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Designing Skid-Trail Networks to Reduce Skidding Cost and Soil Disturbance for Ground-Based Timber Harvesting Operations

Marco A. Contreras, David L. Parrott, and Woodam Chung

Skid-trail locations directly influence the economics and environmental impacts of harvesting operations. Typically, field managers design skid-trail networks manually based on field observations of vegetation and terrain conditions. We designed a model to automatically design skid-trail networks to reduce skidding costs and soil disturbances. The model simulates tree-bunch locations, creates a feasible skid-trail network across the harvest unit, estimates skidding cost and soil recovery cost for each feasible skid-trail segment, and finds the network design that connects each tree bunch to landings while reducing skidding and soil recovery costs. The model was applied to a 24-ha hypothetical harvest unit to test its ability to design optimal networks under different scenarios representing conditions commonly found in timber harvesting operations (e.g., skidding pattern, uneven volume distribution, skidding obstacles, and different weights given to skidding and soil recovery costs). It was also applied to an actual 124-ha harvest unit to evaluate its ability to design skid-trail networks considering more realistic conditions with multiple design factors. The model successfully created optimized skid-trail networks for all scenarios considered, and results suggest that it provides a useful tool to help forest engineers and field managers design economically efficient and environmentally sound ground-based timber harvesting operations.

Keywords: forest operations planning, shortest path algorithm, forest optimization, network programming

Ground-based systems using skidders or forwarders are the most common form of timber harvesting on gentle to moderately steep terrain (Kellogg et al. 1992, Greulich et al. 1999). Skid-trails used by the harvesting equipment to transport logs from stump location to landings directly influence the economics and environmental impacts of harvesting operations. Determining the location of skid-trails is then essential because it affects skidding distances and cycle times. Skid-trail networks are often designed to reduce skidding distances and thus lower skidding cost, which is one of the largest cost components of timber harvesting (Greulich 2003). To reduce skidding costs, skid-trail designs often follow the shortest paths from individual tree-bunch locations to landings, which results in major skid-trails either combining and converging at centralized log-landings or running parallel toward relatively perpendicular access roads when skidding to roadside.

Skid-trails are commonly associated with soil disturbances including soil compaction, displacement, and rut formation, which in turn increases runoff and soil erosion (Rab 1996, Kolka and Smidt 2004, Krueger 2004) and ultimately might lead to loss in soil productivity (Wronski 1984, Zenner et al. 2007, Zenner and Berger 2008). Studies report increases in soil bulk density ranging from 10 to 80% based on soil characteristics such as soil bearing capacity, moisture content, and organic matter (Reisinger et al. 1988) as well as characteristics of the harvesting equipment including vibration and tire pressure (Froehlich et al. 1981). Independent of forest sites and soil types, it has been observed that most soil disturbances are concentrated along skid-trails and centralized log-landings and that most disturbances occur during the first machine passes (Gayoso and Iroumé 1991, Wang et al. 2005, Han et al. 2006, Ampoorter et al. 2007). Best management practices often recommend postharvesting treatments such as disking and seeding, subsoiling, recontouring, and installing water bars to ameliorate soil disturbances (Conrad et al. 2012, Lloyd et al. 2013). Although these treatments reduce negative environmental impacts, they also levy additional costs, causing significant economic impacts on timber harvesting operations (Sawyers et al. 2012).

Studies suggest restricting the traffic of heavy harvesting equipment to designated skid-trails to reduce soil disturbances (Andrus and Froehlich 1983, Garland 1997, Han 2007). Forest engineers and field managers typically design skid-trail networks manually

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Affiliations: *Marco A. Contreras (marco.contreras@uky.edu), Department of Forestry, University of Kentucky, Lexington, KY. David L. Parrott (david.parrott@uky.edu), University of Kentucky. Woodam Chung (woodam.chung@oregonstate.edu), Oregon State University.*

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based on field observations of vegetation and terrain conditions. Although manual designs might effectively reduce these disturbances, it is not possible to evaluate all possible alternatives and obtain optimal designs that concurrently consider planning factors such as machine characteristics, terrain conditions, and skidding obstacles posed by riparian zones and other sensitive areas (Froehlich et al. 1981). Moreover, manually designing skid-trail networks is challenging because it should evaluate the tradeoffs between reducing total skid-trail length to reduce soil disturbances and following shortest paths between individual tree bunches to landings to reduce skidding cost, which often increases total skid-trail length.

Although several recent studies have focused on a similar optimization problem for forest road layouts (Anderson and Nelson 2004, Stückelberger et al. 2007, Chung et al. 2008, Hayati et al. 2013), there is a lack of models developed to automate the design of optimal skid-trail networks. Halleux and Greene (2003) developed an automated approach that can generate skid-trails based on estimates of skidding costs, but it can only consider even volume distribution and flat terrain, thus ignoring terrain conditions that may pose skidding obstacles. Furthermore, the approach was developed to analyze alternative harvest unit layouts and cannot optimize the design of skid-trail networks. Recently, Contreras and Chung (2011) developed an approach to optimize skid-trail network designs to reduce skidding costs and determine individual tree harvesting costs. This approach requires tree-level attributes (i.e., volume) and predetermined location of cut-and-leave trees. Although advances in remote sensing technologies such as light detection and ranging (LiDAR) facilitates the acquisition of tree-level information, such data are still not readily available to landowners and forest companies commonly conducting timber harvesting operations. In addition, this model does not consider soil disturbances and is only able to design skid-trail networks that minimize skidding costs.

To address this research need and facilitate the planning of environmentally sound and cost-efficient ground-based timber harvesting operations, we developed a computerized model to automatically design optimal skid-trail networks for ground-based skidding operations (i.e., skidders and forwarders). The model creates an optimal skid-trail network that minimize skidding costs and soil disturbances alone or simultaneously. Soil recovery costs associated with amelioration treatments along skid-trails after harvesting are considered an economic proxy of soil disturbances. We applied our model to a 24-ha hypothetical harvest unit to test its ability to design optimal skid-trail networks under different scenarios representing conditions commonly found in timber harvesting operations (e.g., skidding pattern, uneven volume distribution, skidding obstacles, and different weights given to skidding and soil recovery costs). Moreover, the model was applied to an actual harvest unit of 124 ha in size to evaluate its ability to design an optimal skid-trail network considering more realistic conditions with multiple design factors.

Computerized Model

After the harvest unit has been delineated, the model designs the optimal skid-trail network to transport tree bunches placed throughout the harvest unit to selected landings while minimizing soil recovery and skidding costs. Given an available procedure to identify tree-bunch locations, either collecting locations on the ground with global positioning systems (GPS) units (handheld or machine-mounted) or using a computerized approach, our model is able to design skid-trail networks for any combination of harvesting method (i.e., whole-tree, tree-length, or cut-to-length) and harvesting system (i.e., manual, semi-mechanized, or mechanized). For the purpose of the model application presented in this study, a tree-bunching routine to determine tree-bunch locations was incorporated into the model. This routine assumes a whole-tree harvesting method as follows: felling is done either manually or mechanically, leaving trees at the stump location; skidding is carried out by a skidder, which is assumed to gather nearby trees using its maximum loading capacity (MLC); and processing is performed at the landing, where trucks have access to load logs for further transportation to conversion facilities.

Our model constructs skid-trail networks based on terrain conditions, distribution of harvestable volume, nontrafficable zones, and location of landings. Several rasterized geographical information systems (GIS) layers are used to represent terrain conditions and volume across the harvest unit. Although digital elevation models (DEMs) of various resolutions are readily available (i.e., 30- and 10-m DEMs from the US Geological Survey), we used a high-resolution, 1-m DEM to accurately represent terrain surface across the harvest unit and increase our ability to detect micro-conditions, such as ditches and rock outcrops, that might present obstacles for skidding operations. A rasterized volume layer is used to represent either the average harvestable volume in the harvest unit or specific volume estimates by stand or small geographic areas inside the harvest unit. This layer can be generated using techniques ranging from advanced remote sensing procedures that assign volume estimates to small areas (i.e., m^3 by 10×10-m cell) to traditional timber inventories that provide volume estimates by forest stand (i.e., $m^3\ ha^{-1}$). The model also considers a rasterized traffic layer to indicate any sensitive areas, such as riparian zones and wet areas, where traffic of heavy machines should be avoided. Last, a layer indicating the location of selected landings where skidders should bring tree bunches for further transportation is required. For consistency, all input raster layers have the same 1-m resolution as the DEM.

To design the optimal skid-trail network, the model first applies the tree-bunching routine to determine the number and location of tree bunches based on estimates of harvestable volume per cell, cell size, and the skidder's MLC, which was considered constant throughout the harvest unit. Second, the model creates a network of feasible skid-trail segments based on terrain characteristics such as slope and whether traffic of heavy machinery is permitted. Third, the model assigns skidding costs and soil recovery costs for each feasible skid-trail segment based on slope distance. Last, the model uses NETWORK 2000 (Chung and Sessions 2003), which uses an approximation algorithm based on Dijkstra's shortest path algorithm (Dijkstra 1959), to determine the optimal skid-trail network connecting all tree-bunch locations to the selected landings while minimizing both soil recovery and skidding costs.

Determining Number and Location of Tree Bunches

The volume and traffic layers along with the skidder's MLC are the main inputs used by the tree-bunching routine to determine the number, volume, and location of tree bunches. The model searches for cells with available harvestable volume, where traffic is allowed, and groups adjacent cells until the MLC is reached (Figure 1). Starting with the first tree bunch ($i = 1$), the model searches the harvest unit area for the first trafficable cell with available volume. This first cell is marked as the ith tree-bunch seed cell and assigned to the tree bunch (cells with diagonal lines in Figure 1). Its volume is added to the tree bunch and its coordinates in terms of row (r) and column (c) number are stored. The model then creates a 3×3 neighborhood window centered on the seed cell ($r \pm 1$, $c \pm 1$) and

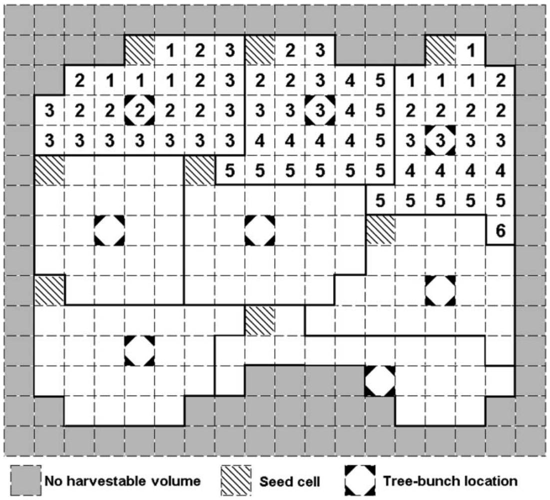

Figure 1. Diagram illustrating the tree-bunching routine showing seed cells, increasing neighborhood windows ("1", "2",...), and tree-bunch location.

searches in a left-right, top-bottom manner for unassigned, trafficable cells with available volume (cells with a "1" in Figure 1). When such a cell is found, the model assigns it to the *i*th tree bunch, adds its volume to the bunch, and stores its coordinates. If the tree-bunch's volume is lower than the skidder's MLC after searching the neighborhood window, the window size is increased by one ($r \pm 2$, $c \pm 2$) and the search process continues (cells with a "2" in Figure 1). The model continues the search process with neighborhood windows of increasing size until the available volume of a cell surpasses the skidder's MLC. This cell signals the end of the search and is not included in the *i*th tree bunch. After all cells forming the *i*th tree-bunch are identified, the average coordinates (row and column) are calculated, and the corresponding cell is assigned as the *i*th tree-bunch location (cells with black corners in Figure 1). The model then resumes searching the harvest unit area for the first unassigned, trafficable cell with available volume to be assigned to the next bunch ($i = i + 1$). The model stops grouping adjacent neighbor cells to determine volume and location of tree bunches when all trafficable cells with available volume are assigned to a tree bunch.

Generating the Feasible Skid-Trail Network

The model discretizes the harvest unit area by creating a network of feasible skid-trail segments formed by a set of nodes regularly spaced throughout the harvest unit and links connecting adjacent nodes. Nodes represent the center of DEM cells, tree-bunch locations, and the location of landings, and links represent the skid-trail segments between adjacent nodes. In the model, each node is connected to its eight adjacent nodes spaced every 5 m over trafficable areas only.

Typically, for safety and productivity reasons, skidder operations are limited to areas with gentle to moderate slopes. Thus, the model checks whether skidder traffic is feasible over the link representing the skid-trail segment and creates the link when its gradient and side slopes are below predefined maximum gradient (MG) and maximum side slope (MSS) values. Link gradients are calculated based on the elevation difference and horizontal distance between the cells corresponding to the from- and to-node forming the link. Side slopes are calculated based on the elevation difference and horizontal distance between the two cells perpendicular to the cell corresponding to the to-node of the link.

Estimating Soil Recovery and Skidding Cost for Skid-Trail Segments

For each feasible skid-trail segment (link), the model estimates the associated soil recovery and skidding cost. Soil recovery costs are used as an economic proxy to measure soil disturbance and provide unit consistency with skidding costs. Soil recovery costs are associated with treatment activities conducted to ameliorate soil disturbances caused by skidder traffic such as disking and seeding, subsoiling, recontouring, and installing water bars in skid-trails. As mentioned above, most soil disturbances occur during the first few machine passes; thus, soil recovery cost was considered a one-time, fixed cost, independent of traffic level. Depending on terrain characteristics (slope and ruggedness) and equipment type, the cost of amelioration treatments for skid-trails can range from \$300 to \$1,500 km^{-1} (Smidt and Kolka 2001, Kolka and Smidt 2004, Sawyers et al. 2012). For demonstration purposes, we considered a value of \$500 km^{-1} for skid-trail, which along with its slope distance was used to obtain the soil recovery cost for each skid-trail segment.

Skidding costs are calculated based on the skidder's cycle time and rental rate (Equation 1)

$$PSC_i = \left(\frac{CT_i}{60}\right) \times RR \tag{1}$$

where PSC_i is the skidding cost (\$) per round trip for the *i*th tree-bunch, CT_i is the round trip skidding cycle time (minutes) between the *i*th tree-bunch location and the landing, and *RR* is the skidder's rental rate, for which we used a value of 85 (\$ hour^{-1}). Cycle times can be estimated using the appropriate regression models that can capture the interactions among skidder equipment, terrain conditions (slope and ruggedness), distance, and load characteristics (volume and number of logs). However, there are no models available to estimate skidding cycle times for short distances such as those obtained from high-resolution DEM. For demonstration purposes, we modified the skidding cycle time models presented by Han and Renzie (2005) and used them in our model applications to estimate downhill and uphill skidding cycle times proportional to skidding distances (Equations 2 and 3). It was also assumed that uphill skidding cycle time (uphill skidding loaded with empty skidder taking the same trail unloaded) was 20% greater than downhill cycle time for equal distance.

$$CT_{ds} = 3.9537 + (0.0215 \times D) \tag{2}$$

$$CT_{us} = 3.9537 + (0.0258 \times D) \tag{3}$$

where CT_{ds} and CT_{us} are the cycle times for downhill and uphill (minutes), respectively, and D is the skidding slope distance (m) from a given tree-bunch location to the landing. The first term in the cycle time equations (Equations 2 and 3) is an estimate of the fixed cycle time due to activities such as hooking and unhooking logs to the winch line for the case of a cable skidder, and the second term estimates the actual skidder travel time along a skid-trail. Thus, because fixed cycle time is independent of the skidding route, the model calculates the skidding cost for each skid-trail segment using the variable cycle time (second term in Equations 2 and 3) and after the least-cost route is selected, the fixed cycle time component is added.

Finding the Optimal Skid-Trail Network

Soil recovery and skidding costs calculated for each feasible skid-trail segment are used as the segment's attributes to formulate a network transportation problem considering fixed (soil recovery)

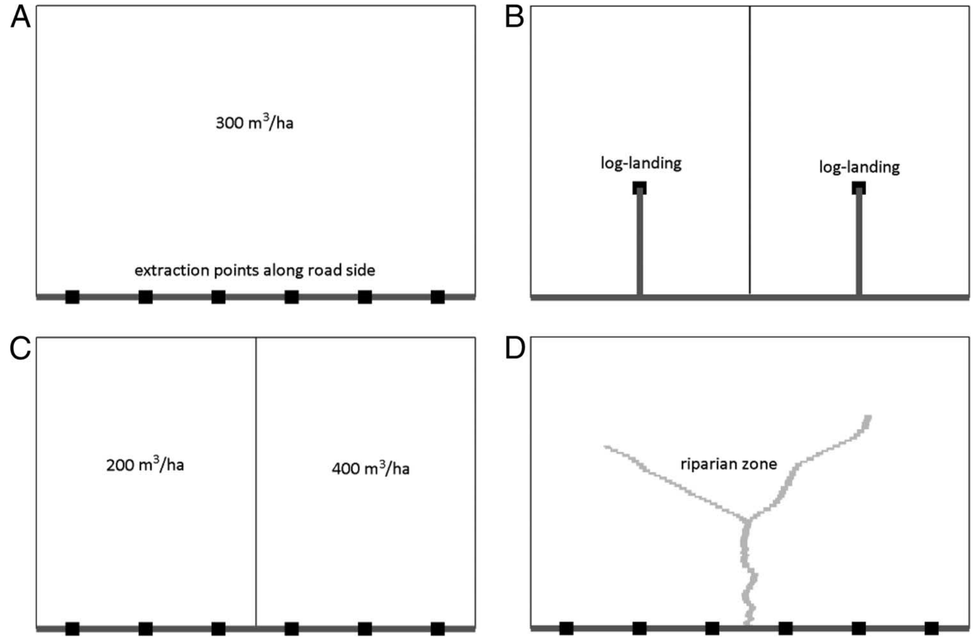

Figure 2. Diagram illustrating harvest unit conditions considered under the six scenarios.

and variable (skidding) costs. The problem of finding the set of least-cost skid-trails connecting each tree bunch to the designated landings can be formulated as follows

$$\text{Minimize } Z = \sum_{i=1}^{n} [w(SC_i \times NT_i) + (w-1)(SRC_i \times B_i)] \tag{4}$$

where SC_i is the skidding cost (\$) associated to the ith skid-trail segment for one turn, NT_i is the number of turns the skidder passes through the ith skid-trail segment, SRC_i is the soil recovery cost (\$) associated to the ith skid-trail segment, B_i is a binary variable that indicates whether traffic exists on the ith skid-trail segment (1 if there is traffic and 0 otherwise), w is a weight ($0 \leq w \leq 1$) that indicates the relative importance of each cost component in the minimization problem, and n is the total number of feasible skid-trail segments.

Transportation problems considering fixed and variable costs are a special case of the fixed charged transportation problem (FCTP), which is in known as an NP-hard combinatorial optimization problem (Steinberg 1970). Mixed-integer programming has been used to optimally solve FCTPs (Adlakha and Kowalski 2003), but its application is limited to small- to medium-scale problems because solution time grows exponentially with problem size. Instead, we used NETWORK 2000 (Chung and Sessions 2003), which has been widely used to efficiently solve large-scale transportation problems with fixed and variable costs (Contreras and Chung 2007, Chung et al. 2008, Jourgholami et al. 2013). NETWORK 2000 finds the set of least-cost skid-trails by iteratively applying the shortest path algorithm (Dijkstra 1959) to take into account the fixed cost and number of passes over each skid-trail segment. The process starts with finding the least-cost skid-trails connecting each tree bunch to the designated landings without considering fixed costs during the first iteration. The number of turns over each skid-trail segment is accumulated so that at the end of the iteration the total SC_i over each segment and SRC_i is taken into account. For the next iteration, the skidding cost for each segment is recalculated (SC_{i_itr}) using Equation 5. The number of turns over all segments is reset to zero, and the next iteration starts using the new set of skidding costs. This process continues until the difference between solutions from two consecutive iterations is within 0.001% of the total skidding and soil recovery cost.

$$SC_{i\_itr} = SC_i + \frac{SRC_i}{NT_i} \tag{5}$$

Model Application

We generated a hypothetical 24-ha harvest unit (600 m east-west and 400 m north-south) with a constant downward slope of 10% from north to south. The model was applied to the hypothetical harvest unit to design optimal skid-trail networks under six scenarios representing conditions commonly found in timber harvesting operations including skidding pattern (roadside versus log-landing), uneven volume distribution, skidding obstacles, and different weights given to soil recovery and skidding costs. Scenario I represented the case of skidding to six landings spaced every 100 m along a road located along the southern border of the harvest unit (Figure 2A). This scenario assumed 300 m^3 ha^{-1} of harvestable volume evenly distributed across the harvest unit and no skidding obstacles and only considered skidding costs to design the optimal skid-trail network. Scenario II considered the same harvest unit conditions (even volume distribution, no skidding obstacles, and only skidding costs), except that it considered skidding to two centralized log-landings. These landings were placed 50 m south of the centroids of two equal-size areas covering the harvest unit (Figure 2B). For scenario III, these two equal-size areas were assigned harvestable volumes of 200 and 400 m^3 ha^{-1} (Figure 2C) with the total volume and other conditions the same as those for scenario I. Scenario IV maintained all conditions of scenario I with the addition of a *y*-shaped riparian zone (Figure 2D) restricting the traffic of heavy equipment and posing a large skidding obstacle. Whereas scenarios I to IV only considered skidding cost ($w = 1$) to design the optimal skid-trail network, scenario V considered soil recovery and skidding costs

Table 1. **Harvest unit conditions considered for the design of optimal skid-trail networks under each scenario.**

Scenario	Extraction point	Volume distribution	Presence of skidding obstacles	Cost components
I	6 landings along road	1 zone; 300 m^3 ha^{-1}	No obstacles	Skidding cost only (w = 1)
II	2 centralized landings	1 zone; 300 m^3 ha^{-1}	No obstacles	Skidding cost only (w = 1)
III	6 landings along road	2 zones; 200 and 400 m^3 ha^{-1}	No obstacles	Skidding cost only (w = 1)
IV	6 landings along road	1 zone; 300 m^3 ha^{-1}	One y-shaped riparian zone	Skidding cost only (w = 1)
V	6 landings along road	1 zone; 300 m^3 ha^{-1}	No obstacles	Soil recovery and skidding cost (w = 0.5)
VI	6 landings along road	1 zone; 300 m^3 ha^{-1}	No obstacles	Soil recovery cost only (w = 0)

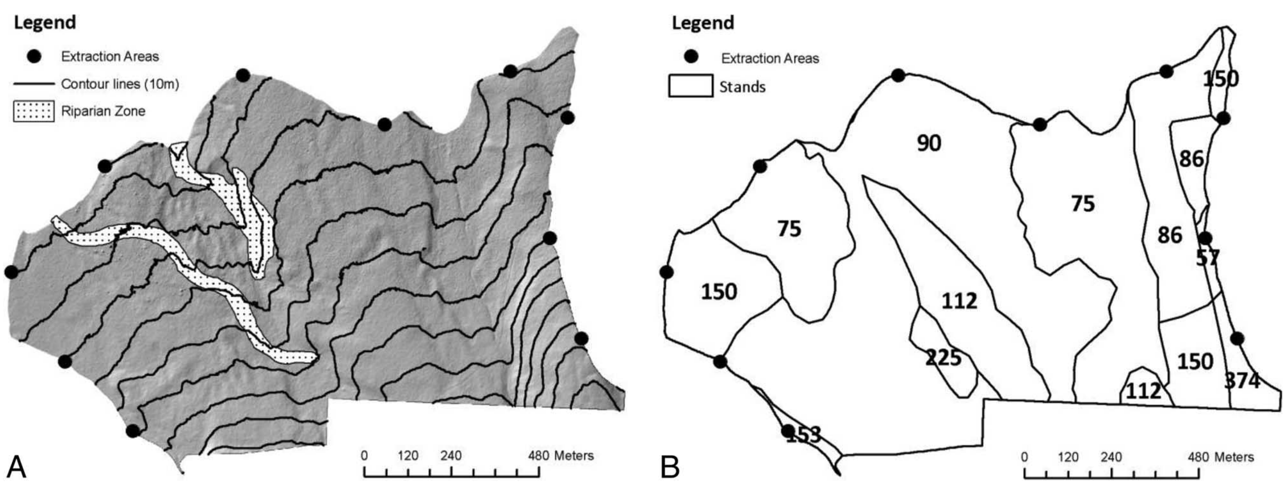

Figure 3. Terrain conditions (A) and harvestable volume (m^3/ha) by stand (B) across the actual harvest unit.

with equal importance (w = 0.5), and scenario VI considered soil recovery cost only (w = 0). All harvest unit conditions for scenarios V and VI were the same as those for scenario I. Table 1 shows a summary of the harvest unit conditions considered in each scenario.

In addition, we applied the model to an actual harvest unit to evaluate its ability to design optimal skid-trail networks considering more realistic conditions with multiple design factors. The harvest unit is 123.6 ha in size, containing multiple stands with different harvestable volumes, 10 landings placed around the boundary, and two major skidding obstacles presented by riparian zones (Figure 3). The same importance was given to soil recovery and skidding costs (w = 0.5) to design the optimal skid-trail network.

Results

The model successfully identified tree-bunch locations and designed optimal skid-trail networks connecting tree bunches to landings for all six scenarios of the hypothetical harvest unit. Table 2 presents a summary of the model results, and Figures 4 and 5 show

Table 2. **Summary of the results of the skid-trail model when applied to the six scenarios in the hypothetical harvest unit.**

	Scenarios						
Model results	I	II	III	IV	I*	V	VI
Harvest unit information							
Harvesting cost ($)					89,428	84,879	129,685
Skidding cost ($)	63,837	44,909	63,780	70,172	63,837	74,865	119,754
Soil recovery cost ($)					25,591	10,013	9,931
Harvesting cost ($ m^{-3})	8.87	6.26	8.86	9.91	12.42	11.79	18.01
Number of tree bunches	1,472	1,469	1,466	1,463	1,472	1,472	1,472
Volume (m^3)	7,200	7,174	7,200	7,080	7,200	7,200	7,200
Skid-trail network length (m)	51,181	57,656	51,243	53,106	51,181	20,027	19,862
Area impacted (%)†	63.9	72.1	64.1	66.4	63.9	25.0	24.8
Per tree-bunch information							
Minimum volume (m^3)	0.03	0.03	0.02	0.03	0.03	0.03	0.03
Average volume (m^3)	4.89	4.88	4.91	4.84	4.89	4.89	4.89
Maximum volume (m^3)	4.98	4.98	5.00	4.98	4.98	4.98	4.98
Minimum skidding cost ($)	5.6	5.7	5.8	5.7	5.6	5.7	5.7
Average skidding cost ($)	12.0	10.2	12.0	13.0	12.0	13.4	19.1
Maximum skidding cost ($)	18.3	14.9	18.3	21.5	18.3	20.9	33.1
Minimum skidding distance (m)	2.8	2.2	5.9	3.6	2.8	2.8	2.8
Average skidding distance (m)	211.6	149.7	210.6	244.4	211.6	255.8	444.6
Maximum skidding distance (m)	416.2	304.7	416.9	520.9	416.2	501.5	902.4

* Skidding cost of scenario I plus soil recovery cost.
† As a percentage of the 24-ha harvest unit and considering a skid-trail width of 3.0 m.

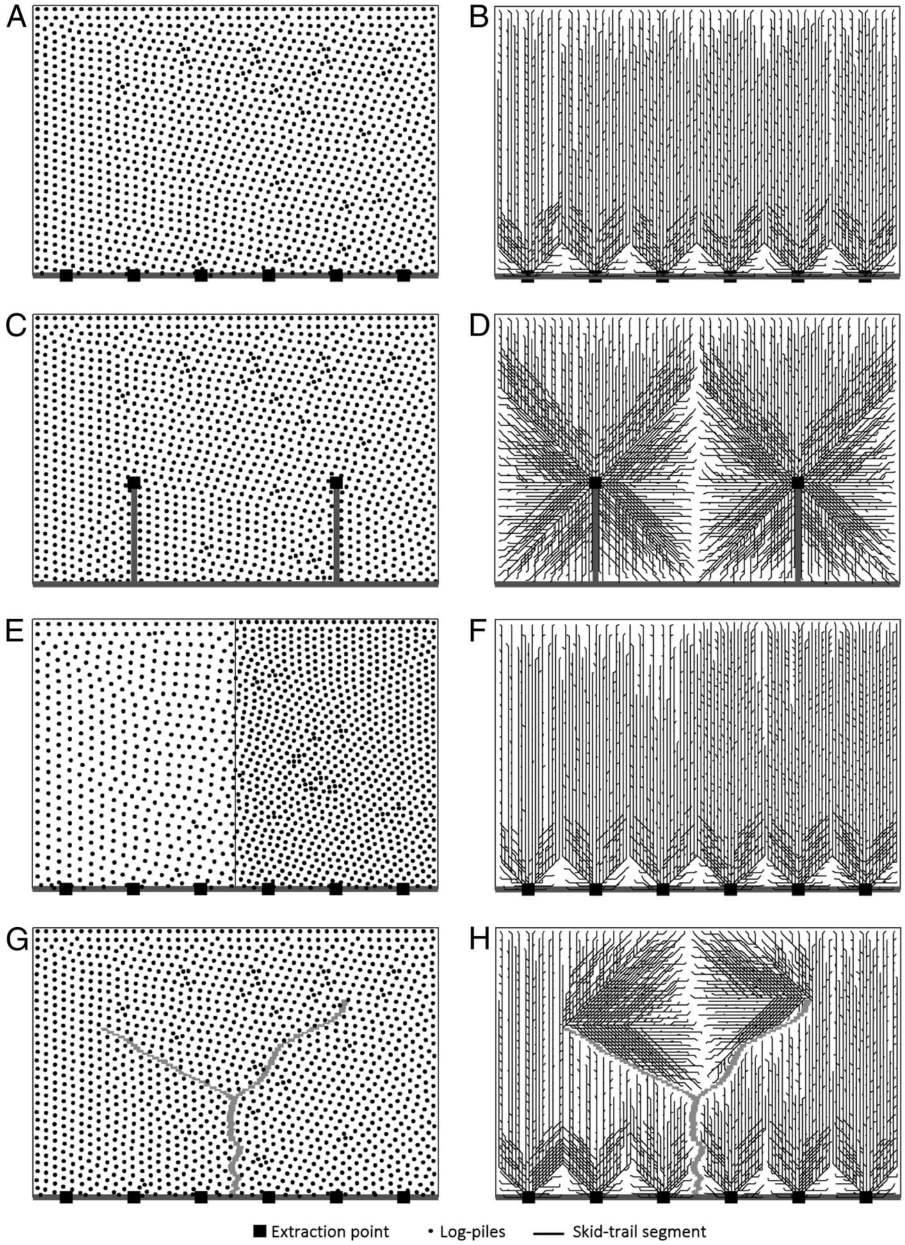

Figure 4. Tree-bunch locations (A, C, E, and G) and optimal skid-trail networks (B, D, F, and H) generated by the model for scenarios I to IV.

the spatial distribution of tree bunches and the optimal skid-trail networks.

Hypothetical Harvest Unit

For scenario I, the model located 1,472 tree bunches with an average of 4.89 m^3 throughout the harvest unit to extract a total of 7,200 m^3 across the harvest unit (Figure 4A). The optimal skid-trail network connecting all tree bunches to the six landings had a length of 51.2 km with skid-trails running mostly parallel in a north-south direction toward the landings (Figure 4B). Average skidding distance along the skid-trails was about 212 m, with distances ranging from 3 to 416 m, and a resulting skidding cost of \$8.87 m^{-3} (Table 2).

For scenario II, which considered two centralized log-landings instead of landings along the roadside, the harvest volume and number of tree bunches were slightly lower than those for scenario I (7,174 m^3 and 1,469 tree bunches) because no volume was taken into account over the two access roads connecting the centralized log-landings to the existing road (Figure 4C). The length of the optimal skid-trail network increased by about 13% (51.2 km versus 57.7 km) compared with that for scenario I. This is mainly because individual tree bunch/landing skid-trails run in different directions, resulting in fewer shared skid-trails (Figure 4D). However, the average and maximum skidding distance decreased by almost 30% from scenario I to about 150 and 305 m, respectively, resulting in a similar reduction in skidding costs (Table 2). Although skidding cost was almost \$19,000 (\$2.60 m^{-3}) lower than that for scenario I because of the shorter skidding distances, comparisons of total harvesting costs between both scenarios should also account for the construction costs for log-landings and access roads.

For scenario III that considered two equal-size areas with different harvestable volumes but same total volume as scenario I, the number of tree bunches identified by the model was slightly

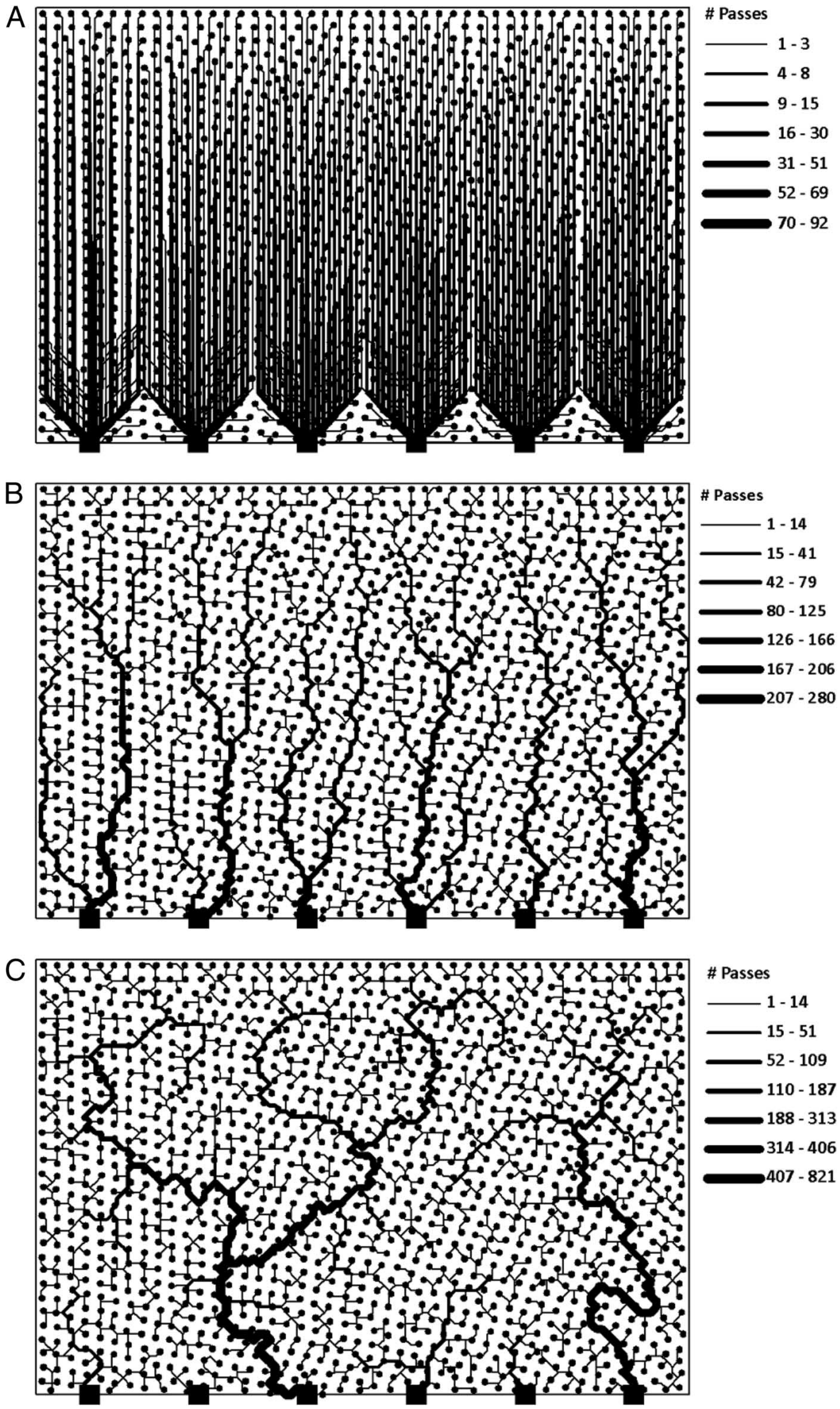

Figure 5. Optimal skid-trail networks connecting tree-bunch locations to selected landings for scenarios I (A), V (B), and VI (C) showing traffic levels in terms of number of machine passes.

lower, and their spatial distribution corresponded with volume distribution. Fewer and sparser tree bunches were located on the 200 m^3 ha^{-1} harvestable volume area (left side of the hypothetical harvest unit) than on the 400 m^3 ha^{-1} harvestable volume area (Figure 4E). The pattern of the optimal skid-trail network was similar to that for scenario I with most skid-trails running parallel toward landings along the existing road (Figure 4F). Thus, skidding distance, skidding costs, and total skid-trail network length were also similar to those for scenario I (Table 2). This was probably because the two areas have the same shape and size, and their common boundary runs parallel to optimal skid-trails. Differences in skid-trail patterns may become more conspicuous when areas (forest stands) with different volumes, shape, and size are considered.

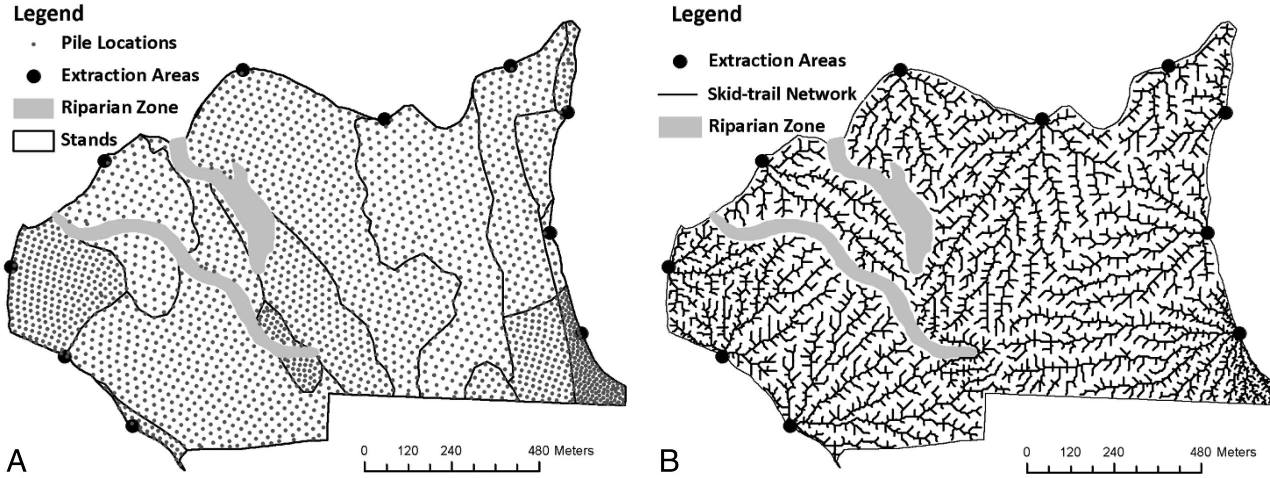

Figure 6. Tree-bunch locations (A) and optimized skid-trail network (B) identified by the model.

For scenario IV, which considered a *y*-shaped riparian zone, the total volume was also slightly lower than that for scenario I (7,080 m^3 versus 7,200 m^3) because no harvestable volume was considered within the riparian zone. Thus, the resulting number of tree-bunches (1,463) was also slightly lower (Figure 4G; Table 2). The total length of the optimal skid-trail network was more than 1.9 km longer than that for scenario I (Table 2) because more than half of the individual skid-trails had to go around the riparian zone to reach the landings (Figure 4H). As expected, the average and maximum skidding distances increased about 15% (33 m) and 25% (105 m) compared with those for scenario I, resulting in an approximately 11% skidding cost increase, from \$8.87 to \$9.91 m^{-3}.

As mentioned above, only skidding costs were considered to design the optimal skid-trail network for scenarios I to IV; thus, each tree-bunch/landing skid-trail was independent from each other. This resulted in skid-trail networks formed by many low-traffic skid-trails running parallel to each other and causing a relatively high total skid-trail network length. For scenario I, although the skid-trails were independent, several skid-trail segments are shared by the individual shortest paths, resulting in skid-trails having multiple turns or machine passes. Skid-trail traffic increased with proximity to log-landings, from a few passes for skid-trail segments connecting tree bunches farthest away from the landings to more than 90 passes for those next to the landings (Figure 5A). Based on the 51.2-km skid-trail network, the resulting soil recovery cost for scenario I was \$25,591, increasing the combined cost to almost \$89,500 (\$12.4 m^{-3}).

In scenario V, which considered both skidding and soil recovery costs, individual tree bunch/landing skid-trails were combined into fewer skid-trails with higher traffic levels to reduce total network length and thus soil recovery costs. Traffic levels in terms of machine passes also increased with proximity to log-landings, resulting in about 10 major skid-trails with more than 100 machine passes, which were further combined near landings (Figure 5B). Compared with scenario I, the total skid-trail network length was reduced by more than 60%, from 51.2 to 20 km (Table 2), causing a similar reduction in soil recovery cost. Skidding costs increased more than 17% compared with those of scenario I because as individual skid-trails combined, they deviated from the shortest path of scenario I, thereby increasing the skidding distance. The average and maximum skidding distances increased by 45 and 85 m, respectively (Table 2). The reduction in soil recovery cost (\$15,578) was larger than the increase in skidding cost (\$11,023); thus, the optimal skid-trail network for scenario V resulted in a lower combined cost than that for scenario I (Table 2).

Last, for scenario VI that only considered soil recovery costs, all skid-trails connecting each tree bunch to the log-landings were dependent and combined into only a few high-traffic skid-trails to minimize the total length of the network. There were only three major skid-trails with more than 400 machine passes that connected 90% of tree-bunches to only two log-landings, and skid-trail segments next to these two landings have more than 800 machine passes (Figure 5C). The total skid-trail network length decreased an additional 165 m from that for scenario V to 19.8 km, resulting in a marginal reduction in soil recovery cost (Table 2). However, average and maximum skidding distance more than doubled compared with that for scenario I and increased about 74 and 80% from those for scenario V, respectively. Consequently, skidding cost increased by almost \$120,000 (an 88% increase from scenario I and 60% increase from scenario V).

Actual Harvest Unit

The model also successfully identified tree-bunch locations and found the optimal skid-trail network for the actual harvest unit. Based on the total harvestable volume of 11,931 m^3, the model identified 2,430 tree bunches, the spatial distribution of which closely resembled the harvestable volume within each stand (Figure 6A). Considering skidding and soil recovery costs equally ($w = 0.5$), the skid-trail network pattern also corresponded to harvestable volumes by stand, where skid-trails were more dense on stands with high harvestable volume and vice versa (Figure 6B). The total length of the optimal skid-trail network was about 56.5 km with an associated soil recovery cost of almost \$28,300 (Table 3). The average and maximum skidding distances were approximately 295 and 760 m, respectively, resulting in an average skidding cost per bunch of almost \$30 (\$6 m^{-3}). Total skidding cost for the harvest unit was almost \$73,000, and the total combined cost was about \$101,000 (\$8.5 m^{-3}).

The branching pattern and the major skid-trails in the optimal skid-trail network became more evident when traffic levels for each skid-trail segment were displayed in terms of machine passes (Figure 7). The extent of the skid-trails also displayed the area skidded to each landing. The number of machine passes for skid-trails connected to landings and thus the number of tree bunches skidded to these landings ranged from about 70 for landing 8 to more than 500 for landing 10 (Table 4). About 57% of the total volume across the

Table 3. Skid-trail model results for the actual harvest unit.

Parameter	Value
Harvest unit information	
Combined cost ($)	101,040
Skidding cost ($)	72,768
Soil recovery cost ($)	28,272
Combined cost ($ m^{-3})	8.47
Number of tree bunches	2,430
Volume (m^3)	11,931
Skid-trail network length (m)	56,543
Per tree-bunch information	
Minimum volume (m^3)	0.01
Average volume (m^3)	4.91
Maximum volume (m^3)	4.99
Minimum skidding cost ($)	5.6
Average skidding cost ($)	29.9
Maximum skidding cost ($)	67.7
Minimum skidding distance (m)	9.5
Average skidding distance (m)	295.4
Maximum skidding distance (m)	758.7

harvest unit was skidded to only three landings (1, 6, and 10). These results also indicate the applicability of the model to evaluate the potential log-landing locations in terms of the volume skidded to each log-landing. When combined with log-landing and access road construction costs, these results can be used to identify log-landings with procurement volumes not sufficient to cover fixed landing construction costs. Then, the model could be used to evaluate the economic benefit of eliminating and/or combining nearby low-volume landings. For example, field managers could use the model to evaluate whether combining landings two and three into a single landing (Figure 7), as well as landings seven and eight, is desirable.

Optimized skid-trail networks are dependent on the location of tree bunches. Thus, we ran the model 10 times with slightly different tree-bunch locations to examine their effect on the optimal skid-trail design. For each run, tree-bunch locations were moved randomly within a maximum distance of 15 m in one of the eight ordinal directions. Results from these 10 runs were very similar with combined costs ranging from \$8.21 to \$8.72 m^{-3} and a coefficient of variation (CV) of 1.7%. Skidding costs were even more similar with a CV of 0.7%, and soil recovery costs and skid-trail length presented the largest variation (CV of 5.1%). As expected, optimized skid-trail networks among the 10 runs changed because individual tree bunches were different. However, about 92% of major skid-trails with more than 20 machine passes were located within a 10-m buffer (twice the node spacing in the feasible skid-trail network). Although low-traffic skid-trails near tree bunches are different, high-traffic skid-trails are located on the same general paths. This is particularly important because it is difficult to simulate the exact tree-bunch locations before harvesting. In addition, most potential economic savings of optimized skid-trail designs are proportional to the number of passes. Thus, it is more critical to correctly locate high-traffic skid trails than those connecting to individual tree bunches.

Discussion

When results from scenarios I, V, and IV of the hypothetical harvest unit are compared, the lowest combined total cost was obtained in scenario V when both skidding and soil recovery costs were considered to find the optimal skid-trail network. This was mainly because of the significant reduction in total skid-trail network length in scenario V compared with that for scenario I and the significant increase in skidding cost compared with that for Scenario VI. The purpose of applying our model to these six different scenarios was not to compare the resulting combined costs (skidding and soil recovery) per se but to illustrate the ability of the model to develop optimal skid-trail networks under different harvest unit conditions commonly found in harvesting practices. However, when all cost components (skidding, log-landing construction, and access road construction) are considered, this model could serve as a tool to evaluate alternative harvest unit layouts, e.g., skidding to landings located along the roadside versus skidding to centralized landings.

Although the model can automatically generate optimized skid-trail networks that simultaneously minimize soil recovery and skidding

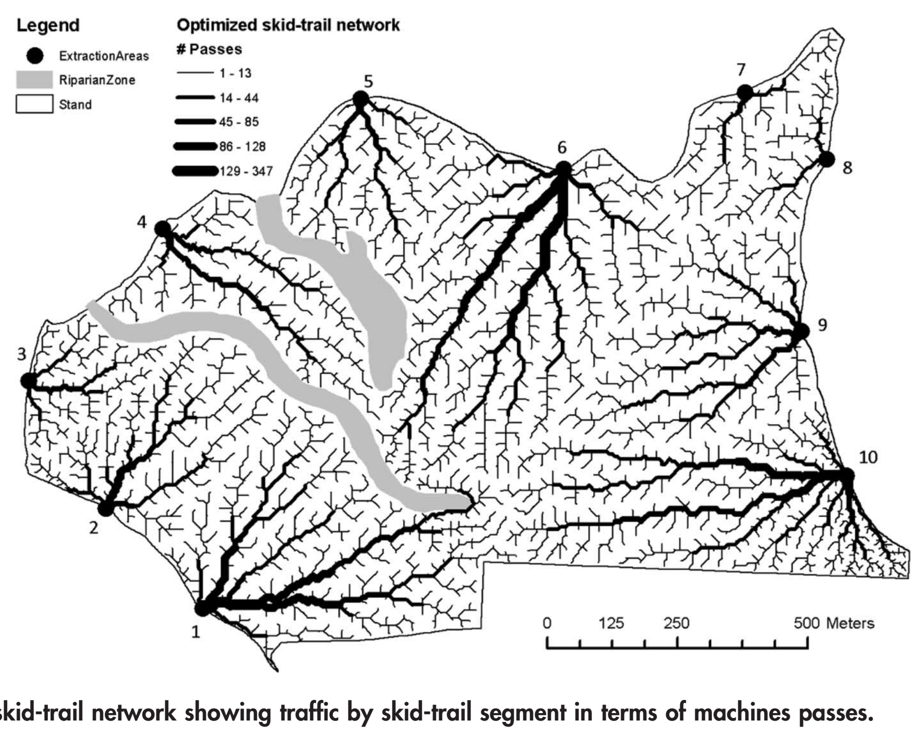

Figure 7. Optimized skid-trail network showing traffic by skid-trail segment in terms of machines passes.

Table 4. Volume and number of tree bunches skidded to each log-landing along the optimized ski-trail network generated by the model for the actual harvest unit.

Landing	Volume	Tree bunches	% of total
1	2,002	415	17
2	1,101	227	9
3	644	129	5
4	785	161	7
5	717	148	6
6	2,273	458	19
7	396	79	3
8	346	71	3
9	1,154	233	10
10	2,513	509	21
Total	11,931	2,430	

costs, field test validation should be conducted to ensure that these optimal networks can be implemented on the ground. In the case of mechanized harvesting equipment with on-board computers, networks can be loaded as GIS layers to help operators travel along the major skid-trails. In the case of less modern harvesting equipment, networks can be flagged on the ground manually before harvesting to help cutters with directional felling and/or feller-bunchers with bunch placement. Additional GIS layers including digital elevation maps, harvest unit boundaries, access roads, log-landing locations, and streams can be used to help identify and flag major skid-trails on the ground. In any case, quantifying costs associated with implementing networks is required to evaluate the real economic benefit of implementing these computer-generated skid-trail networks.

Currently, the model uses two simple regression models for uphill and downhill skidding cycle time, respectively, without directly accounting for ground slopes along skid-trails, number of logs, tree-bunch volume, or the wide range of skidding distance. Although alternative cycle time equations can be implemented easily into the model, there is a need to develop cycle time regression models that can more appropriately capture the interactions among skidding equipment, turn size, and terrain conditions. The simple skid-trail network design (second-order neighborhood pattern considering only the eight adjacent grid cells) might result in skid-trail networks with several sharp turns. Further analysis considering different node spacing and higher order network designs as well as other factors such as the skidder's minimum turn radius, as conducted with forest roads (Epstein et al. 2001), are required to ensure the design of realistic skid-trail networks that can be implemented on the ground.

As mentioned above, the tree-bunching routine used in this study assumed a whole-tree harvesting method where skidding is done by skidders, which gather nearby trees until completing a full load, and the center of the area containing the full load volume is assigned as the tree-bunch location. Alternative routines could also be implemented into the model to consider other harvesting systems such as cut-to-length. For example, log-pile locations can be evenly distributed based on maximum machine reach (either harvesters or feller-bunchers with a boom), and the number of turns can be determined based on volume to better represent operations with more mechanized systems. Alternatively, feller-bunchers with on-board computer and GPS systems can be used to mark the location of individual log-piles when formed. Although using alternative routines will probably result in different spatial distribution of tree-bunches (or log-piles), results showed that high-traffic skid-trails (i.e., with $>$20 machine passes) are located on the same general area. This provides a reasonable level of confidence about solution quality and the approximate location of the optimized skid-trail network

Last, the degree of soil disturbance depends largely on soil physical properties, weather season, machine characteristics, and load size. Several studies have examined the relationship between soil disturbance and machine passes, and, in general, disturbances such as compaction and porosity are mostly altered during the first passes, but other disturbances such as bulk density and soil recovery increase nonlinearly with traffic (Gayoso and Iroumé 1991, Zenner et al. 2007). Although we assumed soil recovery costs will be incurred independent of traffic level, the model could be modified to include different soil recovery costs for increasing levels of machine traffic. The fixed component of the objective function (Equation 4) can be extended to include multiple binary variables to activate the *SRC* corresponding to different traffic levels. For example, $(w - 1)[(SRC_{i,1} \times B_{i,1}) + (SRC_{i,2} \times B_{i,2}) + (SRC_{i,3} \times B_{i,3}) + (SRC_{i,4} \times B_{i,4})]$ considers four binary variables that activate the appropriate *SRC* for skid-trail segments with $NT_i \leq 5$, $5 < NT_i \leq 20$, $20 < NT_i \leq 50$, and $NT_i > 50$, respectively.

Conclusions

The design of skid-trail networks has a direct impact on skidding costs and the amount of area affected by the ground-based harvesting equipment. In this study, we developed a novel model that can automatically design optimized skid-trail networks to simultaneously minimize skidding and soil recovery costs, used as an economic proxy for total affected area. To our knowledge, no prior studies have developed automated approaches to design optimized skid-trail networks applicable to operations considering multiple design factors commonly found in timber harvesting practices. Our model is able to consider irregularly shaped harvest units, uneven volume distribution, nonuniform terrain conditions, skidding obstacles presented by sensitive areas such as riparian zones, and multiple landings. Based on management objectives and environmental considerations, the model can design skid-trail networks that minimize skidding cost only by selecting skid-trails that reduce skidding cycle time from individual tree bunches to the landings, minimize soil recovery cost only by reducing the total length of skid-trails, or minimize both skidding and soil recovery costs simultaneously. This model provides a tool to help forest engineers and field managers design economically efficient and environmentally sound ground-based timber harvesting operations.

The model can be applied to harvesting operations in which skidding is done either to roadside or centralized log-landings. Results from application of the model to the six scenarios in the hypothetical harvest unit and from the actual harvest unit indicate that, when all cost components are considered (skidding, log-landing construction, and access road construction), the model can serve as a tool to evaluate alternative harvest unit layouts. Model results can provide a quantitative approach to determine whether skidding to roadside or to centralized log-landings is preferred or to evaluate and select among alternative potential landing locations. Although the model developed in this study offers a great potential to assist in forest operations planning, model validation involving field comparisons between operator-generated and computer-generated skid-trail networks should be conducted to appropriately evaluate the potential application and benefits.

Literature Cited

ADLAKHA, V.K., AND K. KOWALSKI. 2003. A simple heuristic for solving small fixed-charged transportation problems. *OMEGA Int. J. Manage. Sci.* 31:205–211.

AMPOORTER, E., R. GORIS, W.M. CORNELIS, AND K. VERHEYEN. 2007. Impact of mechanized logging on compaction status of sandy forest soils. *For. Ecol. Manage.* 241:162–174.

ANDERSON, A.E., AND J.D. NELSON. 2004. Projecting vector based road networks with a shortest path algorithm. *Can. J. For. Res.* 35:1378–1388.

ANDRUS, W.C., AND H.A. FROEHLICH. 1983. *An evaluation of four implements used to till compacted forest soils in the Pacific Northwest*. Res. Bull. 45, Oregon State Univ., Corvallis, OR. 12 p.

CHUNG, W., AND J. SESSIONS. 2003. NETWORK 2000: A program for optimizing large fixed and variable cost transportation problems. P. 109–120 in *Proc. of the 8th symposium on systems analysis in forest resources, 2000 September 27–30, Snowmass Village, CO*, Arthaud, G.J., and T.M. Barrett (eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands.

CHUNG, W., J. STÜCKELBERGER, K. ARUGA, AND T.W. CUNDY. 2008. Forest road network design using a trade-off analysis between skidding and road construction costs. *Can. J. For. Res.* 38(3):439–448.

CONRAD, J.L., W.S. FORD, M.C. GROOVER, M.C. BOLDING, AND W.M. AUST. 2012. Virginia Tech forest road and bladed skid trail cost estimation method. *South. J. Appl. For.* 36(1):26–32.

CONTRERAS, M., AND W. CHUNG. 2007. A computer approach to finding an optimal log landing location and analyzing influencing factors for ground-based timber harvesting. *Can. J. For. Res.* 37(2):276–292.

CONTRERAS, M.A., AND W. CHUNG. 2011. A modeling approach to estimating skidding costs of individual trees for thinning operations. *West. J. Appl. For.* 26(3):133–146.

EPSTEIN, R., A. WEINTRAUB, J. SESSIONS, B. SESSIONS, P. SAPUNAR, E. NIETO, F. BUSTAMANTE, AND H. MUSANTE. 2001. PLANEX: A system to identify landing locations and access. P. 190–193 in *Proc. of the International mountain logging and 11th Pacific Northwest skyline symposium, 2001 December 10–12, Seattle, Washington.* Univ. of Washington, College of Forestry, Seattle, WA.

DIJKSTRA, E.W. 1959. A note on two problems in connexion with graphs. *Numer. Math.* 1:269–271.

FROEHLICH, H.A., D.E. AULERICH, AND R. CURTIS. 1981. *Designing skid trail systems to reduce soil impacts from tractive logging machines*. Res. Pap. 44, Oregon State Univ., Corvallis, OR. Available online at ir.library.oregonstate.edu/xmlui/handle/1957/8240; last accessed Mar. 12, 2014.

HAN, H.-S., AND C. RENZIE. 2005. Productivity and cost of partial harvesting method to control mountain pine beetle infestation in British Columbia. *West. J. Appl. For.* 20(2):128–133.

HAN, H.-S. 2007. Economics of soil disturbance. P. 165–177 in *Volcanic ash-derived forest soils of the inland Northwest: Properties and implications for management and restoration, November 9–10, 2005, Coeur d'Alene*, Page-Dumroese, D., R. Miller, J. Mital, P. McDaniel, and D. Miller (tech. eds.). USDA For. Serv., Rocky Mountain Research Station, Fort Collins, CO.

HAN, H.-S., D. PAGE-DUMROESE, S.-K. HAN, AND J. TIROCKE. 2006. Effects of slash, machine passes, and soil moisture on penetration resistance in a cut-to-length harvesting. *Int. J. For. Eng.* 17(2):11–24.

JOURGHOLAMI, M., E. ADBI, AND W. CHUNG. 2013. Decision making in forest road planning considering both skidding and road costs: A case study in the Hyrcanian Forest in Iran. *iForr. Biogeosci. For*. 6:59–64.

GARLAND, J.J. 1997. Designated skid trails minimize soil compaction. In *The woodland book*. EC1110, Oregon State Univ., Extension Service, Corvallis, OR. 7 p.

GAYOSO, J., AND A. IROUMÉ. 1991. Compaction and soil disturbances from logging in Southern Chile. *Ann. For. Sci.* 48(1):63–71.

GREULICH, F.E. 2003. Transportation networks in forest harvesting: Early development of the theory. P. 57–65 in *Proc. of S3.04/3.06/3.07: IUFRO international seminar on new roles of plantation forestry requiring appropriate tending and harvesting operations, 2002 October 2–5, Tokyo, Japan*. International Union of Forest Research Organizations, Vienna, Austria.

GREULICH, F.E., D.P. HANLEY, J.F. MCNEEL, AND D. BAUMGARTNER. 1999. *A primer for timber harvesting*. EB 1316, Washington State Univ., Cooperative Extension, Pullman, WA. 40 p. Available online at faculty.washington.edu/greulich/Documents/eb1316.pdf; last accessed Mar. 12, 2014.

HALLEUX, O.R.M., AND W.D. GREENE. 2003. Setting analyst: An operational harvest planning tool. *Int. J. For Engr.* 14(1):89–101.

HAYATI, E., B. MAJNOUNIAN, E. ABDI, J. SESSIONS, AND M. MAKHDOUM. 2013. An expert-based approach to forest road network planning by combining Delphi and spatial multi-criteria evaluation. *Environ. Monit. Assess.* 185(2):1767–1776.

KELLOGG, L., P. BETTINGER, S. ROBE, AND A. STEFFERT. 1992. *Mechanized harvesting: A compendium of research*. USDA For. Serv., Oregon State Univ. Research Laboratory, Corvallis, OR. 401 p. Available online at scholarsarchive.library.oregonstate.edu/xmlui/handle/1957/32018; last accessed Mar. 12, 2014.

KOLKA, R.K., AND M.F. SMIDT. 2004. Effects of forest road amelioration techniques on soil bulk density, surface runoff, sediment transport, soil moisture and seedling growth. *For. Ecol. Manage.* 202:313–323.

KRUEGER, W. 2004. Effects of future crop tree flagging and skid trail planning on conventional diameter-limit logging in a Bolivian tropical forest. *For. Ecol. Manage.* 188:381–393.

LLOYD, R.A., K.A. LOHSE, AND T.P.A. FERRÉ. 2013. Influence of road reclamation techniques on forest ecosystem recovery. *Front. Ecol Environ.* 11(2):75–81.

RAB, M.A. 1996. Soil physical and hydrological properties following logging and slash burning in the *Eucalyptus regnuns* forest of southeastern Australia. *For. Ecol. Manage.* 84:159–175.

REISINGER, T.W., G.L. SIMMONS, AND P.E. POPE. 1988. The impact of timber harvesting on soil properties and seedling growth in the south. *South. J. Appl. For.* 12(1):58–67.

SAWYERS, B.C., M.C. BOLDING, W.M. AUST, AND W.A. LAKEL. 2012. Effectiveness and implementation costs of overland skid trail closure techniques in the Virginia Piedmont. *J. Soil Water Conserv.* 67(4):300–310.

SMIDT, M.F., AND R.K. KOLKA. 2001. Alternative skid trail retirement options for steep terrain logging. In *Proc. of the 24th annual meeting of Council on Forest Engineering, 2001 July 15–18, Showshoe, WV*, Wang, J., M. Wolford, and J. McNeel (eds.). USDA For. Serv., Northern Research Station, Newtown Square, PA. 6 p.

STEINBERG, D.I. 1970. The fixed charge problem. *Naval Res. Logist. Q.* 17:217–235.

STÜCKELBERGER, J., H.R. HEINIMANN, AND W. CHUNG. 2007. Improved road network design models with the consideration of various link patterns and road design elements. *Can. J. For. Res.* 37(11):2281–2298.

WANG, J., C.B. LEDOUX, P. EDWARDS, AND M. JONES. 2005. Soil bulk density changes caused by mechanized harvesting: A case study in central Appalachia. *For. Prod. J.* 55(11):37–40.

WRONSKI, E.B. 1984. Impacts of tractor thinning operations on soils and tree roots in a Karri forest, Western Australia. *Aust. For. Res.* 14:319–332.

ZENNER, E.K., AND A.L. BERGER. 2008. Influence of skidder traffic and canopy removal intensity on ground flora in a clearcut-with-reserves northern hardwood stand in Minnesota, USA. *For. Ecol. Manage.* 256:1785–1794.

ZENNER, E.K., J.T. FAUSKEE, A.L. BERGER, AND K.J. PUETTMANN. 2007. Impacts of skidding traffic intensity on soil disturbance, soil recovery, and aspen regeneration in North Central Minnesota. *North. J. Appl. For.* 24(3):177–183.