Advantage

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Contents

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Loader-forwarding on sensitive soils in the boreal forest: a case study

Abstract

The Forest Engineering Research Institute of Canada (FERIC) monitored a summer roadside harvesting operation in a hardwood-dominated stand near Dawson Creek in northeastern British Columbia. This report presents the productivity and cost of the harvesting operation and describes the soil disturbance from skidding and loader-forwarding.

Keywords

Harvesting, Soil compaction, Skidding, Loader-forwarding, Productivity, Costs, British Columbia.

Introduction

In the spring and summer, high soil moisture may restrict logging on fine-textured forest soils in the boreal forest due to concerns about soil disturbance and the impact of skidding on site productivity. Skidders can cause soil compaction on sensitive sites if machine traffic is sufficiently concentrated (Henderson 2001). Compaction can lead to the loss of large macropores, resulting in soil gas environments that can limit root growth, reduce sucker initiation of aspen (*Populus*), and retard height growth (Greenway 1999). Site impacts caused by a loader-forwarder are expected to be less than those of a skidder, even with several machine passes (Douglas and Courtin 2001).

The challenge is to harvest economically on sensitive sites not only in the winter when harvesting would occur on frozen ground, but also in the summer by using a loader-forwarder. Logging year round or for an extended period of the year instead of mainly during the winter offers several advantages. It ensures a constant flow of fresher wood to mills, and allows smaller millyard inventories. A longer harvest season ensures the retention of experienced logging crews, and increases yearly machine utilization which results in lower costs.

Louisiana-Pacific Canada Ltd. in Dawson Creek, B.C. and FERIC initiated a study to assess the feasibility of using loader-forwarding to extend the summer harvesting season in areas with sensitive soils normally scheduled for winter harvesting with conventional equipment. The harvesting operations took place from September to October during a dry period. This report presents the productivities and costs of the harvesting phases, and the soil disturbance from loader-forwarding and skidding operations.

Objectives

The objectives of this study were to:

- Determine productivity and cost for the felling, loader-forwarding, skidding, and processing phases.
- Develop productivity and cost functions for the loader-forwarding and skidding phases.
- Determine the amount of soil disturbance caused by loader-forwarding and skidding and if it meets the requirements of the soil conservation guidelines of the

Forest Practices Code of British Columbia (BCMOF and BC Environment 2001).
- Identify operational factors affecting system performance and recommend improvements where appropriate.

Site characteristics

The study block, approximately 70 km south of Dawson Creek, was in the moist warm subzone (Peace variant) of the Boreal White and Black Spruce biogeoclimatic zone (BWBSmw). Table 1 summarizes the pre-harvest site and stand characteristics of the block. The company's silvicultural prescription described two Standards Units (SU)[1] within the block. Areas classified as SU-A had a high compaction hazard rating and were characterized by coarse textured soils, such as sandy loams, and a mesic soil moisture regime. SU-B areas had a very high compaction hazard rating with soils ranging from coarse-textured loamy sands to fine-textured silty clays, and a subhygric soil moisture regime. Because of the very high soil compaction hazard rating on portions of the

[1] An area of the prescription that will be managed through the uniform application of silvicultural system, stocking standards and soil conservation standards (BCMOF and BC Environment 1995).

Table 1. Pre-harvest site and stand characteristics

	Study block
Net area to be reforested (ha)	10.3 (SU-A&B)
Area harvested by loader-forwarder (ha)	4.0 (SU-B)
Maximum forwarding distance (m)	150
Elevation (m)	980–1000
Slope (%)	0–15
Soils	
Mineral soil texture	sandy loam,[a] loamy sand & silty clay[b]
Coarse fragment content	0–20%
Moisture regime	fresh–very moist[a] & moist-wet[b]
Compaction hazard	high[a] and very high[b]
Species composition	
Trembling aspen (%)	75
Balsam poplar (%)	20
Lodgepole pine (%)	5
Stand parameters	
Net merchantable volume (m^3/ha)	228
Stand density (no./ha)	589
Average volume (m^3/stem)	0.41
Average dbh (cm)	27.9
Average tree height (m)	23.1

[a] SU-A.
[b] SU-B.

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block, winter harvesting on frozen ground conditions or with a compressible snow-pack was originally prescribed for the study area. However, an amendment to the prescription was approved allowing harvesting under dry soil conditions using a loader-forwarder.

Harvesting system and equipment

The ground-based harvesting system included a Timberjack 618 feller-buncher, a Caterpillar 518 rubber-tired skidder equipped with 1.1-m-wide tires, a Caterpillar 325FB loader-forwarder with 70-cm-wide tracks, and a Hornet 825 processor on a Caterpillar RB322RL carrier. A Caterpillar EL200B loader was used for loading and a Caterpillar D6 crawler tractor was used for roadbuilding and piling woody debris from roadside processing.

The small 100-kW skidder equipped with wide tires was preferred by the contractor over a larger machine to reduce the impact on these high hazard soils. The loader-forwarder was a modified feller-buncher that was more expensive than a log loader, but also generally more robust. The machine was equipped with a modified grapple from a John Deere 740 skidder. To improve the wood handling capability of the grapple, the length of each tong was reduced by 40 cm (Figure 1). The maximum reach of the boom and grapple was 9 m. Ground clearance was 64 and 60 cm for the skidder and loader-forwarder, respectively.

Both the skidder and loader-forwarder were used for the primary transportation of wood to roadside. The loader-forwarder moved logs from areas with a very high hazard rating to less sensitive ground. From there the wood was skidded to roadside. Both machines sorted stems by species in the block.

The operator of the loader-forwarder was an experienced equipment operator but had no previous experience in loader-forwarding. As a result, he experimented with several operating methods:

- Modified serpentine pattern: the loader-forwarder travelled into the block, created a windrow of stems, and advanced these stems towards the roadside while moving back and forth parallel to the road.[2]
- Up and down pattern: the loader-forwarder moved to the back of the block and forwarded bunches of wood on either side of the machine while advancing in a straight line towards roadside.
- Staggered pattern: the loader-forwarder piled stems into bunches in a staggered pattern in the block, and forwarded them while advancing diagonally towards roadside.

Figure 1. Modified skidder grapple mounted on loader-forwarder.

At long distances the modified serpentine method was used primarily to forward wood to roadside, while the up and down method was used for short distances. Loader-forwarding occurred on level and adverse slopes.

Starting from the back of the block, clear-felling progressed parallel to the haul road with small clumps of 3–5 trees per hectare being retained throughout the block for structural diversity. Bunches were arranged with the butts aligned in the direction of skidding and loader-forwarding (i.e., towards the road). There was no difference in felling method between the areas where the skidder and loader-forwarder worked.

When primary transport of wood began and skidding distances were short, the loader-forwarder was used to deck bunches delivered to roadside by the skidder. Once skidding distance exceeded approximately 50 m, the

[2] For more information on this pattern, see Andersson and Young (1998).

loader-forwarder had to wait for wood from the skidder. The loader-forwarder was then moved onto the block to work on sensitive ground and the skidder delivered the remaining bunches to roadside, decking as necessary.

Study methods

FERIC observed the harvesting operations; collected shift-level data from the felling, skidding, loader-forwarding, and processing phases; and detail timed the skidding and loader-forwarding phases. Net harvested volumes were obtained from the monthly weigh-scale records provided by the company and average stem volumes were obtained from the company's cruise summaries. Productivities, machine availability, and machine utilization were determined for each phase.

The shift-level data were collected daily using Servis recorders installed on each machine by FERIC. For definitions of detailed-timing elements, see Appendix I. Productivities were calculated for each harvesting phase based on the net harvested volumes and total scheduled machine hours (SMH) for each phase.

Skidding and loader-forwarding cycles were detail timed at frequent intervals throughout the study period. Each skidding cycle was subdivided into five time elements: Travel Empty (including moving to the load and accumulating load; Travel Loaded; Deck (includes unloading and piling); and In-cycle Delays. Travel loaded distances and number of stems per cycle were also recorded for each cycle.

For the loader-forwarder, four time elements were identified: Swinging Loaded, Swing Empty, Move, and In-cycle Delays. Individual stems were tagged at progressively further distances from roadside, and both the time required to forward these stems and the number of swings to reach the roadside were recorded along with average number of stems per cycle.

Costs for the felling, skidding, loader-forwarding, and processing phases were calculated using FERIC's standard costing methods (Appendix II). Loader-forwarding and skidding productivities were generated using shift-level and detailed-timing summaries. Felling and processing productivities were derived from shift-level summaries. Loading cost estimates were obtained from Sambo (2002) using data from a similar harvesting system.

Following harvesting, a survey was conducted on a portion of the block to estimate the level of disturbance caused by skidding and loader-forwarding. A point survey transect method was utilized as described in the Forest Practices Code of British Columbia's Soil Conservation Surveys Guidebook (BCMOF and BC Environment 2001). Parallel transects were established within the survey area and excluded the decking area. Dispersed disturbance was assessed at a series of points located along the transect lines.

Results and discussion

Shift-level study

Shift-level summaries and productivities for all the equipment are shown in Table 2. The overall utilization of 88% was assumed for all equipment in the calculation of scheduled machine hours because the length of the study was too short to develop reliable figures for specific machines.

Feller-buncher and processor productivities were 78 m^3 and 62 m^3 per productive machine hour (PMH), respectively, which were similar to that reported in Andersson and Evans (1996) for comparable equipment and tree size. Skidder productivity of 46 m^3/PMH in this study was similar to that reported in Mitchell (1994), also for comparable equipment and tree size.

Loader-forwarder productivity was 25 m^3/PMH. This was similar to the productivity reported in Kosicki (2003), where a smaller 26 000-kg loader-forwarder handling conifer stems of comparable volume was estimated to produce 24 m^3/SMH over an average distance of 70 m. The operator in the Kosicki study had more

Table 2. Summary of shift-level timing on the feller-buncher, loader-forwarder, skidder, and processor

	Feller-buncher	Loader-forwarder	Skidder	Processor
Productive machine hours (PMH)	43.3	39.6	51.6	54.7
Non-mechanical delays (h)	3.3	2.3	2.0	1.6
Mechanical delays (h)	5.5	5.9	1.7	4.5
Scheduled machine hours (SMH)	52.1	47.8	55.3	60.9
Volume harvested (m^3)	3375	1001	2374	3375
Productivity				
m^3/PMH	77.9	25.3	46.0	61.7
m^3/SMH [a]	68.5	22.2	40.3	54.0
Production/8-h shift [a] (m^3)	548	178	322	432
Cost (\$/m^3)	2.40	7.14	2.73	2.61

[a] Because of the short duration of the study, utilization for all equipment was assumed to be the study average of 88%.

experience with loader-forwarding than the operator in this study.

The productivity of the loader-forwarder was approximately half that of the skidder's at 25 m^3/PMH versus 46 m^3/PMH, respectively. The lower productivity combined with a higher machine cost resulted in the overall cost of loader-forwarding being considerably higher than skidding at \$7.14/m^3 versus \$2.73/m^3, respectively. The unit costs of felling, skidding, and processing were similar.

Detailed-timing study

The results of the detailed-timing study for the loader-forwarder and skidder are presented in Table 3.

Loader-forwarding

The loader-forwarder was detail-timed for 16.9 hours. The distribution of the cycle time for the loader-forwarder is shown in Figure 2. The longest element was Swing Loaded at 51%. Without a heel the loader-forwarder had limited control in handling wood. Move was the second longest element at 24% of cycle time. In a study by Gillies (2001) of comparable machines, a greater proportion of time was spent on moving. However, this can probably be attributed to maneuvering around large boulders and operating on steeper slopes (average 30–35%) because the boulders caused track damage and increased the delay times for track repairs. Swing Loaded required proportionally less time in the Gillies study. Compared to flat terrain, the effects of gravity can be used to advantage when swinging logs down steep grades in mountainous terrain.

The loader-forwarder advanced the stems an average distance of 17 m per swing.[3] Grapple load size averaged 5 stems with a maximum of 13 stems (Table 3). Given that Swing Loaded accounted for 51% of cycle time, the goal should be to maximize grapple load size. Observations were that the operator appeared to maximize his grapple loads within the constraints of tree size and the reach and hydraulic capability of the boom and arm.

Skidding

Figure 3 presents the distribution of cycle time for the skidder. The majority of cycle time consisted of Travel Empty at 36% and Travel Loaded at 33%. Travel speed was usually higher for Travel Empty. However, because the operator often did not return empty using the most direct route, Travel

[3] The loader-forwarder occasionally moved ahead during Swing Loaded, which would explain the high average distance for advancing stems.

Table 3. Summary of detailed-timing on the loader-forwarder and skidder

	Loader-forwarder	Skidder
Observed time (PMH)	16.9	10.2
Total grapple swings[a] or cycles[b] (no.)	1 380	241
Stems (no.)	-	1149
Estimated volumes (m^3) [c]	397	465
Average grapple swing[a] or cycle[b] time (min)	0.73	2.54
Stems per grapple swing[a] or cycle[b] (no.)		
Minimum-maximum (average)	1–13 (5.0)	1–15 (4.8)
Average payload (m^3)	2.03	1.93
Loader-forwarding or skidding distance (m)		
Minimum–maximum (average)	20–250 (65)	10–235 (64)
Machine productivity		
Stems/PMH (no.)	58	113
Stems/SMH (no.) [d]	51	99
Volume/PMH (m^3/PMH)	23.5	46.0
Volume/SMH (m^3/SMH) [d]	20.7	40.5

[a] For loader-forwarder.
[b] For skidder.
[c] Using average volume (from stem volume, BCMOF cruise data) of 0.405 m^3/stem.
[d] Utilization for all equipment is assumed to be the shift-level study average of 88%.

Figure 2. Distribution of cycle time for the loader-forwarder.

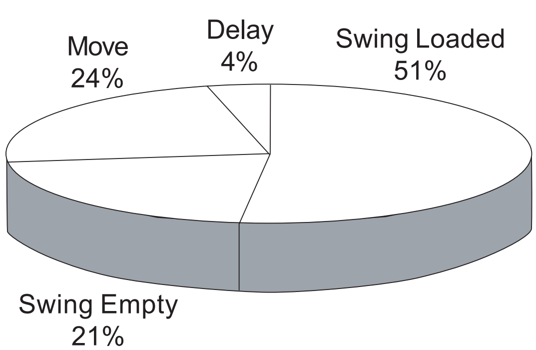
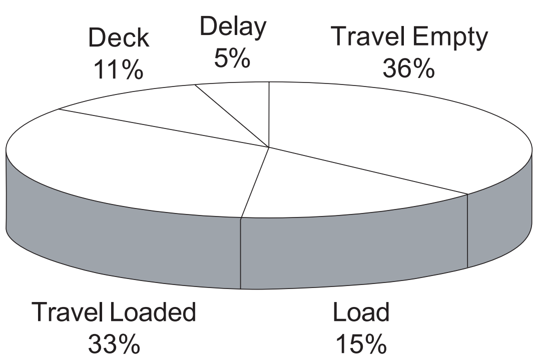


Figure 3. Distribution of cycle time for the skidder.



Empty time was higher overall than Travel Loaded. A full load consisted of one bunch and the grapple load size averaged 4.8 stems with a maximum of 15 stems.

Cycle time, productivity and cost of loader-forwarding and skidding

Multiple regression analyses were performed on the loader-forwarding and skidding cycles. Linear relationships were found between delay-free cycle time and distance for both machines (Equations 1a, 1b, and 4, Appendix III).

Figure 4 presents predicted delay-free cycle time for the loader-forwarder and grapple skidder as a function of distance. Distance had a strong impact on cycle time for both machines but particularly for the loader-forwarder. For a skidding distance of 100 m, for example, predicted cycle time was 3.02 min for the skidder and 5.70 min for the loader-forwarder, an increase of 89%.

The shift-level data and detailed-timing results were combined to estimate productivity during scheduled loader-forwarding and skidding time (Equations 2 and 5, Appendix III). These can be used to predict wood flow and to schedule processing and hauling activities on a shift-level basis. Figure 5 shows predicted loader-forwarding and skidding productivities as functions of distance. Increasing distance from 50 to 150 m results in a 53% decrease in loader-forwarding productivity and a 43% decrease in skidding productivity. At 50 m, the loader-forwarder would achieve 67% of the skidder's productivity. At 150 m, the loader-forwarder would achieve 53% of the skidder's productivity.

Unit loader-forwarding and skidding costs were calculated using Equations 3 and 6 in Appendix III. Figure 6 shows these costs as a function of loader-forwarding and skidding distance. Unit costs for loader-forwarding increase at a rate of $6.30/m³ per 100 m of extraction distance. For skidding, costs increase at a rate of $1.85/m³ per 100 m of skid distance. As distance increases, the unit cost of loader-forwarding increases at a faster rate than for skidding, a pattern that was also apparent in the study by Kosicki (2003).

Figure 4. Predicted skidder and loader-forwarder delay-free cycle times as a function of distance.

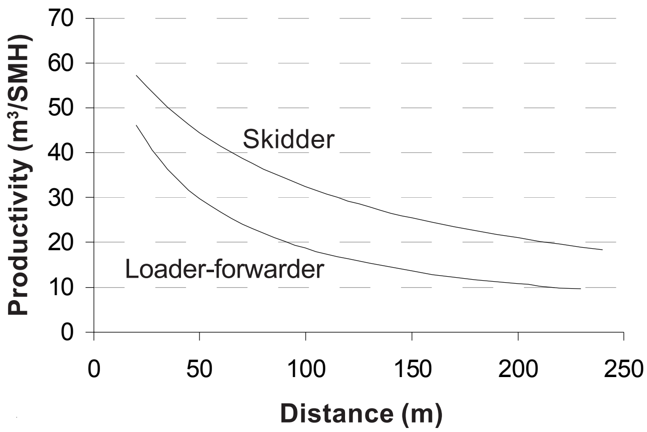


Figure 5. Predicted skidder and loader-forwarder productivities as a function of distance.

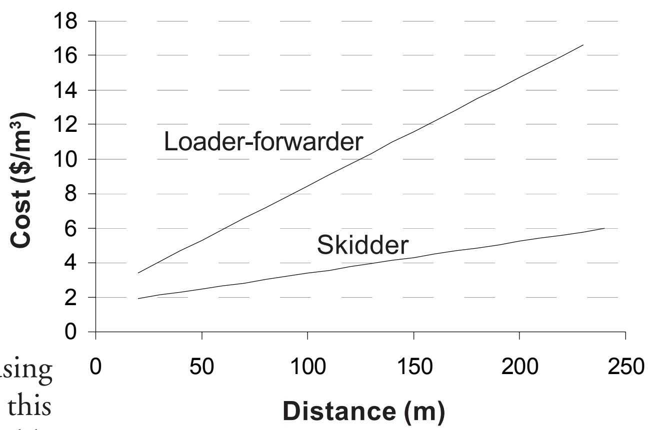


Figure 6. Predicted skidder and loader-forwarder unit costs as a function of distance.

Influence of primary transport equipment on harvesting cost: an analysis

The harvesting cost on the truck, using the loader-forwarder and skidder as in this study, was compared to three other possible scenarios: using a small skidder only, using a loader-forwarder only, and using a larger skidder under conventional winter harvesting conditions. To simplify the comparison, the costs of falling, processing, and loading were held constant and the additional costs of roadbuilding in summer versus winter are not included. Table 4 shows that the costs to harvest during the winter with a large 130-kW skidder are the lowest at $9.25/m³, followed by a smaller skidder with wide tires during the summer at $10.22/m³—an increase of 10% over winter harvesting. Skidding and loader-forwarding as monitored in this study cost $11.05/m³—an increase of 19% over winter harvesting. Using the loader-forwarder only would result in a cost of $14.83/m³—an increase of 60% over winter harvesting.

Soil disturbance

Total disturbance was 6.6% for the skidder area and 2% for the loader-forwarder

Table 4. Comparison of harvesting cost[a] ($/m^3) using four equipment scenarios for primary transport

Equipment for primary transport	Felling	Primary transport	Processing	Loading	Total
	Harvesting component ($/m^3)				
Skidder-and-loader-forwarder (case study)	2.40	4.04	2.61	2.00	11.05
Skidder only (100 kW)	2.40	3.21	2.61	2.00	10.22
Loader-forwarder only	2.40	7.82	2.61	2.00	14.83
Skidder only (130 kW) winter harvest	2.40	2.24 [b]	2.61	2.00	9.25

[a] Felling, skidder-and-loader-forwarding, and processing costs based on shift-level studies, and skidding-only and loader-forwarding-only primary transport costs based on detailed-timing studies assuming a 90-m average travel distance. Loading cost was an estimate.

[b] Cost of primary transport assumes an average productivity for a 130-kW skidder of 55 m^3/SMH based on an estimate of winter harvesting operations. Assumes total ownership and operating costs for a 130-kW skidder of $122.97/SMH.

area (Table 5). These results were less than the allowable disturbance of 10% and 5% for SU-A and B, respectively. After skidding, the majority of disturbance consisted of dispersed trails (5%), forest floor displacement (0.8%), and very wide scalps (<0.4%). Felling and skidding occurred during a dry rainless period and, while soil moisture was not measured, soil samples excavated within 30 cm of the surface were dry to the touch and did not form a cast. This indicates that soil strength was relatively high. For loader-forwarding, the majority of disturbance consisted of track ruts ≥5 cm deep into the mineral soil (1.4%). The ruts were created by one pass of the loader-forwarder crossing a seepage area with high soil moisture (Figure 7).

Figure 7. Rut from loader-forwarder in seepage area.

The degree of soil disturbance recorded during this study was within the limits set out in the silvicultural prescription. In addition to the soil moisture conditions being generally favourable for equipment traffic

Table 5. Soil disturbance from loader-forwarder and skidder

Type of disturbance	SU-A skidder	SU-B loader-forwarder
	Proportion of unit disturbed (%)	
Wheel or track ruts ≥5 cm deep into mineral soil	-	1.4
Wheel or track ruts ≥15 cm deep	-	<0.3
Dispersed trail [a]	5.0	-
Continuous scalp	<0.4	-
Very wide scalp	<0.4	-
Forest floor displacement	0.8	<0.3
Total disturbance	6.6	2.0
Allowable disturbance	10.0	5.0
Soil compaction hazard rating	high	very high

[a] Survey point showed evidence of compaction as indicated by increased soil density relative to surrounding soil.

during harvesting, a number of equipment-related features and operating techniques were effective in minimizing soil disturbance:

- The feller-buncher operator minimized the amount of machine walking by reaching further for the stems and by avoiding walking with cut stems.
- Bunches were positioned parallel to skidding direction to reduce maneuvering and turning by the skidder.
- The skidder was small and equipped with wide tires to reduce overall ground pressure.
- To minimize disturbance, the skidder operator was instructed to make gradual turns in the block and to back up from the decking area rather than turn when skidding close to the road.
- The skidder operator drove the skidder over the existing log deck to increase deck height (Figure 8), rather than use the skidder blade or grapple to manipulate log decks.
- The loader-forwarder was effective at removing stems with minimal soil disturbance from the areas with a very high compaction hazard rating (SU-B).
- The loader-forwarder and skidder used in combination were effective at reducing disturbance both within the block and at roadside. Wood located in areas with a very high compaction hazard rating was forwarded to less sensitive ground where it was skidded the remaining distance to roadside. When extracting wood close to roadside, the loader-forwarder was used effectively in the decking area to pile wood delivered by the skidder (Figure 9). The loader-forwarder piled the stems at the landing while moving in reverse along the deck. Using the loader-forwarder and skidder in combination caused less disturbance at the decking area compared to a more typical system where the skidder with grapple and blade is used for decking activity.

Figure 8. Skidder increasing deck height by driving over deck.

Figure 9. Loader-forwarder decking stems delivered by skidder.

Other measures to reduce disturbance

The following techniques can be utilized to further reduce soil disturbance:

- Pile tops and debris at decking areas using a loader rather than a crawler tractor and blade to reduce the amount of ground traffic unless the ground is frozen (Sutherland 2003).
- When felling close to roadside, pile trees directly onto the log deck to avoid additional transport by the skidder or loader-forwarder.
- When skidding with wide tires on soft ground, disengage differential locks to reduce soil disturbance when sharp turns are unavoidable such as near congested deck areas (Sutherland 2003).
- Utilize tires with rounded lug ends to reduce disturbance during turns.
- Use a loader-forwarder rather than a skidder to reduce soil disturbance in constricted areas, in long narrow extensions, or in irregular shaped blocks where equipment travel is confined.

- Avoid sorting on the block. In this study aspen, poplar, and pine were all skidded separately which required additional machine travel compared to skidding each species as encountered.

Harvest planning

Space for decking was limited which often lead to congestion problems prior to delivered wood being processed and loaded. This contributed to soil disturbance in several ways:

- Without direct access to log decks by loaded skidders, the operator travelled parallel to the road to reach openings in the deck to deliver wood. Skidding distances up to 220 m parallel to roadside were observed during this study. Additional traffic and increased ground compaction occurred near decking areas (Figure 10), and more ground disturbance resulted from sharp turns by the skidder
- Because roadside space was limited, log decks were extended deeper into the block and the work areas were congested. A two-pass decking system was used as shown in Figure 11. The initial deck was piled approximately 5–7 m from the road and 2–3 stems high. Deck height was kept low to prevent line-of-sight problems for the processor operator when piling processed logs. The low deck height meant more area was required to deck the stems. The processed log pile was positioned 1–2 m from the road, and debris accumulated between the log and stem decks. For the next pass, stems were decked beyond the debris pile approximately 12 m from the road. The processor ran over the debris pile from the first pass to process this second stem deck. Skidders building the second deck were forced to turn sharply to avoid the processed logs and the debris pile. Following processing, this second log deck was located approximately 9 m from the road. Both log piles and debris had to be cleared before more stems

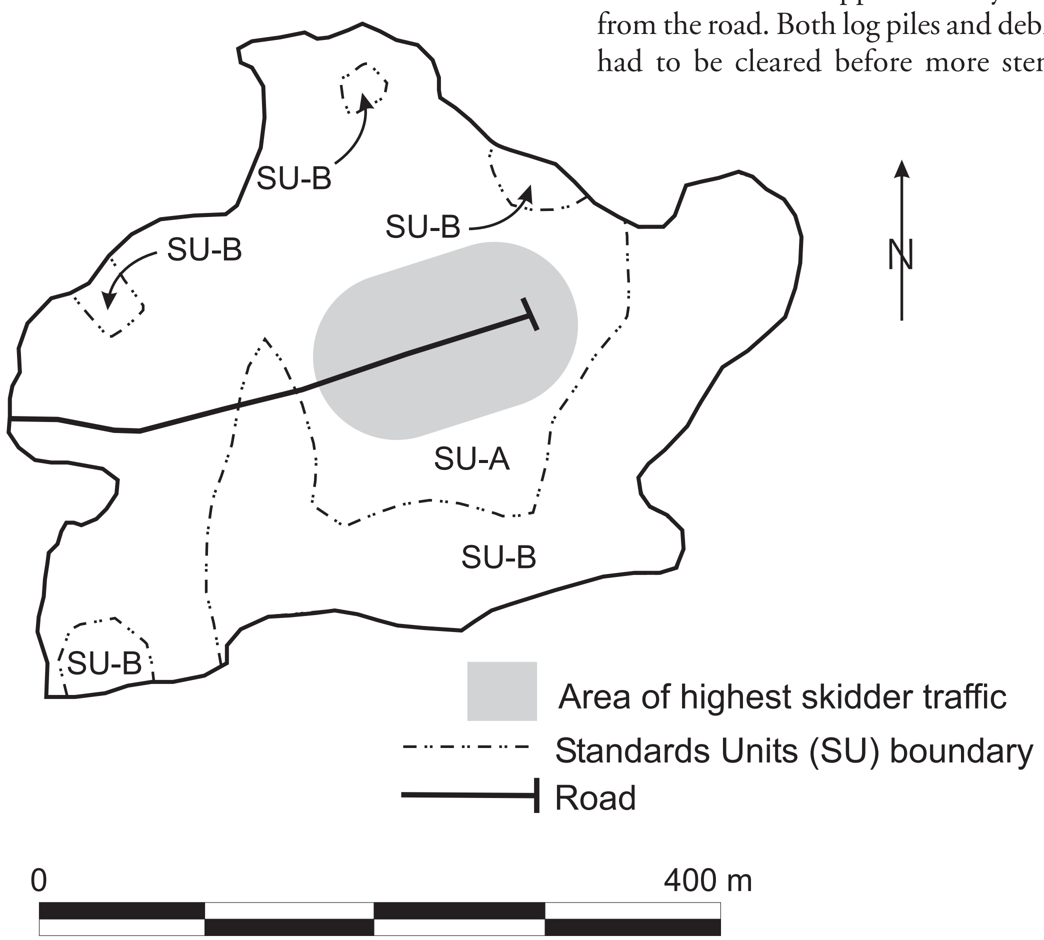


Figure 10. Harvest block showing roadside area with highest skidder traffic.

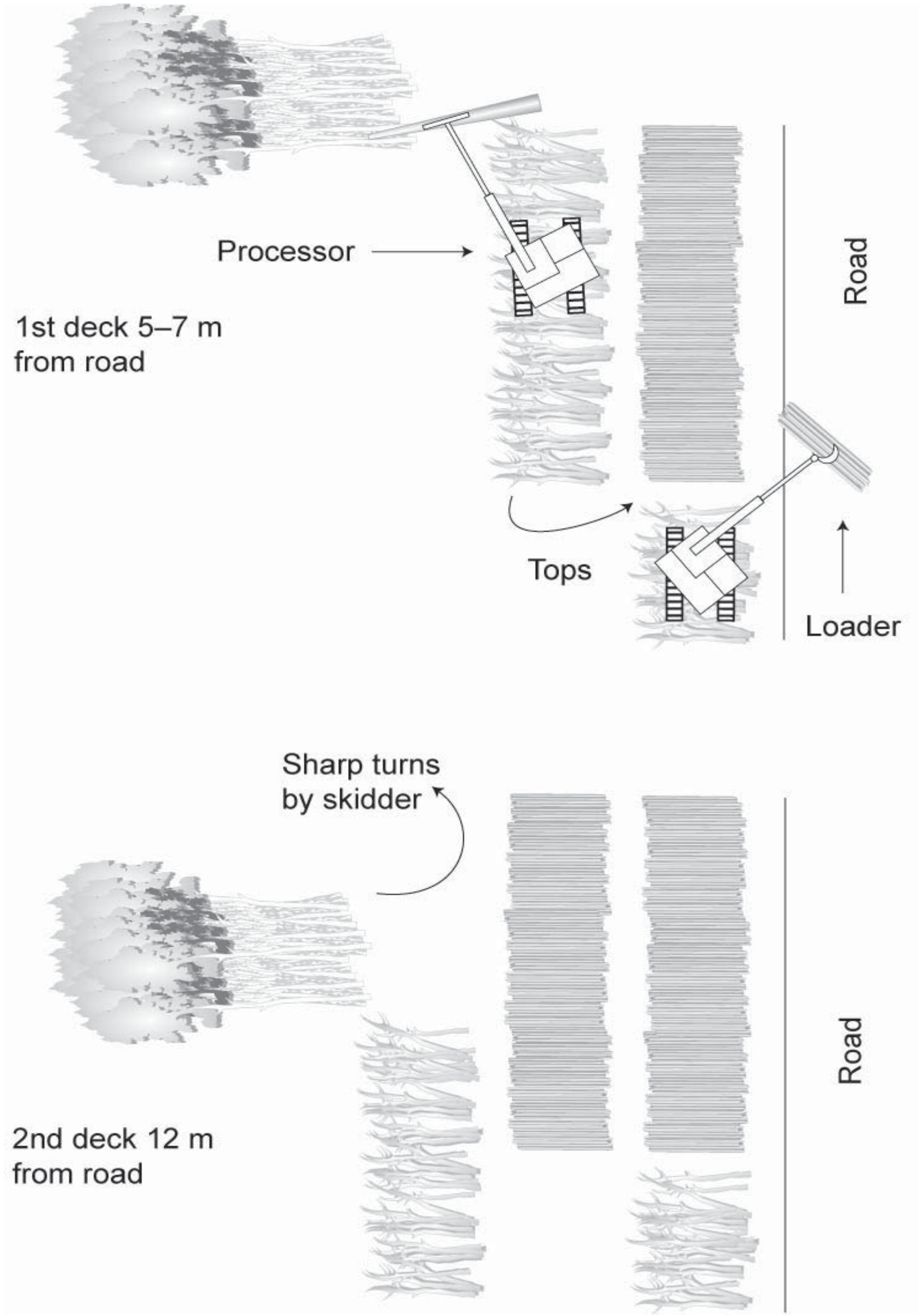


Figure 11. Two-pass decking system used to process wood.

could be skidded to roadside. For a skidding distance of 150 m, bunches were delivered to roadside in four passes; the last three passes were decked over the same area. In addition to increased ground disturbance from equipment maneuvering, the confined space created equipment scheduling problems for skidding, processing, and loading when trying to maintain the flow of wood.

Other observations

Several other observations are worth noting:

- Soil disturbance can be beneficial to aspen regeneration. Disturbance from machine traffic that increases soil temperatures without having negative effects on regenerative capacity of roots, or site conditions, can increase the number of aspen suckers (Frey et al. 2003). The reduced level of disturbance to the forest floor from loader-forwarding compared to skidding may affect the degree of vegetative sprouting of aspen and poplar following harvesting.
- The operating technique used in loader-forwarding can influence the degree of ground disturbance. The goal should be to minimize the extent of machine travel and avoid skid steering as much as possible. Documenting the ground disturbance in future studies of loader-forwarding may help to identify operating techniques that minimize disturbance.
- The loader-forwarder grapple in this operation was not equipped with a heel. As a result, bunched tops were dragged during forwarding and this contributed to forest floor disturbance. For a grapple equipped with a heel, dragging would be eliminated and less forest floor disturbance would be expected.
- When loader-forwarding over longer distances (150 m), the dragging of bunched tops tended to delimb the hardwood stems. Roadside debris piles were therefore smaller for these stems compared to skidded stems.
- While loading trucks, the log loader utilized processor debris as a flotation mat for ground protection. This mat remained as a compacted layer following harvesting and may inhibit sprouting of aspen and poplar.

Conclusions

Results of the soil disturbance survey indicate that both the skidder and loader-forwarder were effective at transporting wood to roadside in non-frozen conditions without exceeding soil disturbance guidelines for these site conditions. Total disturbance was 6.6% and 2.0% for areas trafficked by the skidder and loader-forwarder, respectively. The operating technique used for loader-forwarding may influence the degree of soil disturbance. Further investigation of loader-forwarding operations is recommended to determine the impact that different operating techniques have on the extent of ground disturbance.

The productivity of the loader-forwarder was 22 m^3/SMH, slightly more than half that of the skidder at 40 m^3/SMH. The productivity of the feller-buncher was 68 m^3/SMH while the productivity for the processor was 54 m^3/SMH. The unit costs of the feller-buncher, skidder, and processor were similar at \$2.40/m^3, \$2.73/m^3, and \$2.61/m^3, respectively. The unit cost of loader-forwarding at \$7.14/m^3 was nearly triple the cost of skidding.

A regression analysis showed that travel distance had a major impact on total cycle time for the loader-forwarder and skidder. Productivity was higher for the skidder than the loader-forwarder over all distances. The cost of skidding was less than loader-forwarding, and as distance increased loader-forwarding became less cost-effective.

For loader-forwarding, the major component of total cycle time (51%) was Swing Loaded as the stems were moved closer to roadside. Using a heel may reduce swing loaded time. Maximizing grapple load size is an effective method of reducing the total number of swings required.

The machines were used in a complementary manner and operated efficiently within the prescribed limits for soil disturbance. Stems were forwarded from the most sensitive areas to less sensitive ground, and then skidded to roadside. When operating close to roadside, the loader-forwarder piled the stems delivered by the skidder. This procedure reduces the level of ground disturbance at the decking area compared to the more traditional system where the skidder decks the stems.

A comparison of the harvesting costs on the truck using different combinations of equipment for the primary transport of wood showed that a combined loader-forwarding and skidding operation costs 19% more than a conventional winter operation using larger-sized skidders. This does not account for higher roadbuilding costs in the summer compared to the winter. Skidding with a small wide-tired skidder during the summer costs 10% more than the conventional winter operation. Using a loader-forwarder only was 60% higher than in winter skidding. The increased costs of summer logging may be offset by the additional benefits of a smoother flow of wood to the mills throughout the year and an extended summer work season for the logging contractors.

Implementation

FERIC identified operational techniques to reduce soil disturbance and effectively incorporate loader-forwarding into a fully mechanized conventional roadside system:

- Use a loader-forwarder in conjuction with a low ground pressure skidder on high compaction hazard soils, when dry, to extend the summer harvest season prior to freeze up. However, there may be higher costs involved.
- Use a loader-forwarder to forward wood from low-strength, high-compaction hazard areas to less sensitive ground where wood can be more efficiently skidded to roadside.
- Use a loader-forwarder to pile wood at roadside when skidding distances are short. Wood delivered by the skidder to within reach of the loader-forwarder can be piled more efficiently and with less disturbance of the decking area than with a skidder.
- To help reduce soil disturbance, avoid sharp turns, back up to retrieve wood that is close to roadside, and avoid decking activity with the skidder blade or grapple.
- To optimize loader-forwarder productivity, maximize grapple load size to reduce the total number of swings required to forward wood to roadside.
- Use a loader to pile woody debris accumulations in decking areas as this requires less trafficking of the ground than using a crawler tractor and blade.
- To reduce both the congestion of equipment and the amount of ground disturbance near roadside decking areas, ensure the location and extent of roads are sufficient to accommodate wood delivered directly to roadside by the shortest route possible.

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Appendix I

Cycle elements for detailed timing of skidding and loader-forwarding operations.

Skidder:

Travel Empty:	Begins when the skidder starts moving away from the deck and ends when the skidder stops to load the first stem.
Load:	Begins after travel empty is completed, and ends when the final load is lifted by the grapple.
Travel Loaded:	Begins when the load is lifted by the grapple and ends when the load is dropped on the landing.
Deck:	Begins when the load is dropped on the landing and ends when the skidder starts moving away from the deck.
Delay:	Begins when a productive element is interrupted and ends when a productive element is recommenced. Includes mechanical and personnel delays.

Loader-forwarder:

Swing Loaded:	Begins when Swing Empty is finished and the grapple is used to grasp logs to be forwarded, and ends when the grapple releases the log(s). Includes bunching and double handling to make neat piles or decks within the cutblock, re-handling dropped logs, positioning grapple after Swing Empty stops, aborted Swing Loaded, and swinging loaded while moving.
Swing Empty:	Begins when Swing Loaded or Move stops. Typically occurs after each handling of a forwarded grapple of stems.
Move:	Begins when tracks are engaged and the loader-forwarder travels or repositions itself but not when it has a full grapple.
Delay:	Begins when a productive element is interrupted and ends when a productive element is recommenced. Includes mechanical and personnel delays.

Appendix II

Machine costs[a] ($/scheduled machine hour (SMH))

	Timberjack 618 feller-buncher 26 000 kg	Generic rubber-tired grapple skidder 100 kW	Generic loader-forwarder 30 000–35 000 kg	Generic processor on 115 kW excavator	Generic loader 20 000 kg
OWNERSHIP COSTS					
Total purchase price (P) $	510 000	260 000	470 000	425 000	325 000
Expected life (Y) y	5	5	5	5	5
Expected life (H) h	10 000	10 000	10 000	10 000	10 000
Scheduled hours/year (h)=(H/Y) h	2 000	2 000	2 000	2 000	2 000
Salvage value as % of P (s) %	20	20	20	25	25
Interest rate (Int) %	8.0	8.0	8.0	8.0	8.0
Insurance rate (Ins) %	3.0	3.0	3.0	3.0	3.0
Salvage value (S)=((P•s)/100) $	102 000	52 000	94 000	106 250	81 250
Average investment (AVI)=((P+S)/2) $	306 000	156 000	282 000	265 625	203 125
Loss in resale value ((P-S)/H) $/h	40.80	20.80	37.60	31.88	24.38
Interest ((Int•AVI)/h) $/h	12.24	6.24	11.28	10.62	8.12
Insurance ((Ins•AVI)/h) $/h	4.59	2.34	4.23	3.98	3.05
Total ownership costs (OW) $/h	57.63	29.38	53.11	46.48	35.55
OPERATING COSTS					
Fuel consumption (F) L/h	28.0	25.0	30.0	25.0	25.0
Fuel (fc) $/L	0.64	0.64	0.64	0.64	0.64
Lube & oil as % of fuel (fp) %	10	10	10	10	10
Annual tire consumption (t) no.	-	2.0	-	-	-
Tire replacement (tc) $	-	6 000	-	-	-
Track & undercarriage replacement (Tc) $	30 000	-	30 000	30 000	30 000
Track & undercarriage life (Th) h	5 000	-	5 000	10 000	6 000
Annual repair & maintenance (Rp) $	82 000	41 600	80 000	72 000	52 000
Shift length (sl) h	10.0	10.0	10.0	10.0	10.0
Wages (W) $/h	25.88	23.85	24.98	24.98	24.98
Wage benefit loading (WBL) %	38	38	38	38	38
Fuel (F•fc) $/h	17.92	16.00	19.20	16.00	16.00
Lube & oil ((fp/100)•(F•fc)) $/h	1.79	1.60	1.92	1.60	1.60
Tires ((t•tc)/h) $/h	-	6.00	-	-	-
Track & undercarriage (Tc/Th) $/h	6.00	-	6.00	3.00	5.00
Repair & maintenance (Rp/h) $/h	41.00	20.80	40.00	36.00	26.00
Wages & benefits (W•(1+WBL/100)) $/h	35.71	32.91	34.47	34.47	34.47
Prorated overtime (((1.5•W-W)•(sl-8)•(1+WBL/100))/sl) $/h	3.57	3.29	3.45	3.45	3.45
Total operating costs (OP) $/SMH	106.00	80.60	105.04	94.52	86.52
TOTAL OWNERSHIP AND OPERATING COSTS (OW+OP) $/SMH	163.63	109.98	158.15	141.00	122.07

[a] These costs are estimated using FERIC's standard costing methodology for determining machine ownership and operating costs for new machines. The costs shown here do not include supervision, profit, and overhead, and are not the actual costs for the contractor or the company studied. IWA labour rates effective at the time of the study have been used.

Appendix III

Results of regression analysis

Skidder

Equation 1a: TT = 0.0171SD + 0.4044
n = 241 cycles R^2 = 0.876 S.E.E. = 0.330

where:
- TT = Delay-free travel time (loaded and empty) (min)
- SD = Skidding distance (m)
- n = Number of cycles used in the regression analysis
- R^2 = Multiple coefficient of determination
- S.E.E. = Standard Error of the Estimate

This equation is applicable for skid distances ranging from 10 to 235 m.

Equation 1b: CT = TT + OT

where:
- CT = Delay-free cycle time (min)
- TT = Travel time from Equation 1a
- OT = Load, unload, and decking time of 0.91 min

Equation 2: $\text{Productivity} = \dfrac{60(CV)(U)}{CT + DT}$

where:
- Productivity = Predicted productivity (m^3/SMH)
- CV = Average volume per skidding cycle (m^3)
- U = Utilization (88%)
- CT = Cycle time from Equation 1
- DT = "In-cycle" delay of 0.12 min/cycle

Equation 3: $\text{Unit cost} = \dfrac{HC}{\text{Productivity}}$

where:
- Unit cost = Estimated unit cost ($/$m^3$)
- HC = Estimated machine cost ($/SMH)
- Productivity = Predicted productivity (m^3/SMH) from Equation 2

Loader-forwarder

Equation 4: $CT = 0.0426\ SD + 1.4381$

n = 35 $R^2 = 0.644$ S.E.E. = 1.96

where:

CT	=	Delay-free cycle time (min)
SD	=	Loader-forwarding distance (m)
n	=	Distance increments
R^2	=	Multiple coefficient of determination
S.E.E	=	Standard Error of the Estimate

This equation is applicable for extraction distances ranging from 20 to 230 m.

Equation 5: $$\text{Productivity} = \frac{60(CV)(U)}{CT + DT}$$

where:

Productivity	=	Predicted productivity (m^3/SMH)
CV	=	Average volume per loader-forwarding cycle (m^3)
U	=	Utilization (88%)
CT	=	Cycle time from Equation 4
DT	=	"In-cycle" delay of 0.03 min/cycle

Equation 6: $$\text{Unit cost} = \frac{HC}{\text{Productivity}}$$

where:

Unit cost	=	Estimated unit cost ($/$m^3$)
HC	=	Estimated machine cost ($/SMH)
Productivity	=	Predicted productivity (m^3/SMH) from Equation 5