# PREDICTING THE IMPACTS OF FOREST ROADS ON THE ENVIRONMENT

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## *Abstract*

Forest roads are recognized as one of the primary sources of sediment in many forested watersheds. Research on soil erosion processes on forest roads has been carried out by the authors for over 10 years. This overview of that research summarizes the results of numerous past and ongoing field and computer modeling studies related to road erosion processes and the impacts of road design on road erosion.

## *Environmental Impacts of Forest Roads*

Forests are one of the greatest natural resources in many nations. They can be either native or replanted. Forests cover about 30 percent of the land area worldwide. They are often located on areas that are marginal for other uses due to remoteness or terrain, but with adequate rainfall for forest growth. Frequently, these areas are steep and prone to erosion and instability were it not for the forest cover. Generally, forested areas have minimal erosion unless they are disturbed. Disturbances include fire, harvesting, and road construction.

The three dominant effects of forest roads on the environment are alteration of runoff from forested watersheds, mass wasting and surface erosion. Sedimentation of streams is particularly serious in upland areas where salmonid species require gravel-covered stream bottoms for spawning. Sedimentation can also shorten the life of reservoirs and water supply systems relying on forests for quality water for domestic and industrial uses. Peak discharges may be altered in basins following forest road construction. Forest roads complicate the hydrology in harvested watersheds (Jones and Grant 1996). In watersheds with high infiltration capacity and where hillslope flow is dominantly subsurface, roads have the potential to increase surface runoff and intercept subsurface flow (Wemple 1994). Changing the hydrologic properties of a watershed will often change the upland stream sedimentation processes and adversely impact downstream structures such as reservoirs, bridges, and other features in the stream's flood plain.

In steep terrain, where the climate may lead to saturated road prisms, slope stability failures may lead to greater sedimentation in streams than surface erosion (Reid and Dunne 1984; Megahan 1987; Montgomery 1994). In many cases, the sediment particle sizes from stability failures may be much larger than from surface erosion, and may include large rocks and boulders in excess of a meter diameter.

## *ROAD EROSION AND SEDIMENTATION PROCESSES.*

Soil erosion and sedimentation are the products of complex interactions among soils, climate, topography, and surface vegetation or management (figure 1). On roads, the construction, maintenance, and level of traffic all impact the erosion rate.

A number of components make up a road, and the design and management of each component may influence the erosion of the road or delivery of sediment from the road to a stream system. Figure 2 presents the main road components that impact soil erosion. The design and management of a road determine the flow path which water follows to exit the road. All roads are designed to have a compacted foundation and to shed water. The main cross sectional shapes of roads are crowned, insloping, or outsloping (figure 2). On some forest roads, there is also a set distance in waterbar spacing along the traveledway to limit erosion. In addition, a road designer can choose to add gravel, asphalt or concrete to the surface. Designers may also consider methods to limit erosion from the road surface runoff, such as adding gravel to road ditches or specifying that cross drains deliver water to convex slopes where the water will dissipate over the surface rather than incising a channel. Road erosion rates are influenced by the flow path that surface runoff follows along the road (Packer and Christensen 1977; Foltz 1996), and the road's soil properties of hydraulic conductivity and soil erodibility (Elliot et al. 1994 and 1995).

## Flow Path

The flow path length across the travelway depends on the shape of the road and the presence of wheel ruts. The minimum flow path occurs on a smooth road with a uniform cross-slope. In this perfect geometry condition the flow path length increases with increasing road grade and decreases with increasing cross slope (Elliot and Hall 1997). Because cross slopes are rarely more than 4 percent, a 4-m wide road will rarely have a flow path length less than about 7 m for road grades of 5 percent or more. If the road receives heavy traffic, particularly in wet weather, ruts will form in the road, and eroding water will follow the ruts rather than being diverted to the inside or outside of the road. With a rutted traveledway any benefits from the initial design shape are lost. Even without a rutted traveledway, as wheel tracks begin to flatten and the cross-slope decreases, the path length increases until it is equal to the spacing between any surface structures that divert the water from the road (Foltz 1996). These diversion structures may be called cross drains, water bars or broad-based dips. Figure 3 shows the typical effects of flow path length on road surface erosion.

## Insloping Versus Outsloping Roads

There are ongoing debates about whether insloped or outsloped roads are better. Proponents of insloped roads point to the benefit of controlling the water in a ditch with planned outlets under the running surface. Erosion in the ditch can be minimized by placement of non-erodible rock. The benefit of outsloping is dispersed flow, but at the expense of water flowing over the less erosion resistant fill slope. If the road is allowed to become rutted, the shape makes no difference as the ruts will have concentrated flow that may bypass drainage structures (Hartsog and Gonsior 1973). In general, the most correct road shape depends on the site conditions and road use.

Insloping roads processes were studied in detail with field data and by modeling with the WEPP model (Tysdal et al. 1997). Generally, if roads are well maintained, the majority of erosion in a road prism is in the inside ditch (figure 4). The cutslope contribution to the erosion rate is small, unless the ditch has been treated to reduce erosion. The main contribution to the erosion process from both the cut and the road surface is in generating runoff that may then erode the ditch.

Not all of the sediment that leaves a traveledway enters surface water. Frequently, surface runoff leaving a road infiltrates into the hillslope immediately below the road, where it may deposit all of the eroded sediments (Ketcheson and Megahan 1996). These areas of deposition are often referred to as deposition plumes. These plumes are frequently of interest to forest managers as they try to understand sources and sinks of sediment from forest roads.

## Concentrated Flow Erosion

Concentrated flow causes more erosion than dispersed flow. Wheel ruts and ditches are the primary causes of concentrated flow on forest roads. Wheel ruts are generated most quickly by heavy logging truck traffic during wet road conditions. Ditches are constructed adjacent to the traveledway (figure2). Reid and Dunne (1984) stated that the amount of traffic is probably the single greatest factor affecting sediment production. Burroughs and King (1989) recommended sediment production for a rutted, unsurfaced traveledway be increased by a factor of 2, relative to the yield from a smooth, unsurfaced traveledway. Their recommendation was based on light use logging traffic. Comparing the sediment production between two years on identical road sections where the major difference was frequent logging truck traffic versus no-traffic, Foltz (1996) found sediment production increased by a factor of nine. In simulated high-intensity rainstorms, Foltz (1990) reported a range of 5 to 2 times increase in sediment production for a wide range of soil types. It is clear that keeping a road traveledway free of rutting is an important sediment reduction technique. Seasonal road closures determined by road bearing capacities may be more effective than road maintanence with a grader, by not allowing the ruts to form rather than removing the ruts after they have formed.

Roadside ditches convey runoff from the running surface and from the cutslope and cause concentrated flow. Luce and Black (1997) reported the first year of results from a multi-year study on the effects of road length between water bars, road grade, and cutslope height on sediment production of entire road prisms. From a data set taken from 74 plots in the Oregon Coast range, they show that the condition of the ditch is an important determinant of sediment production in the first year following construction. They found a statistical relationship between the total sediment production and the product of the square of the road gradient and the segment length, factors that have been shown to correlated well in rill erosion studies (McCool et al. 1989; Nearing 1997). There was no relationship between sediment production and cutslope height, indicating that increases in cutslope sediment production do not affect total plot sediment production. A few plots with severely disturbed cutslopes suggest that cutslope condition might become dominant after some period of recovery, mostly through the effect of cutslope sediment on the erodibility of the ditch bottom.

## Hydraulic Conductivity

The hydraulic conductivity of native surface roads is much lower than all other soils, including gravelled roads, agricultural soils, or forest soils (Luce 1995; Elliot and Hall, 1997). Figure 5 shows a comparison on the hydraulic conductivity of various forest conditions. The conductivity varies from under 1 mm/h for a native-surface or nongraveled road to over 80 mm/h in an undisturbed forest. These differences are management effects that tend to overshadow effects due to differences in soils. The presence of large amounts of vegetation and forest litter are responsible for the high infiltration capacity of undisturbed forest soils. Roads are highly compacted resulting in near-zero conductivities on all soils.

Luce and Cundy (1994) showed that roads without gravel have conductivities in the range of 0.1 to 0.5 mm/hr, whereas roads with gravel have conductivities in the range of 3 mm/hr (Elliot and Hall 1997). This leads to a significant difference in runoff and erosion rates, particularly in climates where much of the runoff is from snow melt. Snow melt rates are less than rainfall rates (USACE, 1956), resulting in less runoff. Table 1 shows the difference in road erosion rates due to this difference in conductivity for a snowmelt-dominated United States climate, and a Brazilian climate with no snow. Gravel in the Northwestern United States reduces predicted erosion by over 80 percent, a commonly accepted figure by forest planners, whereas in Brazil the model predicts that aggregate surfacing reduces road erosion by about 30 percent.

## Erodibility

To determine the role of soil properties on road erodibility, the former project leader, Edward J. Burroughs, initiated a series of studies collecting field data from a wide range of native-surfaced roads. From these studies several researchers (Ulman et al. 1994; Burroughs et al. 1992; Elliot et al. 1995) determined that on native surfaced roads, the interrill erodibility is similar to cropland soils, the rill erodibility is similar to rangeland soils, and the conductivity is near zero. Typical values are presented in table 2.

## *MITIGATION*

Our project has been active in researching road erosion mitigation techniques. These techniques include reduced tire pressures, aggregate placement, road closure, and road maintenance and are discussed below.

### Reduced Tire Pressures

In a 3-year study in the United States in the Cascade Mountains in Oregon, Foltz (1995) found that sediment production was reduced by 45 percent when tire pressures were reduced from 620 kPa to 480 kPa on all axles, and by 80 percent when tire pressures were reduced to 480 kPa on the steering axles and 210 kPa or 340 kPa on all other axles (table 3). Foltz and Elliot (1996) observed that the erosion processes occurring on this site showed that reduced tire pressures resulted in less rut formation. With less rutting, water tended to run over the edges of the road, rather than accumulating in flow directly down the ruts which caused erosion from concentrated flow. These results have been well-received by forest managers, and some timber sale contracts in Central Idaho now include reduced tire pressures as one of the methods to reduce road erosion.

### Aggregate Quality

Burroughs and King (1989) reported that 150 mm of good quality aggregate reduced sediment production from a granitic surface road by 96 percent. Swift (1984) found that the thickness of aggregate was important. A 50-mm depth provided no mitigation while a 200-mm depth provided 97 percent mitigation. Neither of these studies were performed in the presence of traffic. For many years forests adopted these mitigation values with little consideration of aggregate quality or traffic. Foltz and Truebe (1995), using loaded logging truck traffic, found the quality of aggregate has an important influence road soil erosion rates. A marginal quality aggregate allowed erosion rates of 4 to 17 times greater than from a good quality aggregate. The range depended upon traffic and precipitation. Foltz and

Elliot (1996) believe that the differences are due to the same effects as observed for tire pressure impacts and gravel addition, namely, conductivity and the presence of ruts. A laboratory study is currently in progress to see if it is possible to measure differences in erodibility of aggregates with rainfall simulation before and after traffic, and to then relate those differences to standard measurable properties of the aggregates.

### Road Obliteration

The offsite impacts of altered runoff hydrographs and increased sedimentation have lead to the partial or complete removal of roads as a frequent practice in Forest Service watershed restoration. There is, however, limited research data to support obliteration decisions. One practice associated with road obliteration is to rip the road with tines mounted on the back of a large crawler tractor. In a recent study on the effectiveness of ripping, Luce (1997) found that road conductivity increased from 0-4 mm/h before ripping to 20-40 mm/h after. The improvement is modest compared to existing forest conductivities (figure 5) but may lead to a substantial reduction in runoff in snowmelt and low precipitation-intensity climates. While the initial ripping yielded infiltration capacities similar to forest soils, subsidence, consolidation, and surface sealing reduced capacities to these modest results. Soil amendments may improve performance. Elliot et al. (1996) noted other concerns related to ripping such as increased conductivity leading to an increased likelihood of the road prism becoming saturated leading to an increased risk of failure from instability.

## *MODELING DEVELOPMENTS*

Natural resource managers require tools to aid them in evaluating the environmental impacts of various decisions on the design and management of forest roads. Numerous soil erosion and road stability models have been developed to assist designers and managers. Erosion modeling is mostly process oriented and based on the Water Erosion Prediction Project (WEPP) model (Laflen et al. 1997).

### Water Erosion Prediction Project (WEPP)

Soil erosion models are based on either empirical techniques or are process based. In empirical methods, such as USLE and RUSLE, the factors believed to influence soil erosion are measured and then described by a mathematical equation. In contrast process based models describe the physics of the erosion process. Empirical models require previous measurements at the sites of interest or similar sites. Process models can be extended to sites without measurements with greater certainty.

The Water Erosion Prediction Project (WEPP) is a process-based soil erosion model developed cooperatively by several federal agencies in the United States. WEPP not only predicts soil erosion rates, but also sediment delivery. Forest Service research (Elliot et al. 1995; Morfin et al., 1996; Tysdal et al. 1997) has successfully validated WEPP for a number of forest road conditions, such as insloped roads with ditches, outsloped roads, roads draining to culverts, and roads with forest floor buffer strips. Forest Service Research is committed to develop applications of WEPP to more fully evaluate the impacts of current or proposed road management and mitigation practices.

## WEPP Forest Files

The road research results of Elliot et al. (1994 and 1995), Foltz (1996), Foltz and Elliot (1996) and other field observations were combined into a set of WEPP templates (Elliot and Hall 1997). These WEPP erosion templates model insloping, outsloping, and rutted roads, as well as conditions where sediment laden-water is routed over a fill slope.

## Simplified Interface Development

We have held several workshops training over 100 Forest Service personnel on the application of the WEPP model to forest conditions. Because most potential users of WEPP are discouraged by the complex interface, we have focused some of our development on simplifying the interface to WEPP. At this time we are developing an interface that will be applicable specifically to roads.

## X-Drain

The X-Drain model is based on a study by Morfin et al. (1997) that developed a database of over 50,000 WEPP runs on a road scenario that included an eroding road surface and fill slope, and a deposition area between the road and the nearest stream. The results of this study are accessed by a user-friendly interface called X-Drain. For a given climate, soil, and topographic condition, the X-Drain program presents the sediment delivery for 20 combinations of road gradient and water bar spacing values. Elliot et al. (1997) describe how to apply this basic configuration to a range of field conditions.

The results of the WEPP runs are currently being analyzed to determine if empirical relationships can be developed to predict road erosion or sediment delivery from a set of simplified variables similar (or equivalent) to the USLE, or from some other regression relationship.

## *RESEARCH NEEDS*

Numerous scientists are currently researching road erosion processes both within the Forest Service and in universities and private industries. Other activities include:

- Research projects on the development of empirical models of the impacts of roads and other disturbances in watersheds at a watershed scale.
- Research to quantify downslope sediment movement from roads.
- Projects related to the role of roads and culverts in hydrologic processes.

Our current road-related research includes the continuation of our road topography and cutslope height study in Oregon, developing a model to describe road erosion armoring and recovery processes, and developing methods to more easily apply WEPP and other models as aids to forest road design and management.

Areas that require further research include:

- Site-specific tools to assist in predicting risks of instability and impacts of failures on downslope streams.
- Tools to aid managers to prioritize roads for maintenance, construction, or removal.
- Testing of current downslope mitigation techniques.
- The development of new techniques to minimize the transport of sediment from roads in a cost-effective and efficient manner.
- Development of road construction, and road removal techniques which allow temporary access to remote sites with minimal long-term impacts.

- Development of models that better incorporate the impacts of roads on forest watershed hydrologic processes

### *Summary and Conclusions*

We have provided an overview of much of the recent research of our work unit in the area of predicting the impacts of forest roads on forest stream systems. We have developed tools to predict soil erosion rates and off-site sediment delivery from forest roads. We have also developed tools to assist in evaluating the stability of road prisms on steep slopes. Current research will expand our understanding of road erosion processes and the impacts of road design and management on road erosion. Some future directions for research in road erosion have been suggested.

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## *Tables*

Table 1. Impact of gravelling on road erosion for a 60-m long, 4 m wide road with 12 percent slope, with climates from Idaho, United States, and Campinas, Brazil, predicted with the WEPP model.

| | Climate | |
|---|---|---|
| | Deadwood Dam, Idaho | Campinas, Brazil |
| Average Annual Precipitation (mm) | 822 | 1361 |
| Runoff (mm) | | |
| Native Surface | 450 | 1046 |
| Gravel Surface | 78 | 681 |
| Sediment Yield (kg) | | |
| Native Surface | 2312 | 4868 |
| Gravel Surface | 432 | 3348 |

Table 2. Typical WEPP erodibility parameter values for forest roads.

| | Soil | | | | |
|---|---|---|---|---|---|
| Property | Clay Loam | Silt Loam | Sandy Loam | Gravelly Loam | Gravelly Sand |
| Gravel % | 20 | 5 | 5 | 60 | 80 |
| Sand % | 30 | 30 | 60 | 40 | 70 |
| Silt % | 40 | 55 | 35 | 40 | 25 |
| Clay % | 30 | 15 | 5 | 20 | 5 |
| Conductivity mm/hr | 0.3 | 0.3 | 1.0 | 2.0 | 3.0 |
| Interrill erodiblity $kg\text{-}s/m^4$ | 1e06 | 3e06 | 2e06 | 1e06 | 2e06 |
| Rill erodiblity s/m | 0.0002 | 0.0006 | 0.0004 | 0.0003 | 0.0003 |

Table3. Effects of tire pressures on measured soil loss for 61 m long road sections with 12 percent gradients in Oregon, United States. Average from 3 years.

| Tire Pressures (kPa) | | Sediment Yield |
|---|---|---|
| Front | Other | (kg) |
| 620 | 620 | 2678 |
| 480 | 480 | 1466 |

| | | |
|---|---|---|
| 480 | 210 Unloaded<br>340 Loaded | 530 |

**Figures**

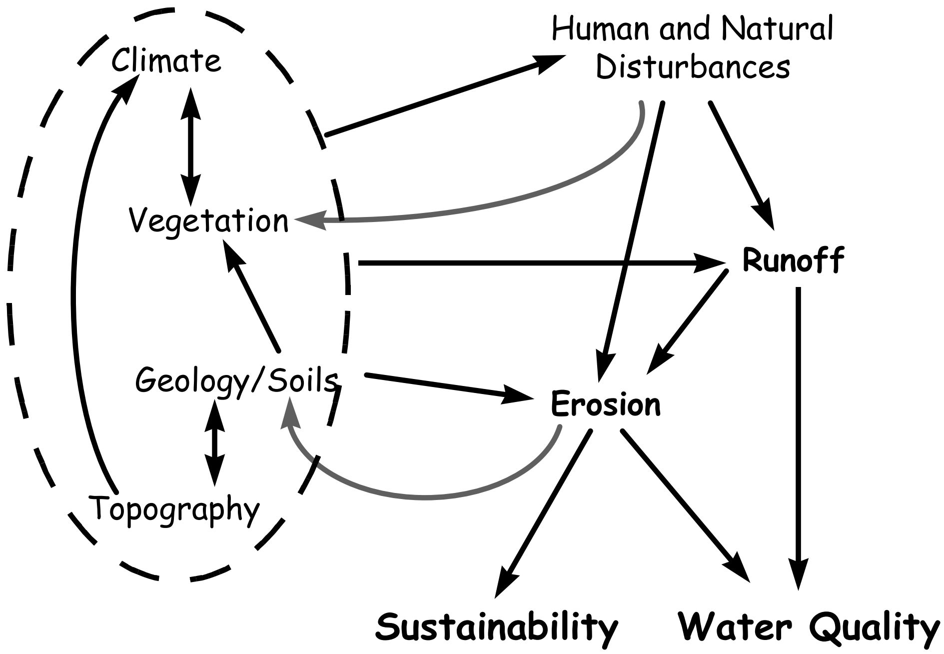
Climate
Vegetation
Geology/Soils
Topography
Human and Natural Disturbances
Runoff
Erosion
Sustainability
Water Quality

Figure 1

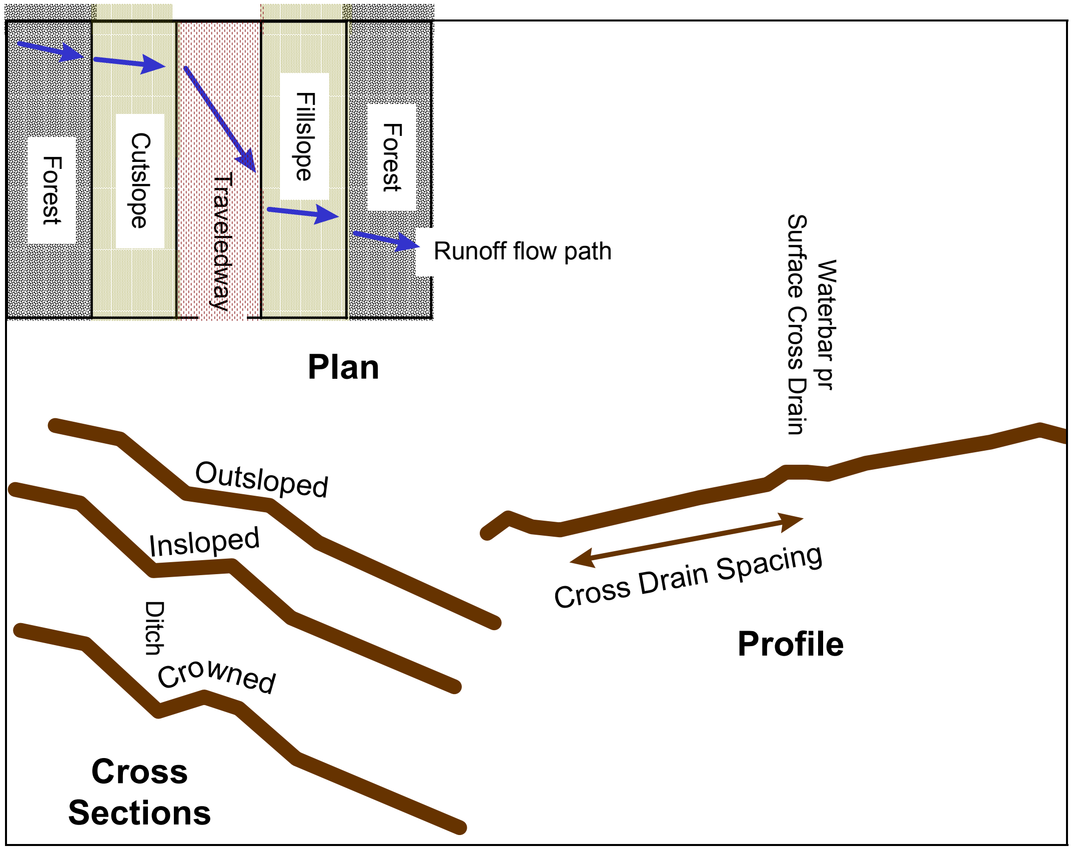


Figure 2

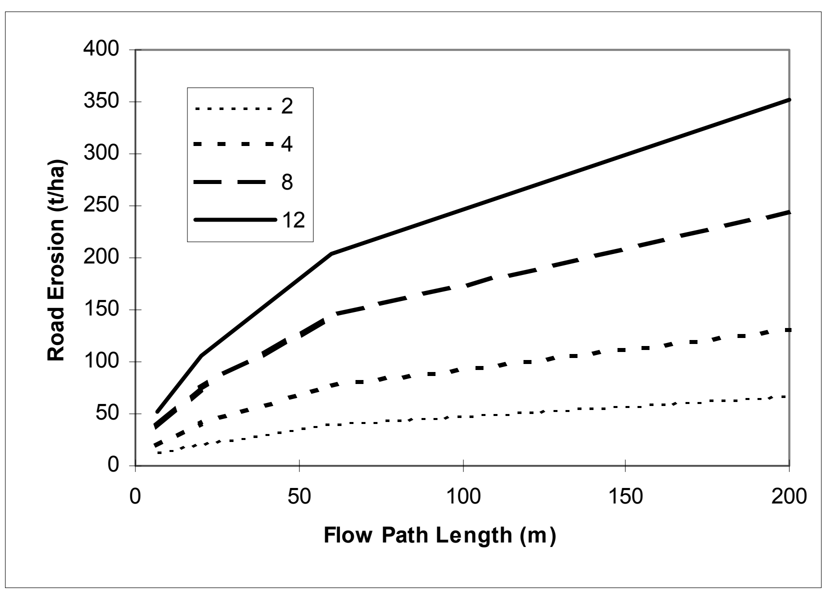


Figure 3

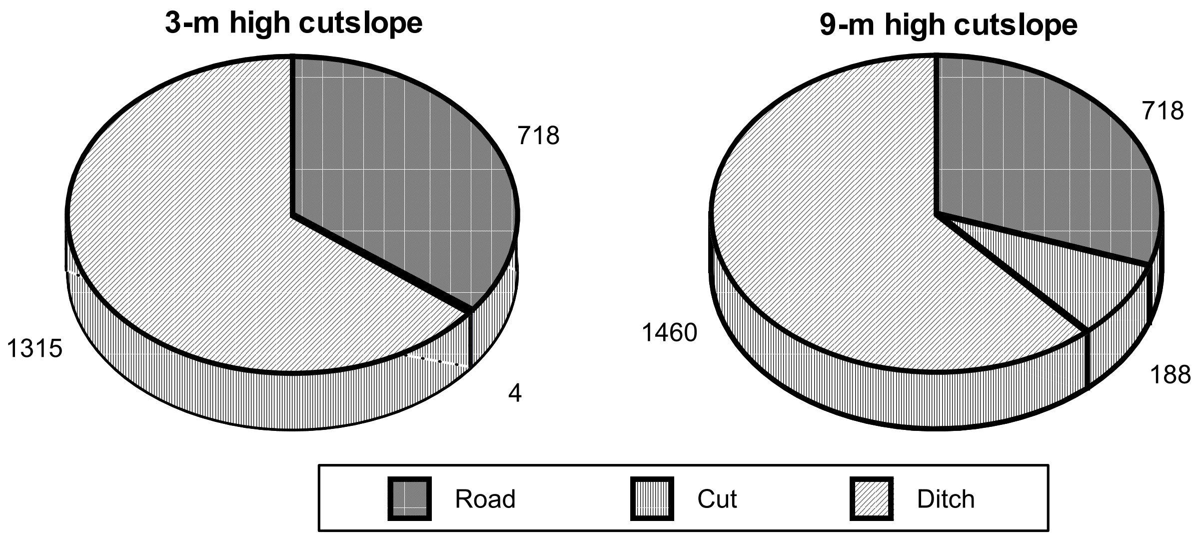


Figure 4

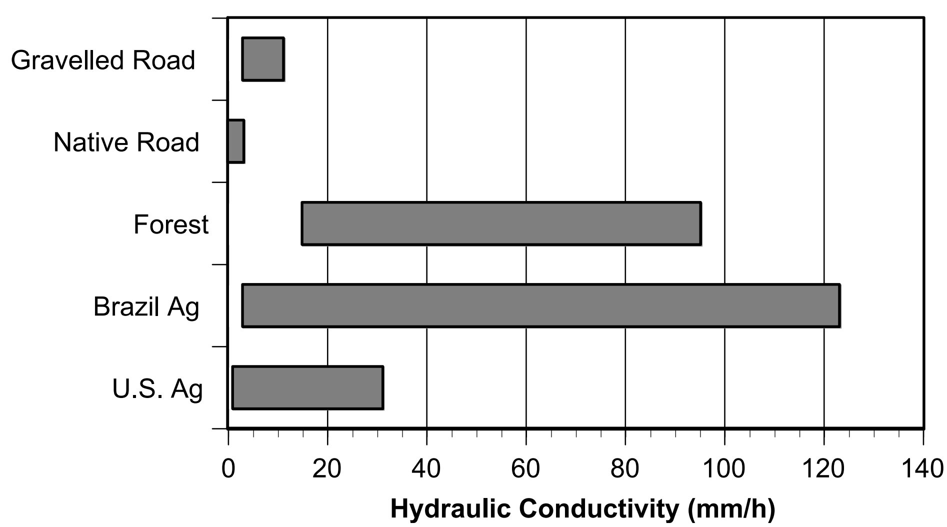


Figure 5

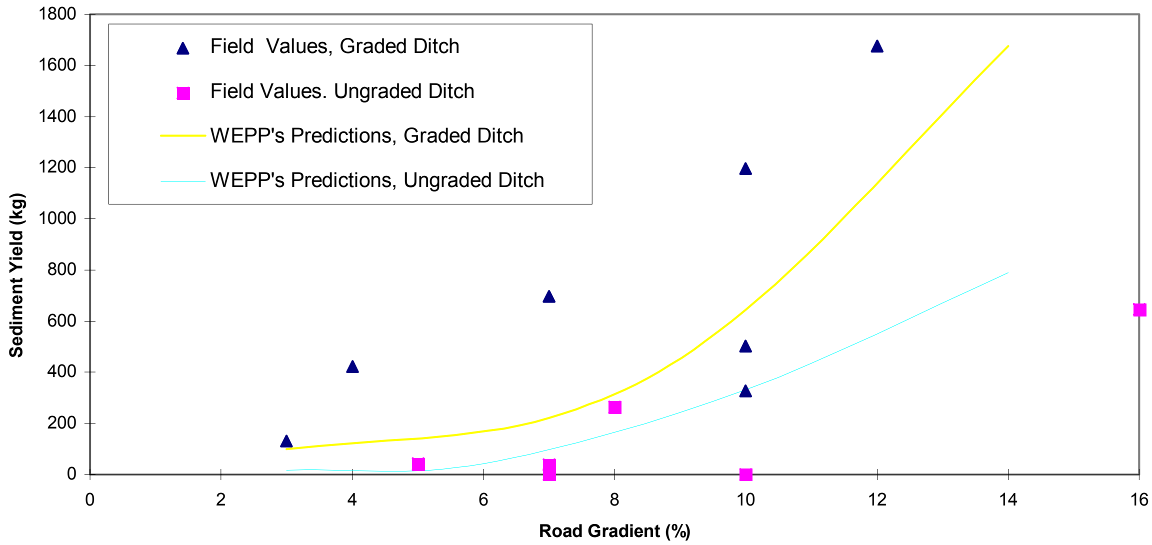
Field Values, Graded Ditch
Field Values. Ungraded Ditch
WEPP's Predictions, Graded Ditch
WEPP's Predictions, Ungraded Ditch
Sediment Yield (kg)
Road Gradient (%)
0
200
400
600
800
1000
1200
1400
1600
1800
0
2
4
6
8
10
12
14
16

Figure 6

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