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SHORT COMMUNICATION

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Retroactive comparison of operator-designed and computer-generated skid-trail networks on steep terrain

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Abstract

Aim of the study: Quantify potential economic benefits of implementing computer-generated skid-trail networks over the traditional operator-designed skid-trail networks on steep terrain ground-based forest operations.

Area of study: A 132-ha harvest operation conducted at the University of Kentucky's Robinson Forest in eastern Kentucky, USA.

Materials and methods: We compared computer-generated skid-trail network with an operator-designed network for a 132-ha harvest. Using equipment mounted GPS data and a digital elevation model (DEM), we identified the original operator-designed skid-trail network. Pre-harvest conditions were replicated by re-contouring terrain slopes over skid-trails to simulate the natural topography and by spatially distributing the harvestable volume based on pre-harvest inventories and timber harvest records. An optimized skid-trail network was designed using these pre-harvest conditions and compared to the original, operator-designed network.

Main results: The computer-generated network length was slightly longer than the operator-designed network (53.7 km vs. 51.7 km). This also resulted in a slightly longer average skidding distance (0.71 km vs. 0.66 km) and higher total harvesting costs (5.1 \$ ton^{-1} vs. 4.8 \$ ton^{-1}). However, skidding costs of the computer-generated network were slightly lower (4.2 \$ ton^{-1} vs. 4.3 \$ ton^{-1}). When comparing only major skid-trails, those with ≥ 20 machine passes, the computer-generated skid-trail network was 28% shorter than the operator network (9.4 km vs. 13.1 km).

Research highlights: This assessment offers evidence that computer-generated networks could be used to generate efficient skid-trails, help determine skidding costs, and assess further potential economic and environmental benefits.

Key words: timber harvesting; forest operations; network optimization; soil disturbances; cost minimization.

Authors' contributions: MC designed the study, prepared final manuscript and revisions; DP performed data collection, preliminary analysis and draft preparation; JS facilitated input data and helped with manuscript preparation.

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Introduction

Timber harvesting operations on gentle terrain are performed with ground-based systems using skidders or forwarders, while cable systems are recommended on steeper terrain (Kellogg *et al*., 1992). However, in many parts of the eastern US such as the Cumberland Plateau region of Kentucky typified by relatively steep, highly dissected terrain with short distances, the effective use of cable systems has been difficult to establish, and ground-based operations are common. As opposed to gentle terrain areas where skidders can travel relatively unrestricted, steeper areas require constructed skid-trails to facilitate cost-effective and safe operations. Consequently, efficiently locating skid-trails becomes crucial as they directly impact skidding and skid-trail construction costs. Typically, skid-trail networks are designed manually by managers using vegetation and terrain characteristics but more often are constructed on-the-fly by a bulldozer operator without careful planning. Typically, bulldozer operators start building skid-trails either along ridge lines or near stream corridors and subsequently along contour lines. This results in relatively parallel skid-trials, spaced between 45 m and 75 m depending on harvest machinery and crew resources to facilitate reaching all harvestable volume between skid trails.

The heavy traffic of harvesting equipment along skid-trails has also been reported to cause significant soil disturbances that can lead to erosion and compaction (Croke *et al.,* 2001; Williamson & Neilsen, 2000), a shift in vegetation composition (Avon *et al.,* 2013; Buckley *et al.,* 2003), and loss of vegetation productivity (Lockaby & Vidrine, 1984). Best management practices including disking and seeding, subsoiling, re-contouring, and installing water bars are often recommended to ameliorate soil disturbances (Conrad *et al.,* 2012). However, these practices carry additional costs ranging from 500 $ to 8,000 $ ha^{-1} that might cause significant economic impacts on timber harvesting operations (Soman *et al.,* 2019; Sawyer *et al.,* 2012). The effort and costs used to ameliorate soil disturbance is partially governed by, and positively related to the traffic-level. Reducing the length of high-traffic skid-trails can help alleviate administrative costs and thus designated skid-trails is typically recommended to also reduce these soil disturbance (Garland, 1983; Han *et al.,* 2006).

There are only a few models to automate the design of optimized skid-trail networks. Halleux and Greene (2003) developed an automated approach to evaluate alternative networks but assumes flat terrain and evenly distributed volume. Gumus & Turk (2016) developed an approach to optimize the design but is also applicable only for flat terrain. Contreras *et al.* (2016) developed a computerized model to generate an optimized skid-trail network that minimizes skidding and skid-trail construction costs based on terrain, volume distribution, and extraction locations. Despite these developed models, there has been no formal comparison between field implementation of computer-generated and operator-designed skid-trail networks to quantify potential economic benefits. One of the main reasons for the lack of these studies is the required coordination and collaboration with forest companies and logging contractors. Other reasons are the logging contractors' unwillingness to change tradition, perceived costs associated with tasks such as flagging skid-trails before construction, and an inherit distrust and misunderstanding of computer-generated resources.

In this study, we retroactively compared an operator-designed skid-trail network for a harvest operation conducted in eastern KY, USA in 2008 with the optimized computer-generated skid-trail network using the Contreras *et al.* (2016) model. This work presents a novel attempt to quantify potential economic benefits of computer-generated skid-trail networks, which can facilitate future more comprehensive ground comparisons and evaluation of model applicability.

Methodology

Study Area

The study site was in the University of Kentucky's Robinson Forest (lat. 37.47° N, long. -84.24° W), located within the Northern Cumberland Plateau region in eastern Kentucky. The landscape is deeply dissected with steep slopes, and the forest overstory is primarily composed of oak (*Quercus* spp.), yellow-poplar (*Liriodendron tulipifera* L.), and hickory (*Carya* spp.). For the study, we focused on three watersheds, totaling 132 ha, harvested in May 2008 to August 2009. A deferment harvest with a target residual basal area of 3.4 m^2 ha^{-1} was performed resulting in the removal of 16,164 tons of merchantable products. Full-benched skid-trails were constructed mostly along contours by the operators of three bulldozers: John Deere 650, John Deere 700, and John Deere 850. On accessible slopes below 30%, a Timbco 445 EXL feller-buncher was used to fell, top, and delimb trees. On steeper slopes the feller-buncher was restricted to the skid-trail and operated within reach of the boom. Trees beyond the reach of the boom were manually processed and merchantable length stems were winched to skid-trails by a bulldozer. Log-piles created by the feller-buncher and the bulldozer were skidded to three landings by Caterpillar 545 grapple skidders. Landings were located on ridgetops resulting in uphill skidding throughout much of the harvested area.

Simulating pre-harvest conditions

A high-density (~25 pt m^{-2}) LiDAR dataset acquired in the summer of 2013 was used to create a high-resolution digital elevation model (DEM) of the study area. While the DEM was created from data collected 5 years after the harvest, the remnant skid-trail network was clearly visible. To ensure a fair comparison with the computerized skid-trail model, we removed these terrain disturbances and created a DEM that mimicked the terrain prior to the harvest for input into the computerized skid-trail model program. Using the high-resolution DEM, aerial photos, and GPS data collected from units mounted on the harvesting equipment, the operator-designed skid-trail network was identified, and each skid-trail segment was digitized as a line through the center of each skid-trail (Fig. 1a). A 6-m buffer centered on the digitized skid-trail network was applied to encompass the entire area disturbed by skid-trail construction. Elevation data from the DEM cells within the buffer were removed and a routine was developed to fill the vacant elevation data. The elevation of a given DEM cell within the buffer was calculated as the inverse distance weighted average of the elevation of the closest DEM cell along eight transects starting from north and generated every 45 degrees.

Harvested volume was spatially distributed across the study area using pre-harvest inventory data consisting of a systematic grid of 186 points. The inventory used a nested variable point sampling for trees with diameter at breast height larger than 33 cm, and the variable point sampling with diameter obviation method described in Beers (1964) for smaller trees. The inventory only recorded trees that were marked for harvest. It was assumed that harvested volume estimates per sample point were representative of the volume distribution across the study area. Then, harvested volume per ha across the watersheds was estimated by interpolating the volume estimates from the sample points. The interpolation procedure used the inverse distance weighted method to create a 1-m distribution raster with the percentage of the total extrapolated volume for each cell covering study area. To ensure that the recreated pre-harvest volume was equivalent to the actual harvested volume, sale tickets from the harvest were used to calculate the exact volume extracted from each watershed. This total volume was then distributed according to the distribution raster.

Computerized skid-trail network model

The model presented in Contreras *et al.* (2016) was used to develop the computer-generated skid-trail network. The model creates an optimized skid-trail network based on a DEM, volume distribution, skidder maximum loading capacity (MLC), obstacles within the harvesting area, and costs of skid-trail construction and skidding. Based on the volume distribution by cell and the skidder's MLC, the model uses a log-bunching routine to identify the location of log-piles. In the volume raster, the routine identifies the first accessible cell with volume and adds the volume to the first log-pile. If the volume is less than the MLC, the routine searches the neighboring cells for additional volume. If present, the volume is added, and the cell is assigned to the log-pile. The search window continues to expand to add additional volume and assign the associated cells to the log-pile until the pile volume equals the MLC. Once this target volume is achieved, the log-pile location is established in the center of the search window area. The model then identifies the next unassigned cell with available volume, adds additional volume from an expanding search window, assigns the cells to the next log-piles, and when the volume meets the target MLC the center of the search window area is assigned as the location of this next-log pile. The process continues until all cells with volume are assigned to a log-pile.

The model creates a network of feasible skid-trail segments formed by a set of vertices regularly spaced throughout the study area and links connecting adjacent vertices. Vertices represent the center of DEM cells, log-pile locations, and landing locations. Links represent skid-trail segments between adjacent vertices. In the model, each vertex was connected to eight adjacent vertices spaced every 6.4 m (20 ft) over trafficable areas with gradient and side slopes below user-defined limits for skidding. Skidding costs for skid-trail segments were calculated based on skidder rental rate and cycle time where the cycle time for uphill and downhill links were determined using the following equations from Contreras and Chung (2007):

$$CT_{ds} = 3.9537 + (0.0215 \times D) \quad [1]$$

$$CT_{us} = 3.9537 + (0.0258 \times D) \quad [2]$$

where CT_{ds} is the cycle time (min) for downhill skidding, CT_{us} the cycle time (min) for uphill skidding, and D the slope distance (m) along the network connecting a log-pile and the landing. Cycle time was used to calculate skidding cost as follows:

$$PSC_i = \left(\frac{CT_i}{60}\right) \times RR \quad [3]$$

where PSC_i is the skidding cost ($) for the i^{th} log-pile, CT_i round trip skidder cycle time (min) for the i^{th} log-pile, and RR the hourly rental rate for the skidder ($).

As model inputs, slope limitations for feasible skid-trail segments (links) were set to not surpass 45% gradient slope and 100% side slope. Skidder rental rate was set at 120 $ SMH^{-1} (US Forest Service, 2011) and MLC was set as 10 ton based on cycle volume observations for similar harvest operations near the study site (Bowker, 2013). To estimate skid-trail construction cost, the same rental rate associated with skidding was used, 120 $ hr^{-1} (US Forest Service, 2011). Construction time was obtained from the GPS positional data with timestamps mounted on the three bulldozers and collected during the original harvest (Bowker, 2013). Using construction time and average terrain side slope along each skid-trail section, we found a 30% decrease in construction time within each 10% increase in terrain slope. Applying this relationship to the average slope and average time of the original harvest, we estimated construction time for each skid-trail segment based on slope distance and terrain side slope. Streamside management zones in the original harvest were identified and considered inaccessible in the model (Fig. 1b). Lastly, NETWORK 2000 (Chung and Sessions, 2003) was used to find the optimal skid-trail network considering variable (skidding) and fixed (skid-trail construction) costs and connecting each log-pile to the three landings at minimum total costs.

Comparison of skid-trail networks

Although constructed skid-trails of the operator-designed network could be easily identified, the location of skid-trails that were not constructed and used to access and pick up individual log-piles were unknown. Thus, to be consistent with the computerized model inputs, the same log-pile locations generated by the log-bunching routine were assumed to represent the locations of the log-piles in the original harvest. These log-piles were then linked to the identified operator-designed skid-trails with Euclidean distance lines with no restrictions on terrain slope. The operator-designed skid-trails were divided into 3.05 m segments, for which skidding and construction costs were calculated following the same procedures as in the computerized model. Routes and skidding cycle times for each log-pile were determined assuming the shortest distance along the operator-designed skid-trail network to the nearest landing. Then, information per log-pile (i.e., skidding distance and costs) was determined, as was information for the entire study area (i.e., skidding cost, skid-trail construction cost, total harvesting cost and skid-trail length). These were calculated and compared with the information from the computer-generated skid-trail network.

The potential economic benefit of optimizing the location of skid-trails is proportional to traffic level. Thus, we compared the total length of both skid-trail network for segments with increasing levels of machine passes. Typically, in moderately steep areas such as our study area, skid-trails need to be constructed even across low-volume areas to be able to reach log-piles. Therefore, we also focused comparisons on major skid-trails.

Results and discussion

The total harvest volume represented by the volume distribution data in the harvest area (Fig. 1c) was 16,021 tons, from which the log-bunching routine identified 1,667 log-piles (Fig. 1d). The average log-pile volume was 9.6 ton, which was near the skidder maximum capacity set at 10 ton. The operator-designed network presented the typical parallel pattern with an average spacing of 56 m (Fig. 1a). Figure 2a shows the complete operator-designed skid-trail network after connecting all log-piles to the closest constructed skid-trails. The number of loaded machine passes ranged from one, for segments connecting log-piles to constructed skid-trails, to 550 for skid-trail segments approaching log-landings.

The computer model successfully generated an optimized skid-trail network (Fig. 2b) connecting all but six log-piles to the three log-landings. These six log-piles were in areas with terrain slope around 75%, which was above gradient allowed for feasible skid-trails. However, as done with the operator-designed skid-trail network, these log-piles were connected to the closest optimized skid-trails and their associated skidding costs were also calculated. The number of loaded machine passes ranged from one to 619 indicating that more traffic was concentrated along fewer skid-trails arriving at the landings. Total skidding cost for the computer-generated network was slightly lower than the operator-designed network ($67,563 vs $69,520, Table 1). The average skidding cost and average skidding distance per log-pile was also slightly lower for the computer-generated network. However, skid-trail construction cost for the computer-generated network was higher ($13,447 vs $8,178) than the operator-designed network. This was because numerous skid-trail segments were located across steeper terrain slope, which increased construction costs. On average in the operator-designed network, skid-trails with fewer than 20 loaded machine passes were placed on areas with terrain slopes of about 29% and skid-trails with more than 20 machines passes were located on areas with terrain slope of about 10%. On the other hand, same traffic level skid-trails, in the computer-generated network, were located on areas with terrain slopes of 43% and 19%. Thus, the resulting total harvesting cost for the operator-designed network was lower than the computer-generated network,

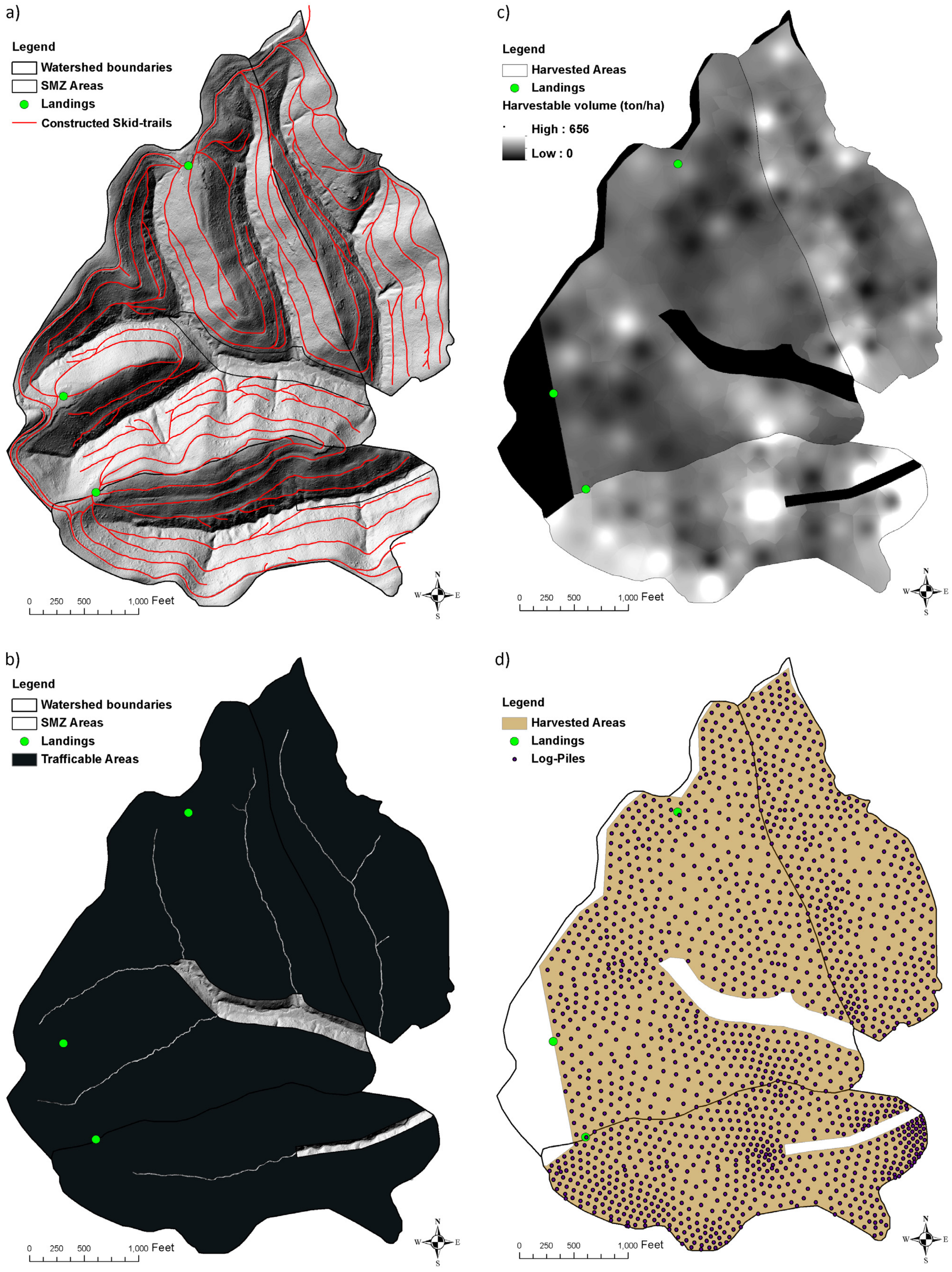

Figure 1. Study area showing the location of constructed skid-trails (a) areas with no traffic allowed on stream management zones and near existing intermittent streams (b) volume distribution derived from 186 pre-harvest inventory plots (c), and the resulted simulated location of 10-ton log-piles (d).

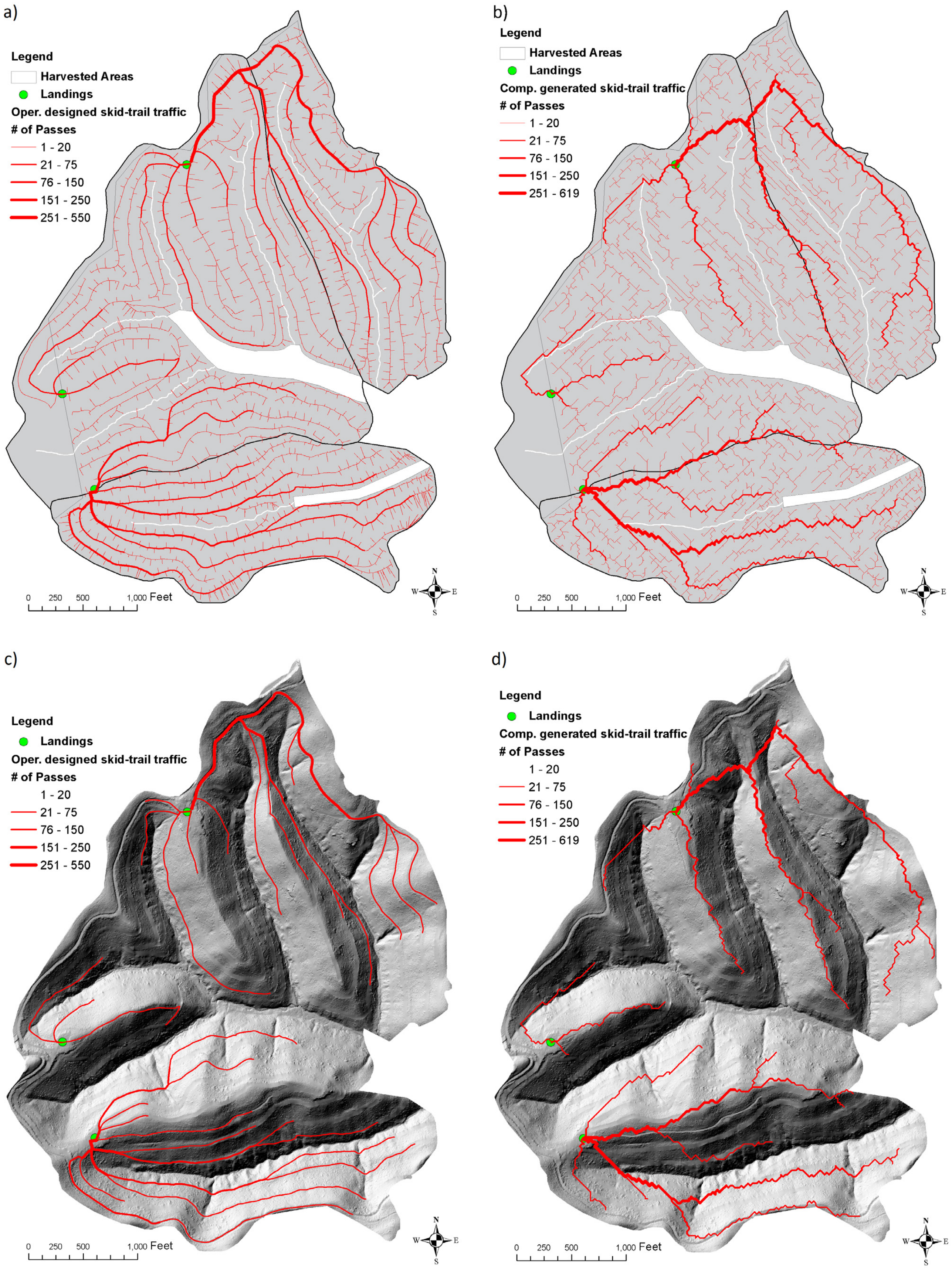

Figure 2. Operator-designed (a) and computer-generated (b) skid-trail networks showing traffic level in terms of loaded machine passes, and location of operator-designed (c) and computer-generated (d) major skid-trails defined as those with 20 or more loaded machine passes.

Table 1. Summary harvesting results from the operator-designed and the computer-generated skid-trail networks.

Summary information	Operator-designed	Computer-generated
Entire harvest unit		
Harvesting cost ($)	77,698	81,011
Skidding cost ($)	69,520	67,563
Skid-trail construction cost ($)	8,178	13,447
Skid-trail network length (km)	51.7	53.7
Per log-pile		
Minimum skidding cost ($)	8.6	8.2
Average skidding cost ($)	41.7	40.6
Maximum skidding cost ($)	92.6	94.9
Minimum skidding distance (m)	7.6	7.1
Average skidding distance (m)	664.8	703.8
Maximum skidding distance (m)	1,667.0	1,872.1

approximately $77,700 and $81,000 or 4.8 $ ton^{-1} and 5.1 $ ton^{-1}.

The total length of skid-trails in the computer-generated network was 53.7 km, which is 2.0 km higher than the length of the operator-designed network. This is likely because log-piles in the operator-designed network were connected directly to the constructed skid-trails without terrain slope constraints and feasible skid-trails in the computer-generated network were allowed only when gradient was below 45%. As most of the skidding costs will be accrued while travelling along the high-traffic skidding routes, the correct location of these paths is crucial because of their large impact on total costs. While the computer-generated results provide information for the entire skid-trail network, the ground implementation of correctly identifying skid-trails connecting individual log-pile locations would be relatively difficult. A more practical application of the computerized model can focus on high-traffic or major skid-trails, which can be flagged on the ground to guide operator before construction. In this context, when comparing the length of skid-trails with more than 20 loaded machine passes, the computer-generated skid-trail network was about 28% shorter (9.4 km vs 13.1 km). This indicates that the computer-generated network has a lower density of high-traffic skid-trails throughout the harvest unit concentrating skidding along fewer skid-trails. This becomes evident when comparing major skid-trails, those with more than 20 loaded machine passes (Fig.2c and 2d). For example, the operator-design network has several major skid-trails arriving at the southern and northern landing following a parallel pattern, while the computer-generated presents fewer major skid-trails following a branching pattern.

Several of these major skid-trails in the computer-generated network also follow ridge lines and branch downslope to follow routes along contour lines. The branching pattern of the major skid-trails and of the entire skid-trail network is typical of studies using a network approach to determine routes that minimize skidding and construction costs (Stückelberger, 2008; Ezzati *et al.*, 2015). The computerized model should also incorporate a two-dimensional smoothing routine to help ensure a path that a loaded skidder can efficiently navigate. This would also reduce skid-trail length, which would also reduce skidding and skid-trails construction cost.

Lastly, there was a dramatic difference in procurement area and volume received among log-landings. About 60% of the total volume was skidded to the northern log-landing, only 15% skidded to the middle log-landing, and the remaining 35% to the southern log-landing (Fig. 2b). The uneven volume distribution among log-landings and the relatively long average and maximum skidding distances (Table 1) suggest that overall skidding productivity and cost could have been improved by relocating both northern and middle log-landings farther north to reduce skidding distances.

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