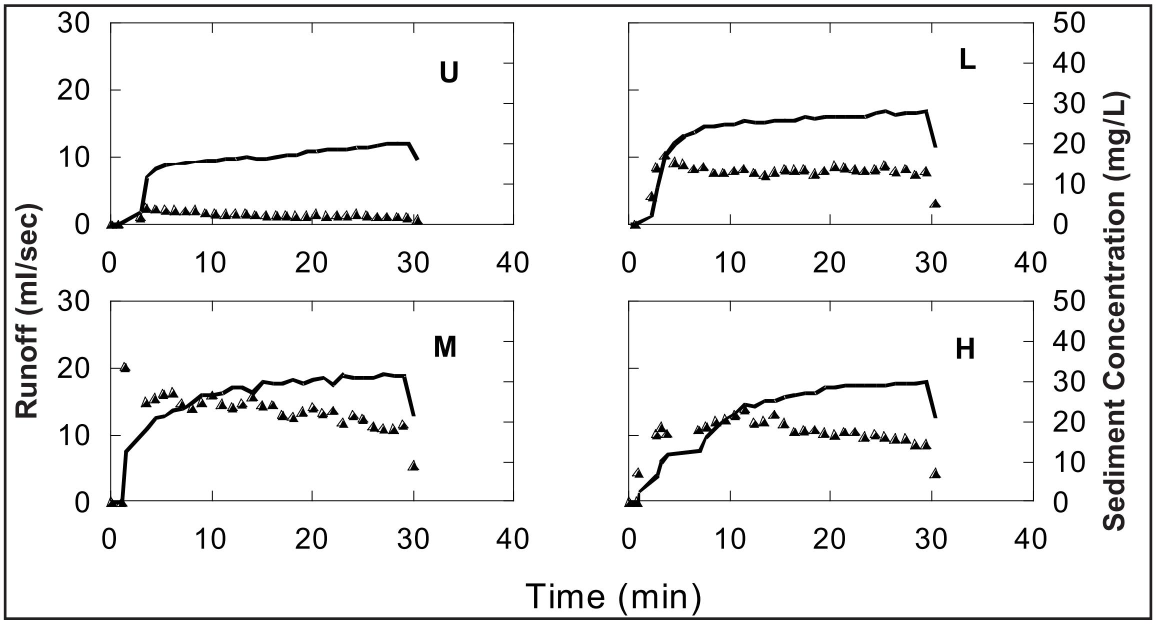

Figure 18—Hydrograph and sediment concentrations for initial runs at Washington.

From the hydrographs and sediment-concentration graphs, the runoff volume and sediment mass were determined. Figure 19 shows the runoff volume for both rainfall simulations for each site and condition class. Noteworthy in this figure are (1) the range of runoff volume for the undisturbed condition, (2) the reduced range for each of the condition classes, and (3) trends with increasing condition class.

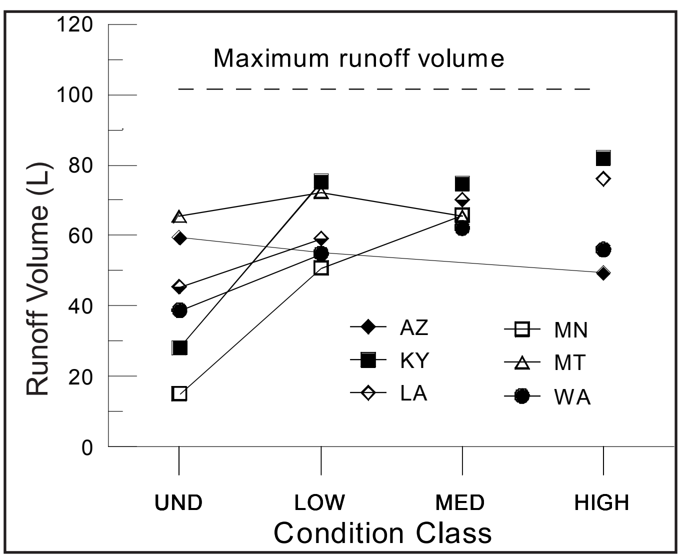

Figure 19—Runoff from both rainfall simulations with all trail features combined for all locations.

Runoff volume in the undisturbed condition varied from 15 to 65 liters, a ratio of 4.3:1. This ratio decreased to 1.5:1 for the low, 1.2:1 for the medium, and 1.7:1 for the high. These ratios represent the variation between sites for the four condition classes. The authors expect that these ratios would apply nationwide for similar soils.

Sediment loss for each site and condition class is shown in figure 20. These values represented the total sediment loss for both rainfall simulations. Notable are (1) apparent clustering of sediment-loss values for the undisturbed class, and (2) the increase in sediment values with increasing disturbance levels.

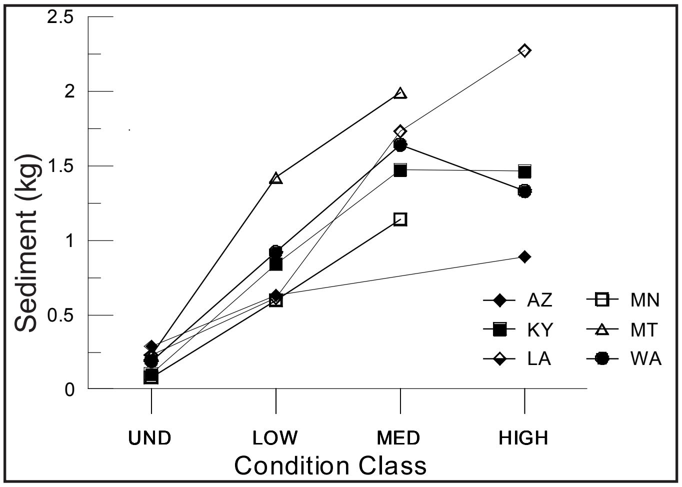

Figure 20—Sediment loss from both rainfall simulations with all trail features combined for all locations.

The ratio of sediment-loss values for the undisturbed class was 3.6:1, for the low class 2.4:1, for the medium class 1.7:1, and for the high disturbance class 2.6:1. These ratios represent the variation between sites for the four conditions classes and would be expected to be similar nationwide for similar soils.

Discussion of Rainfall Results

There were three types of hydrographs. The first, and most common, was characterized by runoff from the undisturbed class being notably lower than any of the disturbed classes. In this group were Kentucky, Louisiana, Minnesota, and Washington. The second group was characterized by runoff from the undisturbed class being comparable to the disturbed classes. Montana was in this group. The final group was characterized by the runoff from the undisturbed class being greater than from the disturbed classes. Arizona fell in this group.

The group characterized by runoff from the undisturbed class being notably lower than the disturbed class was expected. The ATV traffic compacted the soil, reducing infiltration and increasing runoff. This is the phenomenon that occurs on unsurfaced forest roads. Vehicle weights and number of passes are different, but the mechanism of traffic causing compaction and increased runoff appears to be similar.

Runoff from the undisturbed and the disturbed classes were comparable only on the Montana site. This site was characterized by a soil texture of gravelly sand, mean diameter of 0.89 millimeters, and one of the lowest ground covers. The geologic parent material was decomposed granite, and the soil-moisture contents were low. In unpublished studies at the Forest Service's Rocky Mountain Research Station, Robichaud (2006) found that similar undisturbed decomposed granite soils exhibited high runoff rates. Bone-dry soil, bone-dry organic matter, and a volcanic ash layer were believed to be responsible for this runoff response. In the ATV study performed in August 2004, the prerain soil moisture saturation for all nine plots was 14 percent, the organic matter was quite dry, and there was a volcanic ash layer.

The final group was characterized by high runoff from the undisturbed plot and lower runoff from the disturbed plots. The sole member of this group was Arizona. Prior to ATV traffic, there was a soil crust, which subsequent traffic destroyed and exposed the underlying sand-texture soil. Table 13 shows that the crust soil layer had a smaller d_{84} and d_{50} which would tend to reduce infiltration compared to the underlying soil. As the soil crust was destroyed, higher infiltration rates and less runoff would occur.

Sediment concentrations tended to increase with increasing disturbance levels. The Montana site (figure 17) was a good example of this trend. Sediment concentrations during the rainfall simulation predominantly decreased (see figures 14, 16, 17, and 18 for Kentucky, Minnesota, Montana, and Washington, respectively). The Arizona site (figure 13) had sediment concentrations that remained relatively constant during the simulation. At Louisiana (figure 15) the undisturbed, low, and medium classes decreased during the simulation, while the high class had increasing sediment concentrations.

A decreasing sediment concentration was indicative of the flow removing sediment faster than it could be generated by raindrop splash, concentrated flow, or small-bank sluffing. This is the condition usually encountered on native-surface roads and is often called armoring. A constant sediment concentration rate was caused by either of two mechanisms. One was a balance between sediment removal by flow and generation by splash, concentrated flow, or bank sluffing. The other was by sediment being generated more rapidly than it could be removed. Due to the higher slopes of the ATV trails, generation likely exceeded the removal rate. The increasing sediment concentration found on the high disturbance class at Louisiana was caused by needle-dams breaking and releasing their dammed up water and sediment into the overland flow.

A trend of increasing runoff with increasing disturbance class was exhibited by four of the six sites, namely Kentucky, Louisiana, Minnesota, and Washington. These are the same four that were grouped together by hydrograph appearance and can be explained by increased compaction and reduced infiltration caused by ATV traffic. The Montana site showed an increase from undisturbed to low followed by a decrease from low to medium. These changes are attributable to removal of the water-repellent duff layer and breakup of the water repellent conditions of the dry soil by ATV traffic. The Arizona site showed a continuing decrease in runoff from undisturbed to low to high due to the breaking of the soil crust by ATV traffic.

All six sites had increasing sediment loss with increasing condition class from undisturbed through low to medium. Only Washington had less sediment loss on the high condition class than the medium, with the remaining five sites continuing to have increasing sediment loss as the condition class increased.

Erosion Parameters

Erosion parameters of hydraulic conductivity and interrill erosion were determined for each set of rainfall-simulation tests. The purpose was to eliminate differences in runoff and sediment loss due to differences in plot slope and antecedent moisture condition. Comparison of hydraulic conductivity and interrill-erosion coefficients between sites is an improvement over comparing runoff and sediment loss because differences in plots have been taken into account. Additionally, these erosion parameters are needed for the WEPP model to make erosion predictions.

Figures 21 and 22 display the hydraulic conductivity (h_c) and interrill-erodibility coefficient (K_i) for each site and each condition class. Smaller values of hydraulic conductivity (h_c) result in less infiltration and more runoff, while larger values of K_i result in more sediment loss.

There were three hydraulic conductivity responses to increasing condition classes. The most prevalent one was a continuing decrease in h_c as the condition class went from undisturbed to low to medium to high. Sites in this category were Kentucky, Louisiana, Minnesota, and Washington.

This indicates that ATV traffic compacted the soil, increased the runoff, and decreased the hydraulic conductivity. The second type was characterized by Montana, where the condition class appeared to have little impact on the hydraulic conductivity or the runoff. The final type was an increase in hydraulic conductivity with increasing condition class. Arizona was the sole member of this group. Groupings by h_c were the same as previous ones.

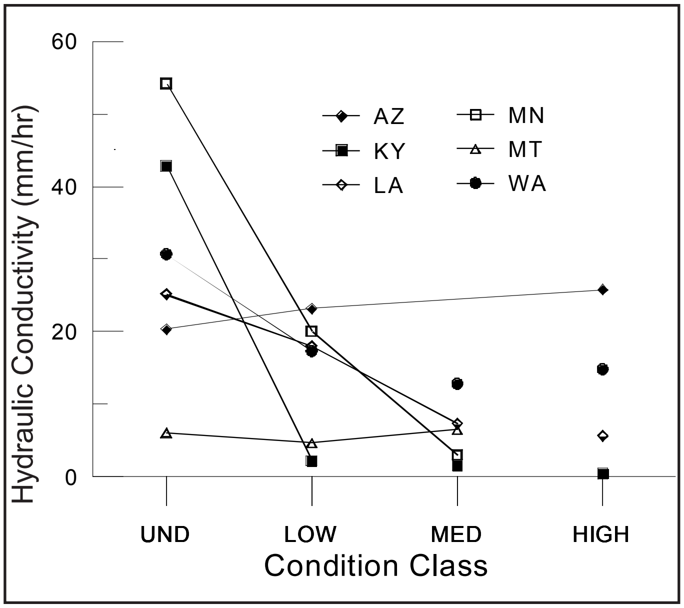

Figure 21—Hydraulic conductivity.

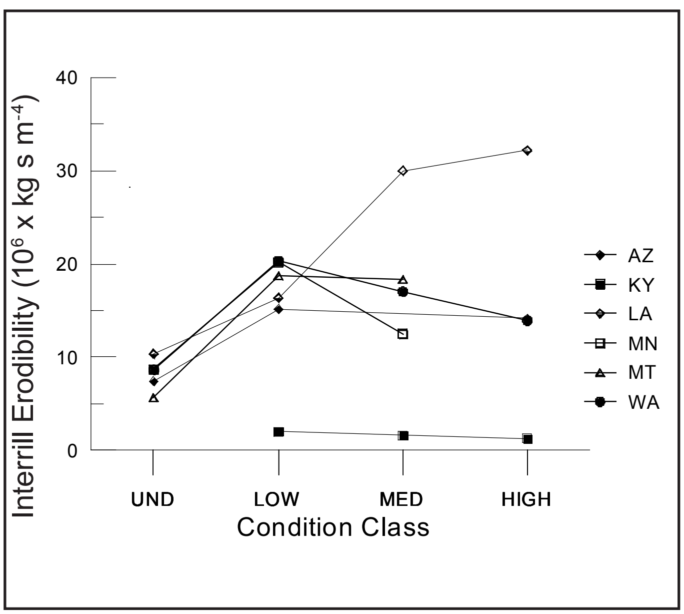

Figure 22—Interrill erodibility.

Statistical Analysis

A statistical analysis was performed to determine if condition class, site, and interaction between condition class and site could explain the variability in both hydraulic conductivity and interrill erosion. The results are shown in tables 15 and 16.

For hydraulic conductivity, the analysis showed that some linear function of the model parameters was significantly different from zero (p-value of < 0.0001). This p-value and the model r^2 means that some combination of condition class, site, and interaction between the two explained 74 percent of the variation in the hydraulic conductivity values. The condition-class variable had a p-value of < 0.0001, indicating that there was a significant difference among the undisturbed, low, medium, and high conditions. The site variable had a p-value of < 0.0001, indicating that there was a significant difference among the locations where the study was performed. The interaction (condition by site with p-value of < 0.0001) indicated that trends in condition class were not the same at all the sites visited.

The analysis for interrill erosion indicated similar results, namely that some linear function of the model parameters was significantly different from zero (p-value of < 0.0001) and the combination of condition class, site, and interaction between the two explained 63 percent (value of model r^2) of the variation in the interrill-erodibility parameter. Results indicated that there were significant differences among the disturbance classes (p-value of < 0.0001) and among the sites (p-value of 0.0001). The interaction was also significant (p-value of 0.008) with interrill erodibility trends among condition classes not being the same at all the sites.

Table 15—Statistical analysis of hydraulic conductivity equals condition class, site, and interaction between condition class and site.

Source	Degrees of Freedom	Mean Square	F	p-value
Model	20	1160	15.1	< 0.0001
Error	105	77		
Condition class	3	2968	38.6	< 0.0001
Site	5	811	10.6	< 0.0001
Cond * site	12	668	8.7	< 0.0001

Table 16—Statistical analysis of interrill-erosion parameter equals condition class, site, and interaction between condition class and site.

Source	Degrees of Freedom	Mean Square	F	p-value
Model	19	393	8.6	< 0.0001
Error	95	46		
Condition class	3	741	16.27	< 0.0001
Site	5	915	20.11	< 0.0001
Cond * site	11	115	2.53	0.008

Because there was interaction between classes and sites, the analysis for both hydraulic conductivity and interrrill-erosion parameter was investigated further. Those results (appendix A) suggested that the four condition classes could be reduced to two; undisturbed and disturbed, because there was often no statistical difference between the low, medium, and high classes. Table 17 displays the hydraulic conductivity and interrill-erosion coefficient after reclassifying the condition class into either undisturbed or disturbed ($\alpha = 0.05$).

Table 17—Hydraulic conductivity and interrill-erodibility coefficient from both rainfall simulations after reclassifying disturbance classes into either undisturbed or disturbed.

Site	Hydraulic Conductivity (h_c) (mm/hr)		Interrill-Erodibility Coefficient (K_i) (10^6 * kg s m^{-4})	
	Undisturbed	**Disturbed**	**Undisturbed**	**Disturbed**
AZ	20.33	24.50	**7.42**	**14.67**
KY	**42.83**	**1.42**		1.60
LA	**25.17**	**10.33**	**10.33**	**25.94**
MN	**54.17**	**17.25**	8.67	18.92
MT	6.05	5.58	**5.68**	**18.50**
WA	**30.67**	**15.00**	**8.62**	**17.08**
Values in **bold** indicate statistically significant differences at the 95-percent confidence				

One can conclude that a site is either undisturbed or it is disturbed, and attempting to quantify levels of disturbance from a hydraulic conductivity and raindrop splash viewpoint are unlikely to be successful. Robichaud (2000) observed a similar result when measuring sediment loss from three levels of burn severity. He concluded that there was either low sediment loss from the unburned or high sediment loss from the low-, medium-, or high-burn severity. In the ATV case, a site is either disturbed or it is not, with the undisturbed producing low sediment loss and the disturbed producing high sediment loss.

Sediment loss is a combination of runoff and raindrop-splash erosion. Investigation of changes in both hydraulic conductivity (h_c) and raindrop splash (K_i) can indicate how erosion changes as a result of ATV traffic. It is possible for h_c and K_i to independently increase, decrease, or remain the same, resulting in a total of nine combinations. A decrease in h_c results in an increase in runoff. This additional runoff has the potential to increase sediment loss solely due to the increased runoff. In combinations where the K_i also increases, sediment loss has the potential to increase in excess of that from just the increase in runoff alone. Actual erosion increases would, however, depend on the transport capacity of the runoff, which is primarily a function of the slope steepness.

The combination that results in the greatest increase in erosion would be a decrease in h_c and an increase in K_i. Runoff would increase and the erodibility of the soil would increase, resulting in an increase in sediment loss due to both the runoff and the more erosive soil. The least impact, and in fact a reduction in sediment loss, would result from h_c increasing and K_i decreasing. In this case, runoff would decrease and the soil's erodibility would decrease, resulting in less sediment than before the ATV traffic.

In this study there were only four of nine possible combinations of changes in h_c and K_i. The sites with the largest potential increase in sediment loss were Louisiana and Washington, where h_c decreased and K_i increased. Both of these sites had a rock-free soil texture of loamy sand. Note that Washington had a sufficiently high fraction of rock fragments to make its classification a gravelly loamy sand. At these locations, ATV traffic would be expected to increase runoff and increase sediment loss in excess of that caused by increased runoff. At both of these sites, hydraulic conductivity was approximately halved after traffic, and K_i was approximately doubled after traffic. These sites and ones with similar soils would be expected to have increased runoff and increased sediment loss in excess of that due to the increased runoff when compared to undisturbed areas.

Hydraulic conductivity decreased and interrill erosion remained unchanged at Minnesota and Kentucky. Soil texture for both of these sites was gravelly sandy loam. Here, runoff would increase due to impacts of ATV traffic. At Minnesota and Kentucky, post-traffic h_c's were 1/3 and 1/40 of their original values, respectively. Both sites would be expected to have large increases in runoff from ATV trails. The increased runoff would potentially increase erosion in proportion to the increase in runoff. These sites—and ones with similar soils—would be expected to have increased runoff and increased sediment loss proportional to the increased runoff when compared to undisturbed areas.

At the Arizona and Montana sites, h_c was unchanged and K_i increased, indicating that runoff would be unchanged but sediment loss would potentially increase due to the soil's increased erodibility. Both Arizona and Montana had soil textures of gravelly sand that did not compact during ATV traffic. Additionally, Arizona had a soil crust on the undisturbed condition, which ATV-traffic destroyed. Because the sand was not compacted, there was no statistically significant change in h_c from the undisturbed to the disturbed condition. The soil erodibility at Arizona doubled, while at Montana, it tripled. These sites—and ones with similar soils—would be expected to have similar runoff and increased sediment loss in excess of the runoff when compared to undisturbed areas.

Groupings of the sites based on soil texture were identical to groupings based on changes in h_c and K_i (i.e., loamy sands at Louisiana and Washington, which had decreased h_c and increased K_i; gravelly sandy loam at Minnesota and Kentucky, which had decreased h_c and unchanged K_i; and gravelly sand at Arizona and Montana, which had unchanged h_c and increased K_i). The soil texture with the highest potential for increased soil loss was loamy sand. The lowest potential for increased soil loss was from the gravelly sand with the gravelly sandy loam as the intermediate.

Recommended Erosion Parameters

Table 18 compares values for hydraulic conductivity, interrill-erodibility coefficient, rill erodibility (K_r), and critical shear (T_c) for forest, range, and agricultural lands from the literature and values determined in this study. The ATV undisturbed hydraulic conductivity values are similar to those reported for forest lands with the exception of the Arizona site, which was in a desert. The Arizona hydraulic conductivity was similar to rangeland, which does include desert habitats. The hydraulic conductivity caused by ATV disturbance was below undisturbed forests, higher than forest roads, and similar to agricultural fields. The notable exception was Kentucky, where 30 years of ATV traffic resulted in h_c values approaching those of an unpaved forest road.

Table 18—Typical range of values for hydraulic conductivity (h_c), interrill erodibility (K_i), rill erodibility (K_r), and critical shear (T_c). Values are from WEPP Technical Documentation, WEPP User Summary, and Fangmeier et al.

	h_c ($mm*hr^{-1}$)	K_i (10^6 $kg*s*m^{-4}$)	K_r ($s*m^{-1}$)	T_c (Pa)
Forest	30 – 60	0.4	0.0005	1
Range	3 – 30	0.01 – 2	0.0001 – 0.0006	1.5 – 6
Agricultural	5 – 30	5 – 6	0.001 – 0.025	2 – 2.5
Forest roads	0.4 – 10	3	0.0003 – 0.002	1– 3
Forest skid trails	10	2	0.003	2
ATV – Undis	6 – 55	5 – 10		
ATV – Dist	1 – 24	2 – 26		

Undisturbed interrill-erodibility values from the undisturbed condition were higher than those reported for forest conditions and similar to agricultural conditions. In the ATV disturbed category K_i values were among the highest reported and exceeded those for agricultural fields.

Rainfall simulation on 1-meter-square plots allows determination of infiltration and raindrop splash parameters, but not interrill erosion (concentrated flow) parameters. On an ATV trail with ruts, concentrated-flow erosion would likely be a major contribution to soil erosion. The length of ruts and the distance that concentrated flow occurs is of major concern. The rainfall simulation found no statistically significant difference between the low, medium, and high condition classes. The typical rut depths for the low were up to 3 inches, 3 to 6 inches for the medium, and greater than 6 inches for the high.

Observations by the authors on native surface forest roads are that deeper ruts tend to be longer than shallow ones. This would also be expected on ATV trails and would likely increase the sediment loss on the medium and high disturbance classes. Such an increase could result in a statistically significant difference between the low, medium, and high disturbance classes. Determination of concentrated-flow-erosion parameters is straight forward and should be performed.