Environmental impacts of forest roads:

An overview of the state of the knowledge

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Summary

This paper reviews the environmental impacts of forest roads at the on-site and the watershed scale. The components of a road prism--the cut slope, ditch, running surface, and fill slope--are defined and a description of the infiltration and flow processes are made for both insloped and outsloped roads. The perceived advantages of both are discussed. Flow on the road prism without traffic and a long-term study of the sediment production also follow. Some of the differences in sediment production between traffic and no-traffic conditions are highlighted, and the results of three studies of sediment production from roads with traffic are also discussed. Two methods to mitigate the impact of road traffic are reviewed. At the watershed scale, two studies that used the same data, but reached opposing conclusions are discussed. There is also a review of a study investigating the connection of a road system and stream network. The paper concludes with suggestions for further research on both on-site and watershed scales.

***Keywords**: forest roads, watershed, environmental impact*

Introduction

Roads in forest environments exist to allow for removal of forest products, to allow human access for enjoyment of the forest, and for human transportation through it. From this perspective, while forest roads provide a societal benefit, they also have environmental liabilities. The objectives of this paper are to review the state of the knowledge of both on-site impacts and watershed scale impacts and to suggest topics for further study. The paper has a western United States perspective and will only focus on surface erosion.

On-site Impacts

The environmental impacts caused by a road and the accompanying forest floor tens of meters below it will be referred to as on-site impacts. Figure 1 shows the components of a typical forest road. The major components are: the cut slope, ditch, running surface, and fill slope. The cut slope is cut into the hillside; thus, the composition is often weakly weathered rock. Slopes range from vertical to 1:1. The ditch, if present, lies at the base of the cut slope. Its purpose is to convey water in a controlled manner via a culvert to the forest floor. The running surface is where traffic movement takes place. The change in elevation along the running surface is known as the road grade which varies from zero up to around 14%. The running surface may be either sloped toward the cut slope (insloped), sloped away from the cut slope (outsloped), or be crowned with half the running surface flowing toward the ditch and the remaining half flowing toward the fill slope. Finally, the fill slope is the transition from the running surface to the forest floor. Typical slopes range from 1.3:1 to 1.5:1.

Road Runoff Without Traffic

During precipitation or snow melt, the road modifies infiltration and surface flow in several ways. Infiltration on the undisturbed forest floor is often in the 40 to 80 mm/hr range. Few rainstorms or snow melt events will cause overland flow on the forest floor. The running surface, ditch, and cut slope have infiltration rates from 0.1 mm/hr to 10 mm/hr and thus cause overland flow. Fill slope infiltration rates are intermediate with rates from 10 to 20 mm/hr (Elliot and Hall 1997).

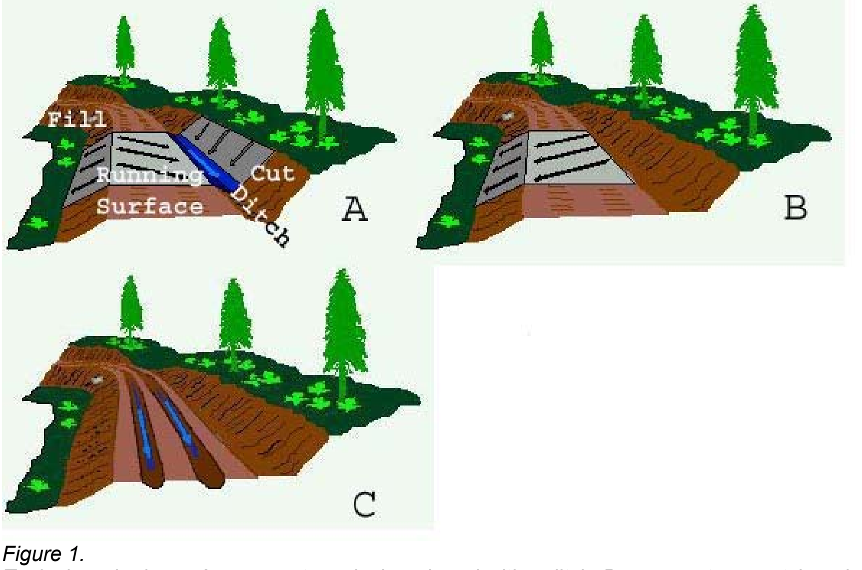

Figure 1.
Typical road prisms. A represents an insloped road with a ditch. B represents an outsloped road. C represents a road with wheel ruts.

The flow paths of the overland flow depend on road geometry. On insloped roads, water from the cut slope and running surface flow to the ditch, while flow paths on the fill slope exit onto the forest floor. The ditch flow reaches the forest floor via the culvert (Figure 1A). On outsloped roads, water flows from the cut slope, across the running surface, and down the fill slope (Figure 1B).

Both insloped and outsloped road designs have strong advocates. Those who prefer insloped roads maintain the benefits are: 1) the ability to control the concentrated flow and direct it where the road designer wants it to go, 2) an absence of concentrated flow over the structurally weaker fill slope which could cause rills and possible fill failures, and 3) traffic safety on slick surfaces where a slipping vehicle will go into the hillside rather than over the fill slope and down the hill. The advocates of outsloping prefer: 1) less concentrated flow because water drains over the fill slope before it has an opportunity to concentrate, 2) no movement of concentrated flow parallel to the hillslope, 3) fewer culverts to reduce the possibility of plugging resulting in overtopping of the running surface and dam break-type scenarios, and 4) no opportunities for out-of-basin transfers of water along the road from one watershed to any adjacent watershed.

If ruts are allowed to form in the running surface or if routine road maintenance leaves a small berm at the edge of the fill slope, flow paths on the running surface will be altered from the design conditions. These ruts will extend the flow path on the running surface (Figure 1C). On insloped roads this may result in bypassed relief culverts, while on outsloped roads it will prevent shallow sheet flow from extending over the fillslope. Under these conditions where proper road maintenance is not performed, either due to monetary constraints or poor maintenance practices, the perceived benefits of either insloped or outsloped roads will not be achieved.

One of the classic studies of long term sediment production from road prism segments was reported by Megahan (1974). This study was performed on four sites in Idaho where precipitation averaged 823 mm/yr on a soil derived from granitic parent materials. Sediment production from the full road prism was measured beginning in the year of construction and for each of the following five years. In the year of construction and the following year there was heavy truck traffic. Later years had little heavy truck traffic. The first year sediment production was 19760 tonnes/km^2, but decreased to 830 tonnes/km^2 in the second year. After five years the production was 225 tonnes/km^2. Revegetation of the cut and fill slopes and low traffic was responsible for this decrease. This study has been used as a template for several sediment yield models including Washington Forest Practices (1995) and WATBAL (Patten 1989).

Road Runoff With Traffic

Without traffic precipitation events wash away the fine material on roads resulting in a decrease in sediment concentration over time. This decrease is observable on time scales ranging from the duration of a storm to a period of several years. With traffic, however, new fine material is generated via the traffic by two mechanisms. Either one of these mechanisms will prevent the decrease in sediment production observed in no-traffic studies.

Crushing of the larger size soil or aggregate particles by tires results in new material being available for transport by the road runoff. In a study in western Oregon, Foltz and Truebe (1995) observed that 20% of the material finer than 0.075 mm in diameter was eroded from a structurally-weak aggregate over a period of three months. During this period there were 668 mm of rainfall with truck traffic of 884 logging truck trips. The gradation of the aggregate did not change from prior to the study to after the study; thus, they concluded that truck traffic generated 0.5 m^3 of fines.

Traffic also causes movement of fines to the surface from below. Tires create excess pressures on the saturated aggregate and fine materials move through the pore spaces to the surface.

Bilby et al. (1989) measured five aggregate surfaced road sections in southwestern Washington where precipitation during the 23-week study period was 1850 mm. Both a valley bottom mainline road and a midslope secondary road were included. Traffic use varied on the roads from 30 axles per day to 3000 axles per day. Routine maintenance was performed on the mainline road once or twice per week while the secondary road received maintenance three times during the study period.

Bilby et al. reported that precipitation and use rate of the road had the greatest potential to influence the rate of sediment delivery to ditches. Sediment concentrations in ditchflow on the secondary road was related to the daily traffic rate since the last occurrence of runoff; however, for the mainline sites there was a poor correlation between use-rate and the average sediment concentration during storms. They suggested that under conditions of extremely heavy traffic (greater than 100 axles per day) sediment production appeared to be independent of use rate.

This study estimated sediment production rates over the 23-week study period to be 10 tonnes per kilometre for the secondary road and 26 tonnes per kilometre for the mainline road. A study reported by Reid and Dunne (1984) estimated that annual sediment yield from secondary roads in western Washington with precipitation of 3900 mm/yr was 3.8 tonnes per kilometre for lightly used roads to 500 tonnes per year for heavily used roads. Bilby et al. surmised that the differences of an order of magnitude was likely due to differences in precipitation and measured versus estimated traffic levels.

Many of the widely used road sediment estimation techniques assume that impacts are additive. Washington Forest Practices (1995) increase sediment production due to heavy traffic by 20 to 120 times depending on the annual precipitation. It also modifies the running surface erosion by a factor of 1.0 to 0.03 depending on the surfacing material. Each of these factors are applied independently.

Luce and Black (2001) reported a study testing the validity of applying adjustment factors independently. They conducted a study in western Oregon where the annual precipitation ranged between 1800 and 3000 mm on both sand and silt soils. Twelve road segments received either no-traffic and no-ditch maintenance, no-traffic and ditch maintenance, traffic and no-ditch maintenance, or traffic and ditch maintenance. The traffic was 10 round trips per day of a heavy truck for a period of one month. Sediment collection took place during truck passes and for a period of time after traffic ceased each day. Similar sediment collection occurred six months after the heavy traffic ceased.

They concluded that the difference between grading-only and grading-with traffic was not statistically significant, implying that there was little difference in sediment production between traffic and no-traffic plots with a graded ditch. They stated that applying adjustment factors independently overestimates the effect of traffic on new roads or recently maintained roads. They also suggested that the effects of traffic persist for periods up to several months beyond the termination of traffic.

Traffic Mitigation Techniques

The studies of Bilby et al., Reid and Dunne, and Luce and Black used heavy truck traffic with tires inflated to 620 kPa. If truck tire inflation is reduced in a radial ply tire, the foot print will lengthen and reduce the contact pressure with the running surface. Greater flexing of the tire at these reduced pressures will occur, but if speeds are kept below highway speeds, as often occur on forest roads, heat build up will not be a problem.

Foltz and Elliot (1996) reported on a study in Oregon that compared the sediment production from an aggregate surfaced road subjected to 620 kPa (highway pressure), 480 kPa (Constant Reduced Pressure), and 340 kPa (Central Tire Inflation) tire pressure in heavy trucks. (Central Tire Inflation systems allow the driver to change tire pressure while the truck is in motion). The study was performed over three winters when average precipitation was 335 mm, and truck traffic averaged 700 round trips.

Their study found that sediment production from the CTI road section was reduced an average of 80% when compared to the highway pressures. Similar, but smaller, reductions of 45% were observed for the CRP treatments compared to the highway pressures.

These results were used by Weyerhauser Company to justify the purchase of 65 CTI equipped logging trucks in western Washington for the purpose of reducing the impact of truck traffic on company-owned lands. Additionally, the Boise National Forest in Idaho offered two timber sales on environmentally sensitive land that included a reduced tire pressure requirement for access.

Aggregate quality is a qualitative assessment of the suitability for use as a road surfacing material. Resistance to crushing and weathering are often included. While good quality is always preferred, it is often not economically feasible. In order to assess the impact of using different aggregate qualities, Foltz and Truebe (2002) conducted a study of 20 aggregates. Road segments were simulated by placing the aggregate in shallow metal frames to simulate a forest road. The runoff and sediment from a high intensity, long duration simulated rain storm was measured. Basic aggregate characteristics along with a number of tests intended to predict the susceptibility to erosion were performed. Each test was statistically evaluated to identify those which best predicted perceived aggregate quality and sediment production potential.

The two best indicators of aggregate quality were Sand Equivalent and Oregon Air P20 test results. The best indicator of either runoff or sediment production was the fraction passing the 0.6 mm sieve. The twenty widely used aggregates exhibited sediment production that varied over a two order of magnitude range. This study illustrates the importance of attention to aggregate quality.

Watershed Scale Impacts

All of the previous studies dealt with the impacts of roads at the on-site scale. Fewer studies attempt to observe the impact of roads at the watershed scale of tens to thousands of hectares.

Changes in Stream Flow Due to Roads

Jones and Grant (1996) reported on a study of changes in stream flow characteristics caused by roads and timber harvesting. They looked at stream flow records as long as 30 years from three small watersheds varying in size from 60 to 101 ha and three large watershed from 60 to 600 ha located in western Oregon. Precipitation in this area averaged 2250 mm/yr.

They concluded that: 1) forest harvesting increased peak discharges by as much as 50% in small basins and 100% in large ones, 2) these increases were a result of the increased drainage efficiency due to integration of the road system into the stream channel network, and 3) the entire population of peak discharges was shifted upward by clear-cutting and roads. These conclusions were at odds with those reported by Harr (1979), who based his conclusions on 11 locations from British Columbia to California and reported that the results of watershed studies indicated that the size of peak flows may be increased, decreased, or remain unchanged after logging.

Using the identical data as Jones and Grant , Thomas and Megahan (1998) reported that they could not detect any effect of cutting on peak flows in one of the large basins, and that results were inconclusive for two of the other large basins. On the small watersheds they concluded that small events were different among the watersheds, but for 2-year return intervals or greater there were no detectable differences among the watersheds. Thomas and Megahan also concluded that treatment effects decreased over time and were still found after 20 years on the clear-cut watershed, but for only 10 years on the patch-cut and roaded watershed.

This discussion between well-qualified researchers using the same data illustrates the difficulty in detecting differences due to roads and timber harvesting at the watershed scale.

Expansion of Stream Networks by Roads

Wemple (1994) conducted a study of two adjacent 5th order basins in western Oregon on clay and silty clay soils where precipitation averaged 2250 mm per year to evaluate the long-term, cumulative effects of a road network on forested lands. The conclusions of this study were: 1) roads function as surface flow paths to channel appreciable volumes of runoff, and 2) a substantial portion of the road network in the study area (nearly 60%) was hydrologically integrated into the stream network.

Gaps to be Filled

At the on-site scale many of the major questions have been addressed by studies. Some areas that would benefit still remain such as the impact on runoff increases and water quality changes from conversion of unsurfaced roads to paved ones. The short- and long-term impacts of road removal also needs further study. Many of the descriptions of erosion mitigation techniques are black box that would benefit from descriptions of the processes at work.

At the watershed scale much work remains to be done. Studies to achieve a better understanding of runoff processes from forested slopes with and without harvesting and roads with an emphasis on the role of macropores have been suggested by Thomas and Megahan (1998). The degree of integration of the road network with the stream should be done on different soil types and precipitation regimes.

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