Forest Resource Transportation Planning with Consideration of Forest Road Erosion*

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Abstract

This research incorporates an environmental impact of forest roads into an economic analysis for resource transportation planning. The Forest Service WEPP: Road, which is a road erosion prediction model, is combined with NETWORK 2000, an extensive economic forest transportation network planning model. WEPP is used to estimate the sediment delivery from each road segment to streams. Based on the estimated sediment delivery, NETWORK2000 produces alternative road systems that minimize both transportation costs and overall sediment delivery. This methodology is applied to the Mica Creek watershed in Northern Idaho. The results provide economically efficient and environmentally friendly alternatives for a forest road network in the watershed. The methodology and results are presented.

Keywords: road network design, network algorithm, environmental impacts, road management

1. INTRODUCTION

Research by forest land managers and technical specialists nation-wide indicates that forest roads are the greatest single source of sediment delivered to streams in forested watersheds (Burroughs 1991). Unfortunately, forest road networks are not currently optimized as a means to minimize sediment delivery to streams. This is partially because there is no method to directly incorporate sediment delivery into the economics of forest transportation planning.

The decisions people make about ecosystems imply valuations; and people choose whether to make these valuations explicit or not (Costanza et al. 1997). Forest transportation has been evaluated for environmental impacts (Girvetz and Shilling 2003), but has never had these impacts methodologically incorporated into an economic analysis with a monetary value. The logic of market failure has led economists, and increasingly scientists as well, to argue that the critical environmental resources need to be incorporated into the market system (Hanemann 1988).

Increased stream sedimentation, associated reductions in fish habitat productivity and mass road failures are just a few of the impacts that result from forest roads (USDA 1998). Sediment delivery from roads results from a combination of direct delivery at stream crossings, indirect delivery at culverts or other drainage structures, and from mass wasting events that deliver sediment to the stream channel (Madej 2001, Elliot et al. 1999). Studies have shown that the overall sediment produced in forested basins increases from road-related erosion processes (Wemple 2001).

This study was designed to develop alternative road network systems that minimize both the economic costs and environmental impacts represented by sediment yields for the Mica Creek Watershed in Idaho. Predicted sediment amounts from each road segment were estimated using the United States Forest Service (U.S.F.S.) WEPP: Road erosion prediction model (Elliot et al. 1999). The environmental costs were then calculated as a dollar amount per pound of sediment leaving the road and per pound of sediment delivered to the stream channel. The forest transportation economic analyses were carried out using the NETWORK 2000 forest transportation planning model. Based on the estimated sediment delivery, NETWORK 2000 produces alternative road systems that minimize both transportation costs and overall sediment delivery. Results for five different alternatives were attained; four results employed an environmental cost, and an optimal result with no environmental cost was found for comparisons.

The purpose of this study is to incorporate an environmental cost into an economic analysis that is used in forest transportation planning to reduce the undesired environmental impacts, while minimizing the economic costs. Putting a price on the environment is a controversial topic and has no existing standard method (Costanza et al. 1997). Our intention in this study is not to accurately estimate the environmental cost of sediment, but rather to analyze the effects of considering sediment into forest transportation planning with optimal road networks.

2. STUDY AREA

The study area is located within the Mica Creek watershed, which is part of the St. Joe River Basin in Idaho, about forty-two miles southeast of Coeur d’Alene. Potlatch, a private timber company, owns and manages most of the watershed. The watershed is 13,046 hectares (32,238 acres) and includes 756 kilometers (470 miles) of roads. The study area is situated in the upper part of the Mica Creek watershed, and is 7,495 hectares (18,520 acres), or 58% of the entire watershed (Figure 1). The study area elevation ranges from 818 to 1,688 meters. The precipitation falls mostly in the form of rainfall with an average annual rainfall of 138.7 to 144.3 centimeters, and an average annual snow water equivalent of 0 to 63.8 centimeters of snow in the winter months (i.e. October - May) (NRCS 2002). The slopes are generally gentle in this area, but have some steep slopes up to 51.6 degrees. Parent materials consist of quartzite and schist (11%), quartzite (5%), siltite/argillite (16%), and siltite/quartzite (68%) (Potlatch 2005a). The quartzite has very low mass wasting potential and surface erosion potential, and the quartzite and schist has the highest. Eighty-nine percent of the soils in the watershed are silt loam, and the rest is sandy loam. Roads made up of surface soils that are of high clay or silt content have a higher surface area than roads that are of a rocky soil or that have a gravel surface. A higher surface area results in less infiltration of precipitation and greater overland flow. Thus, the roads containing surface soils of higher clay or silt content will generate more runoff and contribute more fine sediments to streams.
3. METHODS

A total of 3,889 sediment delivery points were identified throughout the field data collection and GIS analysis for surveyed, unsurveyed, and proposed roads. These delivery points represent stream crossings, drainage structure locations, or low elevation points along the road, where water collects and drains. These points were then used to split roads into multiple segments along with intersection points and high points on the road which divert water into two opposite directions. Sediment yields were then estimated from each road segment using WEPP:Road (Elliot et al. 1999), and converted into a dollar amount per pound. NETWORK2000 (Chung and Sessions 2003) was used to develop alternative road network systems that minimize both transportation costs and overall sediment delivery. Detailed methodology is described below.

3.1 Using WEPP:Road

The U.S.F.S. WEPP:Road erosion model predicts runoff and surface erosion from a road segment, and the sediment yield to an adjacent stream channel. This physically-based model was developed from the original Water Erosion Prediction Project (WEPP) model that predicts hillslope erosion (Elliot et al. 1999). Results from WEPP:Road consist of the mean annual
sediment yield from the road surface and leaving the forest buffer or delivered to stream channels.

WEPP:Road assumes that there are three overland flow elements: a road, a fillslope, and a forest (Elliot et al.1999). Elliot et al. (1999) noted that runoff and erosion from these elements varies with climate, soil and gravel addition to the road surface, local topography, drain spacing road design and surface condition, and ditch condition. In order to provide the WEPP:Road model with information on these factors, the following input data are required:

- Road Segment Length (meters or feet)
- Segment Width (meters or feet)
- Segment Gradient (percent or degree)
- Surface Soil Texture: clay loam, sandy loam, silt loam, or loam.
- Road Design: outslope, outslope rutted, inslope vegetated or rocked ditch, or inslope bare ditch.
- Road Surface: gravel, native, or paved, and % rock content.
- Fill Slope (percent or degree)
- Fill Length (meters or feet)
- Buffer Slope (percent or degree)
- Buffer Length (meters or feet)

### 3.2 Field Data Collection

Using a Magellan Meridian GPS receiver, 1,298 points were surveyed along 136 kilometers (41%) of road within the Mica Creek Watershed. At each point during the survey, seven attributes were measured: road width, fill slope length, fill slope gradient, road design, road surface content, soil texture and percent rock content.

Locations of high points were recorded along with any road failures (i.e. debris flows, land slides, slumping). High points are essential to capture for situations where a high point in a road will direct water down in two distinct directions, and the elevation of the high point is needed to find the two segments gradients. These points were then displayed in ArcMap to acquire the rest of the spatial data and were linked with their specific attributes.

All stream crossings were recorded as delivery points but were noted as stream crossings in particular for later specifications in WEPP:Road. Sediment delivery was assumed equal to one hundred percent of the predicted erosion rate at stream crossings (Elliot et al. 1999). At stream crossings, fill and buffer attributes were assigned the lengths of 0.03 meter (0.1 foot), and slopes of 0.3%. Sediment leaving the buffer can be used for this estimate, although deposition on the fill or buffer may be overestimated (Elliot et al. 1999).

At each survey point along the road, surface soil texture was determined by hand. Soil texture was found to be similar throughout the study area and was compared to SSURGO Soil Survey database (NRCS 2003); to ensure differentiation of textures were accurate. Comparisons revealed little differences, and SSURGO data was then used for identifying soils for the non-existing proposed roads and roads that were not measured within the study area.

Climate data for WEPP:Road was generated from the St.Maries climate station approximately twenty miles from the Mica Creek Watershed. A fifty year simulation period was used for the WEPP:Road analysis to ensure that an adequate number of wet years was simulated.
3.3 Data Acquisition Using GIS

A 1 meter Digital Elevation Model (DEM) of the Mica Creek Watershed derived from LIDAR (Evans 2005) was used for GIS analyses in this study. Elevation and the length between each point were retrieved from the DEM. The data were used to find the segment gradient and the directional flow of runoff for each segment. The buffer slope and length were also retrieved from the DEM. Buffer lengths were measured from the delivery point location on the road to the nearest stream channel below and then the recorded fill slope length was subtracted from this. Buffer slopes were estimated using the elevation of the delivery point and the elevation of the nearest point on the stream channel below.

GIS data was used in post-sampling to provide replication of road segments from measured roads for 274 km (170 miles) of unsurveyed roads and proposed roads. Replication was focused on attributes such as road usage, slope, aspect, soils, geology and elevation. Replicated segments were assigned delivery points using the DEM. Using ArcGIS and the raster data from the DEM, the lowest points in elevation along the roads were located for every 90 to 150 meters depending on the averages applied to each road. These low points became the delivery points, as well as any stream crossings visible from the map in ArcGIS. High points were located after the delivery points to divide segments into the appropriate directional flow.

3.4 Other Assumptions for WEPP:Road

The WEPP:Road model predicts sediment amounts with a custom interface that assumes certain inputs. The soil properties for each soil texture are generalized from research findings. The road is assumed free of vegetation, the fill slope has around 50% ground cover, and the buffer contains forest litter of generally 100% (Elliot et al. 1999). Error to model predictions may result from using ArcGIS and assuming accuracy from a segment of road represented by an average gradient and width (Brooks et al. 2003).

3.5 Using NETWORK 2000

All of the predicted sediment amounts produced from WEPP:Road were incorporated into environmental costs, which were further combined with actual transportation costs and analyzed in NETWORK 2000 (Chung and Sessions 2003). NETWORK2000 is an economic analysis model for forest transportation that uses a heuristic algorithm for optimizing large fixed cost (road construction) and variable cost (timber hauling) transportation problems. It has been widely used by public agencies and forest industries to analyze alternative forest transportation routes and identify the least cost road network that connects timber sale locations (landing locations) to the mill.

NETWORK 2000 inputs are arranged by links, or road segments. These segments are identified by a beginning and ending node. Each link has a variable cost (hauling cost) which is defined by a road class factor (Table 1) multiplied by the length of segment. The variable cost units are set as dollar per thousand board feet (MBF) in this study. A fixed cost (road construction cost) can be also assigned to each proposed road segment. For proposed roads, a fixed cost is calculated and assigned using a construction cost of an assumed $40,225 per kilometer ($25,000 per mile) multiplied by the road segment length, where as zero construction cost is assigned to existing road segments. In addition, in order to include the environmental impact of each road segment in the model, the environmental cost for each road segment was
added to the fixed cost as sediment yield in pounds multiplied by a cost factor (i.e. $25/pound and $50/pound of sediment).

Table 1. VARIABLE COST MULTIPLIERS

<table>
<thead>
<tr>
<th>ROAD CLASS</th>
<th>MULTIPLIERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAVED HIGHWAY</td>
<td>$.60 / mile/MBF</td>
</tr>
<tr>
<td>PAVED OR ROCKED LOCAL</td>
<td>$1.00 / mile/MEF</td>
</tr>
<tr>
<td>PRIMARY</td>
<td>$2.00 / mile/MEF</td>
</tr>
<tr>
<td>SECONDARY</td>
<td>$3.00 / mile/MEF</td>
</tr>
</tbody>
</table>

Another required input data set for NETWORK 2000 is sale information. The harvest schedule provided by Potlatch Corp. was incorporated by identifying log landing point(s), harvest volume in MBF, year of harvest, and destination (mill) for each sale. Log landings and destination points are referred to as the entry nodes and destination nodes respectively. The harvest schedule from Potlatch for the Mica Creek Watershed is for seventy years, includes 276 harvest units, for 1,556 sales, and for 412 MMBF. The mills selected for the analysis are St. Maries, Medley Santa, and Clarkia, the three nearest mills to the Mica Creek watershed (Figure 2).

Figure 2. Road network in the study area.

3.6 Alternative Routes
NETWORK 2000 was run for the same harvest schedule for four different alternatives using environmental cost factors of $25 and $50 dollars per pound of predicted sediment yield, and for one with no environmental cost for result comparisons. The entire network of roads used for this program was 855 kilometers (531 miles), including all the primary, secondary, local roads, and highways that connect to the mills outside the watershed (Figure 2).

WEPP:Road gives two predictions, the annual sediment yield from the road segment surface and the annual sediment yield leaving the forest buffer or entering stream channels. Although the environmental concern is based from the sediment yield delivered to stream channels, to locate areas with high risk of potential erosion both of these predictions were used for the alternatives. The environmental cost factors were chosen without rationale other than to provide a scale for comparison.

Alternative 1 does not use an environmental cost and provides comparison of optimal routes and associated costs. Alternatives 2 and 3 use the predicted sediment yield leaving the road surface with the environmental costs of $25 and $50 dollars per pound of sediment. Alternatives 4 and 5 use the predicted sediment yield leaving the forest buffer or delivered to stream channels applied to the same two environmental costs factors. The alternative transportation routes that resulted from NETWORK 2000 are compared in terms of road construction and hauling costs as well as total sediment yields from each road network alternative.

4. RESULTS AND DISCUSSION

The WEPP:Road erosion prediction model results show 96% of the road segments evaluated have some sediment yield leaving the road surface, and 55% have some sediment yield leaving the forest buffer and delivered to stream channels. Results show an average of 2.12 tons per hectare (0.86 tons per acre) annually leaving the road surface, and an average of 1.57 tons per hectare (0.23 tons per acre) leaving the forest buffer and entering the stream channels for the entire study area (reported totals: 180.5 tons (397,853 lbs) from road surface; 49.2 tons (108,502 lbs) leaving forest buffer).

Five different alternative transportation routes were found from using the NETWORK 2000 program. For each alternative route a total variable cost, a total fixed cost and an overall network cost was reported (Table 2). The total variable cost is the total hauling cost, and the total fixed cost is the construction costs for proposed roads added with the environmental costs, and the total network cost is all of these added together. Whereas the total variable costs are more or less the same among the alternatives, the total fixed costs sharply increase as the environmental cost factors increase. The total variable costs do not vary much (3.9% at most) because the same timber volume, landing locations, and mill locations were used for all the alternatives. There are large changes in fixed costs because they consist of not only road construction costs, but also environmental costs which were represented by sediment yield multiplied by the cost factor.

Table 2. NETWORK 2000 results
To compare total network costs of all the alternatives only the total variable cost and the associated construction costs from the total fixed cost are used (Table 3). The actual construction cost shown in Table 3 is the total reported fixed cost minus the associated environmental cost since it is not an actual monetary value. Table 3 also shows the total length of roads chosen in each road network alternative with the total sediment amounts estimated leaving road and delivered to streams from the alternative.

Table 3. Comparisons of actual costs and predicted sediment delivery

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Environmental Cost</th>
<th>Hauling Cost (millions)</th>
<th>Construction Costs (thousands)</th>
<th>Total Network Cost (millions)</th>
<th>Total Road Length (km)</th>
<th>Total Sediment Leaving Road (tons)</th>
<th>Total Sediment Delivered to Stream Channels (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NONE</td>
<td>17.9</td>
<td>121.6</td>
<td>233.3</td>
<td>162.9</td>
<td>162.9</td>
<td>162.9</td>
</tr>
<tr>
<td>2</td>
<td>$30 /ha</td>
<td>18.1</td>
<td>121.4</td>
<td>239.1</td>
<td>163.1</td>
<td>163.1</td>
<td>163.1</td>
</tr>
<tr>
<td>3</td>
<td>$30 /ha</td>
<td>18.6</td>
<td>122.3</td>
<td>245.9</td>
<td>163.6</td>
<td>163.6</td>
<td>163.6</td>
</tr>
<tr>
<td>4</td>
<td>$35 /ha</td>
<td>18.0</td>
<td>125.9</td>
<td>250.2</td>
<td>164.2</td>
<td>164.2</td>
<td>164.2</td>
</tr>
<tr>
<td>5</td>
<td>$30 /ha</td>
<td>18.1</td>
<td>127.7</td>
<td>256.5</td>
<td>165.4</td>
<td>165.4</td>
<td>165.4</td>
</tr>
</tbody>
</table>

The hauling costs are the same as the variable costs from the NETWORK 2000 output, and have an increasing trend with the increase of each environmental cost factor. The construction costs are the fixed costs from the NETWORK 2000 output minus the associated environmental costs for each alternative and do not vary by more than 5.8%. The total network cost in Table 3 is the hauling cost added to the construction costs for each alternative, and also has an increasing trend with the increase of the environmental cost factors. Total actual costs for all five alternatives do not vary by more than 4.3%.

The results show a slow increase in total cost and the rapid decrease in sediment yield, with the increase of the environmental cost factors for the alternatives. Although the environmental concern is the amount of sediment leaving the forest buffer and delivered to stream channels, the alternatives using the WEPP:Road sediment prediction from the road surface (alternatives 2 and 3) were found to have a lesser amount of sediment delivered to stream channels than same cost factors from alternatives 4 and 5. This is because 96% of the total road segments evaluated by WEPP:Road have some sediment yield predicted to be leaving the road surface and only 54% of the segments have a predicted sediment yield delivered to stream channels. This means that 96% of the segments had an environmental cost for finding the alternatives 2 and 3, and only 54% of the segments had an environmental cost for finding alternatives 4 and 5. All road segments that have a predicted sediment yield delivered to streams also have a predicted sediment yield from the road surface. But not all segments that have a predicted sediment yield from the road surface have a predicted sediment yield delivered to streams. Therefore, minimizing sediment yield for more road segments (i.e. Alternatives 2 and 3) results with less sediment yield delivered to streams.
Alternatives 2 and 3, and alternative 1 show a decreasing trend in sediment yield with the increase of the environmental cost factors, for both the total sediment yield leaving the road surface and delivered to stream channels (Table 3). Alternatives 4 and 5 and alternative 1 also show a decreasing trend in sediment yield delivered to stream channels with the increase of the environmental cost factors (Table 3).

Overall trends can be seen in the percent increase in cost from alternative 1 versus the percent decrease in predicted sediment yields (Figures 3 and 4). The trend follows a slow steady increase in cost with a rapid decrease in sediment yields. The total network costs for all the alternatives are within $0.8 million dollars of the total network cost for alternative 1 or maximum 4.3% increase in cost compared to alternative 1. However, these four alternatives produce at least 53.4 tons less sediment yield (or 33% decrease) than alternative 1 for sediment predicted leaving the road surface, and at least 12.3 tons less sediment yield (or 28% decrease) than alternative for predicted sediment amounts leaving the forest buffer and delivered to stream channels. These results indicate that a relatively large amount of sediment can be reduced at the expense of a slight cost increase.

Figure 3. Rate of cost increase with sediment yield decrease for alternatives 1 through 3 using sediment yield from road surface
In finding these five alternatives, at least 50% of the 779 kilometers (484 miles) of current total road network length can be reduced while maintaining access to each stand for future harvesting activities. These alternatives at the very least can guide Potlatch forest managers in locating roads that are unnecessary and roads identified having a high risk of erosion. The roads deemed unnecessary will continue to cause environmental impacts if left untreated and abandoned. Erosion rates remain higher than background levels as long as roads remain in place, making them a chronic sediment source (Parker 2005).

Roads that are identified to have a potential high risk of erosion can increase maintenance costs and the associated environmental impacts. Road design improvements such as increasing the drainage structures and decreasing distance between structures can be used to reduce this risk. Seeding and mulching of new culvert installations, slides and areas of disturbed soil and/or areas of potential erosion problems is another way to decrease the risk of erosion (Potlatch 2005b).

5. CONCLUSION

Combining WEPP:Road with the NETWORK 2000 program resulted in the development of improved road networks that consider environmental impacts as well as overall costs. The environmentally considerate alternatives were able to reduce sediment yields by as much as 39% from Alternative 1 and increase the cost by 4.3% at most. The roads that were evaluated and determined to no longer have an economic use in this watershed could be closed, decommissioned, or obliterated upon the decisions of Potlatch forest managers. The results indicate that our approach to incorporate environmental impacts into transportation planning can generate alternative road networks that minimize both transportation costs and overall sediment delivery from the network.
A large amount of data was needed to successfully run the U.S.F.S. WEPP:Road and the NETWORK 2000 models together, but has shown to be an effective method of evaluating a large watershed with only a portion of field data needed. GIS knowledge of raster data from a DEM is required to accurately, and efficiently retrieve the data for these two models. The use of a 1 meter DEM is recommended for more accurate elevation and slope data, but may be difficult and/or expensive to attain. This transportation planning method was not replicated and should be used for the Mica Creek Watershed only as guidance for decision making on road management.

This method does not currently consider maintenance costs, but incorporating the maintenance schedule and costs into this method would be more realistic in road management and could significantly improve the results. Results would also improve based on a more realistic economic cost associated with each road segment for NETWORK2000.

There is no set method for choosing an appropriate environmental cost factor for predicted sediment yields from the road surface and delivered to stream channels. A forest manager would need to assess the final network costs for all the alternatives relative to budget constraints, maintenance costs, willingness to reduce sediment yields at the expense of increasing costs, and would also need to assess the conditions of the actual routes in the field. These alternatives at the very least can guide Potlatch forest managers in locating roads that are economically unnecessary and roads having a high risk of erosion. The integration of an environmental cost into the NETWORK 2000 economic analysis not only improves the economic efficiency of the transportation network, it adds conservation to forest transportation management.

6. LITERATURE CITED


