Advantage

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Evaluation of a Caterpillar 535B grapple skidder in a second-growth forest in coastal British Columbia

Abstract

The Forest Engineering Research Institute of Canada (FERIC) undertook a study to investigate the feasibility of using a grapple skidder to complement a loader-forwarding operation in a second-growth cutblock on northern Vancouver Island. This report presents productivity and cost results of the skidding operation, identifies the factors that influence performance of the grapple skidder, and describes the soil disturbance resulting from skidding.

Keywords

Caterpillar 535B grapple skidder, Extraction, Harvesting, Skidding, Loader-forwarding, Second-growth, Productivity, Costs, Coastal British Columbia.

Introduction

The opportunity to use ground-based harvesting systems is increasing in coastal British Columbia as more harvesting of second-growth stands occurs. Loader-forwarders have been used extensively on the coast since the early 1990s (Andersson 1997) to harvest timber on gentle to moderate slopes, in broken terrain, and on sensitive soils. In recent years, there has been increased interest in the use of conventional rubber-tired grapple skidders as many loader-forwarding sites are suited to skidding with grapple skidders working alone or in tandem with loader-forwarders (Kosicki 2003). In the fall of 2003, Canadian Forest Products Ltd. (Canfor), Englewood Division undertook a study to investigate the feasibility of using a grapple skidder to complement a loader-forwarding operation. The study took place on northern Vancouver Island in a second-growth cutblock that was originally laid out for loader-forwarding only. FERIC monitored the study and the results are presented in this report.

Objectives

The goals of this study were to assess the economic and operational feasibility of skidding with a rubber-tired grapple skidder as an alternative or complement to loader-forwarding, and to determine whether grapple skidding could meet applicable soil disturbance standards. The specific objectives were to:

- Determine overall productivity and cost for the skidding phase.
- Identify factors that influence performance of the grapple skidder.
- Evaluate the grapple skidder as a component of a typical coastal roadside harvesting operation.
- Develop productivity and cost functions for the skidding operation.
- Estimate the effects of substituting a grapple skidder for a loader-forwarder on overall harvesting productivity and cost.
- Suggest strategies to optimize combined skidder/loader-forwarder operations.
- Document levels of soil disturbance on the harvest site.

- Suggest ways to minimize soil disturbance on the site when using combined skidder/loader-forwarder systems.

Site and stand description

The study site was located approximately 13 km south of Port McNeill on northern Vancouver Island. The harvesting prescription specified clearcutting with retention and wildlife tree patches that constituted about 15% of the gross cutblock area. Table 1 summarizes the site and stand features.

The site was classified as Coastal Western Hemlock very wet maritime (CWHvm1) (Green and Klinka 1994). The topography was generally uneven to rough with slopes ranging from 0 to 40%.

Table 1. Site and stand descriptions

Total area under prescription (ha)	45.3
Site characteristics [a]	
Ecological classification [b]	CWHvm1
Elevation range (m)	50–110
Terrain	hummocky
Average slope (%)	15
Soil compaction hazard	moderate
Surface soil erosion hazard	moderate to high
Soil displacement hazard	low to moderate
CPPA terrain classification [c]	1.3.2
Species composition (%)	
Western hemlock	94
Amabilis fir	3
Other	3
Net merchantable volume (m^3/ha)	670

[a] From Silviculture Plan.
[b] Green and Klinka 1994.
[c] Mellgren 1980.

Forest cover consisted primarily of second-growth western hemlock with small proportions of amabilis fir and other species, and averaged 670 m^3/ha and 1.52 m^3/stem.

Harvesting operations

Overview

The cutblock was accessed by a network of permanent and in-block roads with a total length of 2420 m (Figure 1). The cutblock was initially laid out for loader-forwarding, but the harvesting prescription was amended to allow selected portions of the cutblock to be harvested with a grapple skidder. Depending on the topography and maximum extraction distances, areas were designated for loader-forwarding only, grapple skidding only, or both. Areas designated for loader-forwarding only included those portions of the cutblock with slopes ranging from 20 to 45% and extraction distances not exceeding 60 m. The portions of the cutblock designated for grapple skidding had slopes ranging from 5 to 25%, with skidding distances not exceeding 300 m. The roads were mostly located on higher ground, so uphill loader-forwarding and skidding were required. Some steep areas near the block backline were not accessible to the skidder, so a combination of loader-forwarding and skidding was designated for these areas.

Although the road density in the study block was relatively high (53 m/ha), several sections of road were located on slopes or in cuts, and these sections were not suitable as decking areas for the skidder. Because portions of the cutblock had to be extracted with a loader-forwarder, the planners decided to use the loader-forwarder to assist the grapple skidder deck skidded stems.

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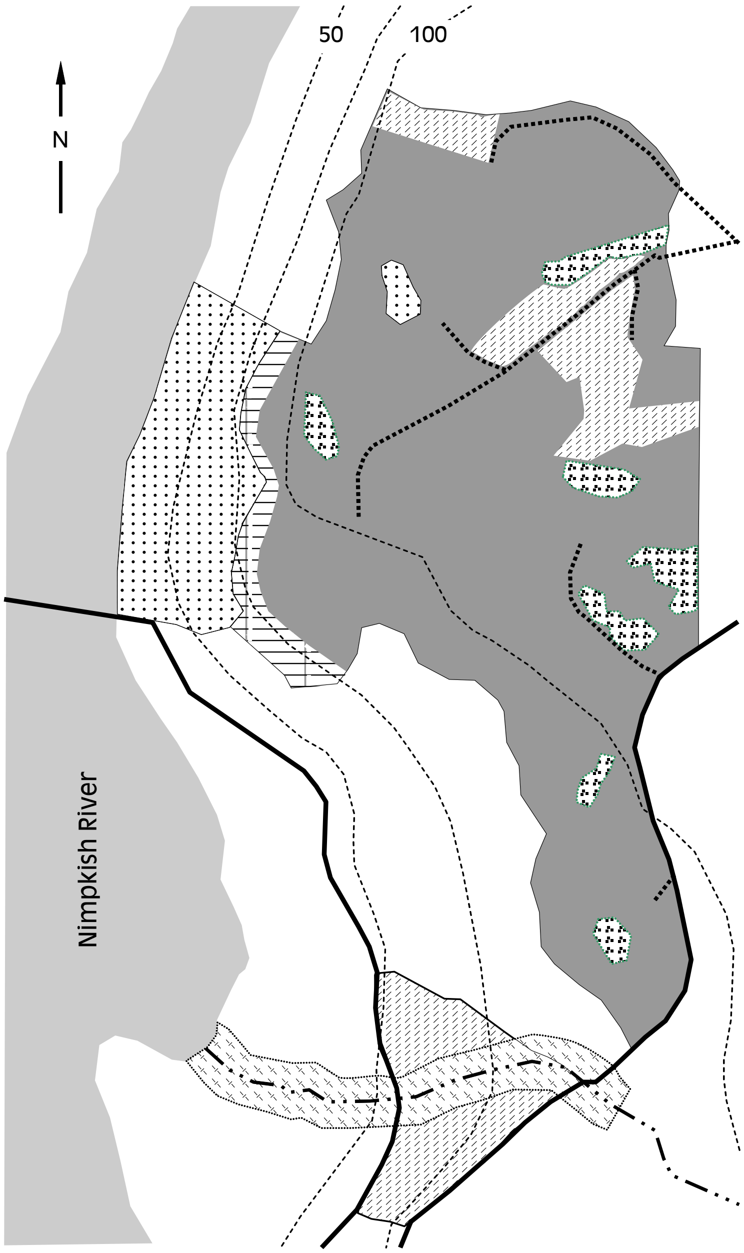


Figure 1. Map of the cutblock.

A fully mechanized roadside harvesting system was used on this site, consisting of a Risley TK-1162 feller-buncher with a Rotosaw HF2229 sawhead, a John Deere 892E LC loader-forwarder, a Caterpillar 535B grapple skidder, a Morgan SX-706 SB grapple skidder,[1] and two Denharco stroke delimbers on Caterpillar 322C hydraulic excavators used for processing.

The entire study block was felled before the skidding/loader-forwarding phase began. Bunches prepared by the feller-buncher consisted of 1 to 10 stems and averaged 4.7 stems/bunch. Most of the bunches were aligned with the butts facing the presumed direction of extraction.

Skidding and loader-forwarding operations

Skidding with the Caterpillar 535B grapple skidder and forwarding with the John Deere 892E LC loader-forwarder (Figure 2) were performed from October 2003 to early January 2004. These machines worked on a single-shift basis five and seven days per week, respectively. The feller-buncher, loader-forwarder, and processor

[1] A Morgan SX-706 SB grapple skidder worked on the study block for two productive shifts only. Field data collected by FERIC during this period were not sufficient to draw reliable conclusions about this machine's productivity and cost.

Figure 2. John Deere 892E LC loader-forwarder.

operators were experienced but had not worked previously as a team with a grapple skidder. The skidder operator had not run this type of machine before.

Most of the study block was skidded uphill on slopes ranging from 5 to 25% and averaging 10%. Skidding distances were up to 300 m. When skidding short distances of 50 m or less, the operator preferred to travel in reverse from the decking area to the loading point. For longer distances, the operator travelled forward when unloaded and typically used the same skid trail several times, both unloaded and loaded.


Figure 3. Caterpillar 535B grapple skidder intercepts bunches forwarded by the John Deere 892E LC loader-forwarder.


Figure 4. Decking with the Caterpillar 535B.


Figure 5. Stems skidded by the Caterpillar 535B are decked by the John Deere 892E LC loader-forwarder.


Figure 6. Stems skidded by the Caterpillar 535B are decked by the John Deere 892E LC loader-forwarder below a hillside road.

Because some steep portions near the backline could not be reached by the skidder, and were too far from the road for efficient loader-forwarding, a two-stage extraction system was used. First, the loader-forwarder swung bunches of stems from the machine to locations accessible to the Caterpillar 535B, which then skidded them to roadside (Figure 3).

At the roadside, skidded stems were handled in one of four ways:

- Decking by the skidder only. In terms of cost and safety, this option was the most desirable but it required ample room for maneuvering which was rarely available. To build up higher decks, the skidder had to travel over the first layers of stems (Figure 4) or push up the deck with its blade.
- Decking by the skidder and loader-forwarder. The skidder dropped off the loads at the roadside but did limited decking, resulting in low log decks. Shortly before all available decking area at a stretch of the road was used, a loader-forwarder moved to the decking area and re-piled the stems into higher decks (Figure 5). During re-piling, the skidder continued skidding directly to loader-forwarder or to the still-available decking area. After clearing more decking area for the skidder, the loader-forwarder returned to the extraction area.
- Hot processing. Immediately upon delivery at roadside, skidded stems were processed into logs by a stroke delimber.
- Decking by the loader-forwarder. This was the only option when the skidder had to skid stems to roads on steep slopes and in confined decking areas with large concentrations of skidded stems (Figure 6).

Skidder description

The Caterpillar 535B grapple skidder is a four-wheel-drive rubber-tired skidder equipped with a 5-speed countershaft transmission. It is suited to skidding large loads over long distances on steep or sensitive ground (Figure 7 and Table 2). The long, wide wheelbase helps to maintain stability when travelling on slopes or broken terrain.

To reduce soil disturbance and compaction, the Caterpillar 535B skidder was equipped with 35.5L-32 tires[2] with chains on front and rear wheels (Figure 8), a hydraulically operated bunching grapple[3] with continuous 360-degree rotation, and a dual-function arch. The grapple has a maximum opening of 3.1 m and an accumulating area of 1.34 m². The long reach of the arch (up to 2.89 m behind the rear-wheel axle), coupled with the grapple rotator, reduces the time and maneuvering required to position the skidder when accumulating its loads.

Study methods

FERIC observed the skidding and loader-forwarding operations and collected shift-level and detailed-timing data on the grapple skidding phase. Shift-level data for the skidding phase consisted of datalogger charts, operators' reports about daily production and major delays (>15 min/occurrence), and net harvest volumes from Canfor scale records.

Skidding cycles were detail-timed at frequent intervals throughout the study period. Each timed cycle was divided into six elements: travel unloaded, load, travel loaded, unload, deck, and in-cycle delays. Skidding distances, number of bunches and stems per cycle, slope of the skidding route, and reasons for observed delays were also recorded.

The detailed-timing data were analyzed using regression techniques to determine relationships between travelling times and skidding distances. The results of the regression analysis were then combined with average values for loading, unloading, and decking times to develop equations to predict delay-free cycle time and to derive production functions.

Figure 7. Caterpillar 535B grapple skidder.

Figure 8. Caterpillar 535B grapple skidder was equipped with 0.9-m-wide tires and wheel chains.

Table 2. Technical specifications for the Caterpillar 535B grapple skidder

Engine	Cat 3126 DITA diesel
Net power – ISO 9249 (kW)	134
Length (m)	6.20
Width (m)	3.39
Wheelbase (m)	3.53
Ground clearance (m)	0.58
Operating mass (kg)	16 920
Travel speed (km/h)	
Forward	6.4–27.5
Reverse	6.2–18.6

Production functions in this report were developed to predict hourly skidding productivity, unit skidding cost, and total unit cost for the skidder/loader-forwarder extraction system. Production functions for the skidding phase were derived by using an average payload per cycle, and adjusting predicted cycle times to reflect both in-cycle and shift-level delays encountered in the skidding phase. Loader-forwarding cost functions were based on recent studies conducted in similar terrain and stand

[2] Standard tires for this machine are 30.5L-32.

[3] The 535B model may be equipped with a cable winch or a dual arch grapple.

conditions (Kosicki and Dyson 2004; Pavel 2004a, 2004b). Hourly skidder and loader-forwarder costs were calculated using FERIC's standard costing methods (Appendix I).

Following harvesting, soil disturbance was assessed using provincial standards and procedures in effect at the time of the study (BCMOF and BC Environment 2001; Curran and Thompson 1991). The soil disturbance assessment used point sampling from transects radiating from 52 geometric grid-point centres.

Results and discussion

The Caterpillar 535B grapple skidder was able to travel smoothly over rough terrain. The long reach of its arch and the grapple rotator enabled the skidder to pick up bunches efficiently, even when the orientation of the bunches differed sharply from the direction of skidding.

Skidding productivity and cost

The total volume harvested from the study site was 20 343 m³. The Caterpillar 535B and the Morgan SX-706 SB skidded 16 179 and 952 m³, respectively. The remaining 3 212 m³ were extracted by the loader-forwarder.

Table 3. Shift-level summary and productivity for the Caterpillar 535B grapple skidder

Description	
Productive shifts (no.)	31
Scheduled time (SMH)	282.4
Productive time (PMH)	262.6
Utilization (%)	93
Volume skidded (m³)	16 179
Cycles (no.)	2 217
Stems (no.)	10 678
Volume/cycle (m³)	7.30
Stems/cycle (no.)	4.8
Volume (m³/stem)	1.52
Productivity	
m³/PMH	62
m³/SMH	57
Machine cost ($/SMH)	115.21
Skidding cost ($/m³)	2.02

Shift-level study

During the study, the Caterpillar 535B grapple skidder worked 31 shifts ranging from 5.0 to 9.5 h in length and averaging 9.1 h. Table 3 summarizes shift time structure, productivity in cubic metres per productive machine hour (PMH) and scheduled machine hour (SMH), and cost in $/m³.

For the study period, the skidder's utilization was 93%, well above the long-term utilization level of 85% that is more typical for logging equipment (Kosicki 2002).

Sizes of bunches prepared for skidding by the feller-buncher and loader-forwarder matched the Caterpillar 535B's capacity, and cycle loads consisted mostly of single bunches. Payloads of two or three bunches were rare. If a single bunch was too large for the skidder's grapple, the bunch was skidded in two cycles. The skidder had an average payload of 4.8 stems at a volume of 7.30 m³.

For single shifts, skidding productivity varied from 32 to 119 m³/PMH. The average for the study period was 62 m³/PMH. At an hourly cost of $115.21 for the skidder, this produces a skidding cost of $2.02/m³.

Detailed-timing study

The Caterpillar grapple skidder was detail-timed for 31.5 hours, and the study results are summarized in Tables 4 and 5. The longest elements of the skidding cycle were travel unloaded, load, and travel loaded (Table 4). Each of these elements accounted for about 29% of the total cycle time. For all decking modes, the combined unload and deck elements accounted for about 9% of the total cycle time.

During the detailed-timing period, payloads skidded by the Caterpillar 535B consisted of 1 to 3 bunches/cycle and averaged 1.13 bunches/cycle. Overall, 89% of turns consisted of a single bunch, while payloads of 3 bunches/cycle accounted for less than 3%. The number of stems in a payload varied from 1 to 12 and averaged 5.06 stems/cycle.

Table 5 summarizes unloading, decking, and combined unloading and decking times for the Caterpillar 535B by decking method. Decking with the skidder was the most time-consuming method. The supporting action of the loader-forwarder at the roadside reduced or even eliminated decking from the skidder's cycle time. Hot processing also substantially reduced the time spent by the skidder in the decking area.

The average skidding productivity in the detailed-timing study was greater than in the shift-level study (107 m^3/PMH vs. 62 m^3/PMH, respectively). Because the average payloads in the shift-level and detailed-timing studies were similar, the differences in skidding productivities can be attributed to differences in skidding distances and decking methods.

Cycle time, productivity, and cost of skidding

Regression analysis based on the detailed-timing data found a significant relationship between travel unloaded and travel loaded times and skidding distances (Equations 1 and 2, Appendix II). These equations, combined with an average loading time of 1.25 min/cycle, and average unloading and decking times shown in Table 5, were used to derive delay-free skidding cycle times (Equations 3 to 6, Appendix II).

Figure 9 presents predicted delay-free cycle times for the Caterpillar 535B as a function of skidding distance for two decking methods: decking with the skidder and decking with loader-forwarder support. At any given skidding distance, the difference in average cycle times between these decking options is 0.5 min.

The third regression line in Figure 9 represents cycle time as a function of skidding distance for a Timberjack 660D grapple skidder in similar terrain and skidding conditions from an earlier FERIC study (Kosicki 2003). The results for the Timberjack 660D and the Caterpillar 535B (both decking with skidder) are almost identical.

The cycle time equations were combined with the average payload of 7.69 m^3/cycle and average delay time of 0.12 min/cycle (Table 4) to estimate productivity during scheduled skidding time, using an assumed

Table 4. Detailed timing for the Caterpillar 535B grapple skidder

Description	
Productive time (min)	1 660
Productive machine hours (PMH)	27.6
Total cycles (no.)	384
Average skidding distance (m)	85
Stems (no.)	1 943
Average cycle time (min)	4.32
Distribution of cycle time (min)	
Travel unloaded	1.29
Load	1.25
Travel loaded	1.25
Unload	0.25
Deck [a]	0.16
Delays	0.12
Estimated volume (m^3) [b]	2 953
Average stems/cycle (no.)	5.06
Average load (m^3/cycle) [b]	7.69
Productivity (m^3/PMH)	107

[a] Average values for all decking methods.
[b] Using average volume per stem from shift-level study.

Table 5. Summary of unloading and decking times for the Caterpillar 535B by decking method

Method of decking	Unload (min/cycle)	Deck (min/cycle)	Unload and deck (min/cycle)
Skidder only	0.30	0.52	0.82
Skidder and loader-forwarder	0.20	0.12	0.32
Loader-forwarder	0.20	0.00	0.20
Hot processing	0.25	0.01	0.26
All methods	0.25	0.16	0.41

Figure 9.
Estimated delay-free cycle times as a function of skidding distance.

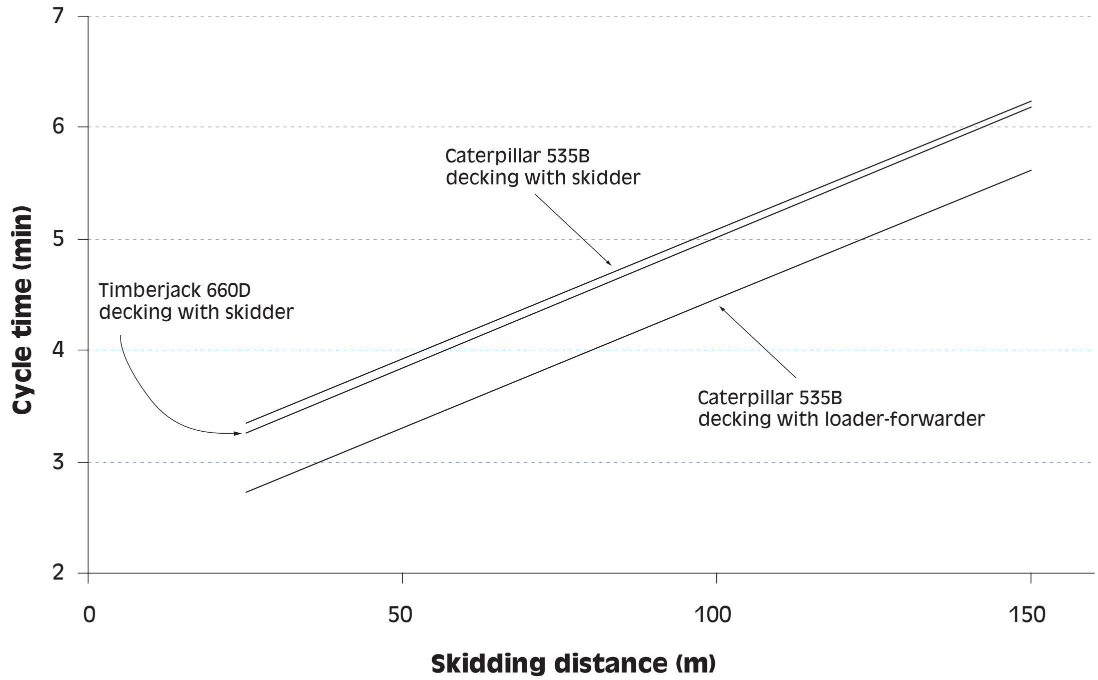
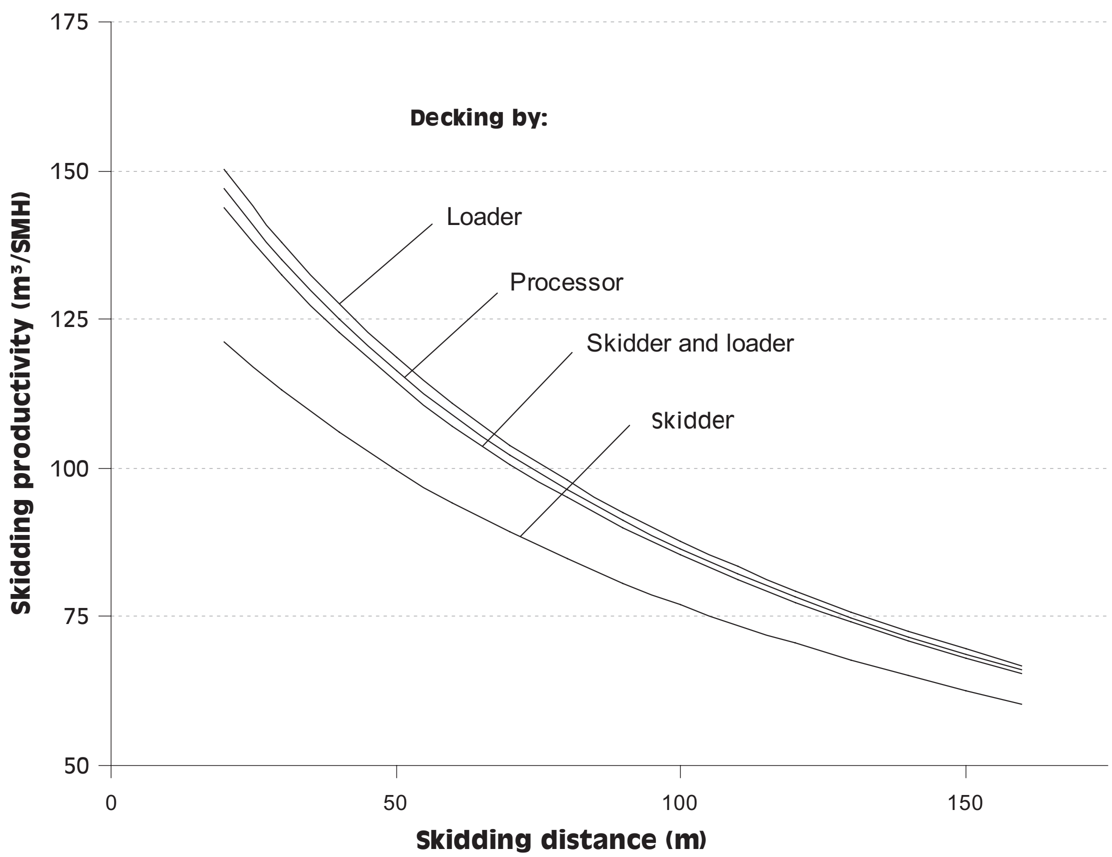


Figure 10.
Estimated skidding productivities as functions of skidding distance and decking method.



long-term utilization rate of 85% (Equation 7, Appendix II).

Figure 10 presents predicted skidding productivities for the Caterpillar 535B as functions of skidding distance and methods of decking. The lowest skidding productivity is predicted if the skidder decks its own turns. Decking with the loader-forwarder only, decking with both the skidder and loader-forwarder, and hot processing at roadside all had a beneficial effect on skidding productivity. For an average skidding distance of 85 m in this detailed-timing study, skidding productivities with "supported" decking were 12 to 15% greater than the productivity of skidding and decking with the skidder only.

Skidding costs in $\$/m^3$ for the Caterpillar 535B were computed using Equation 8 in Appendix II and an hourly skidder cost of \$115.21/SMH (Appendix I). Figure 11 presents skidding costs in $\$/m^3$ as a function of skidding distances for two methods of handling skidded stems at the roadside. In the first method, skidded loads are decked by the skidder, and in the second method decking is eliminated because the loads released at the roadside are hot-processed. Hot processing with no skidder decking results in a cost reduction of $\$0.17/m^3$ for the skidding phase.[4]

The effect of the loader-forwarder's support at roadside on combined skidding and decking costs will be discussed in a later section, "Combined skidding and decking costs."

Skidding cost vs. loader-forwarding cost

In Figure 12, the predicted skidding costs for the Caterpillar 535B and the decking-by-skidder variant were compared with cost predictions for loader-forwarding from earlier FERIC studies in similar terrain conditions. For the average extraction distance of 85 m for the detailed-timing studies, the loader-forwarding cost is three times more than the skidding cost with the Caterpillar 535B ($\$4.60/m^3$ vs. $\$1.51/m^3$). This comparison demonstrates that using a grapple skidder to complement a loader-forwarding operation is a cost-effective solution.

Combined skidding and decking costs

Figures 9, 10, and 11 show that both decking skidded stems with a loader-forwarder and hot processing at roadside to eliminate the need for decking improve the skidder's cycle time, productivity, and costs.

In the case of skidding with decking supported by a loader-forwarder, the estimate

[4] In this study, the effect of the hot processing on the processing productivity and cost was not studied.

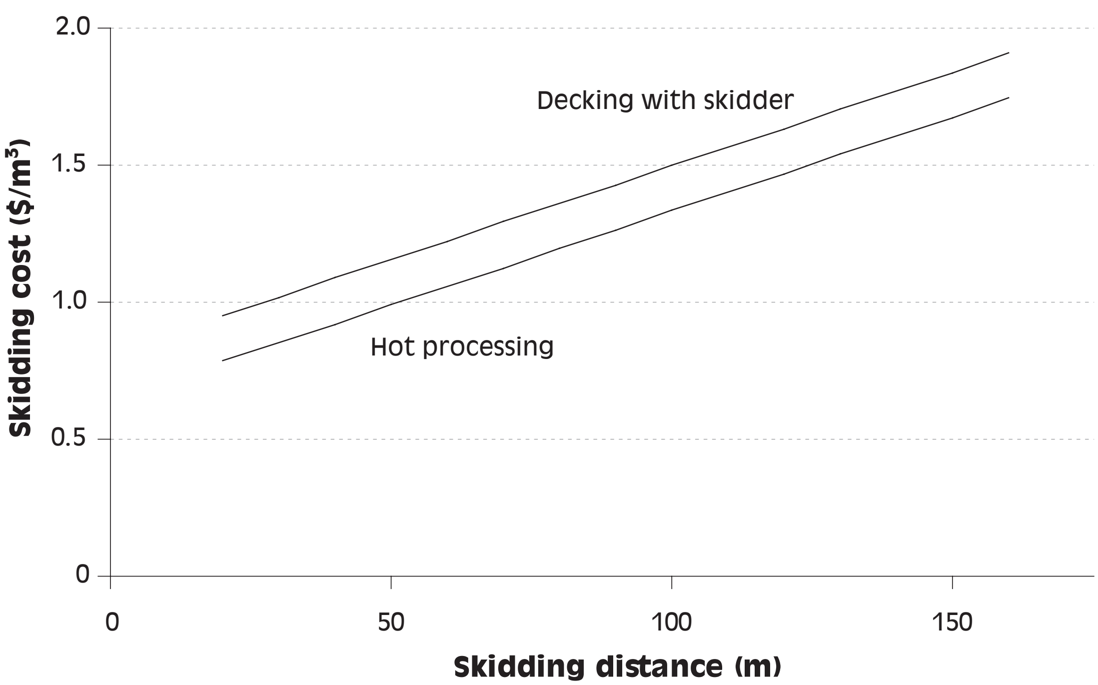


Figure 11. Estimated skidding costs as a function of skidding distance.

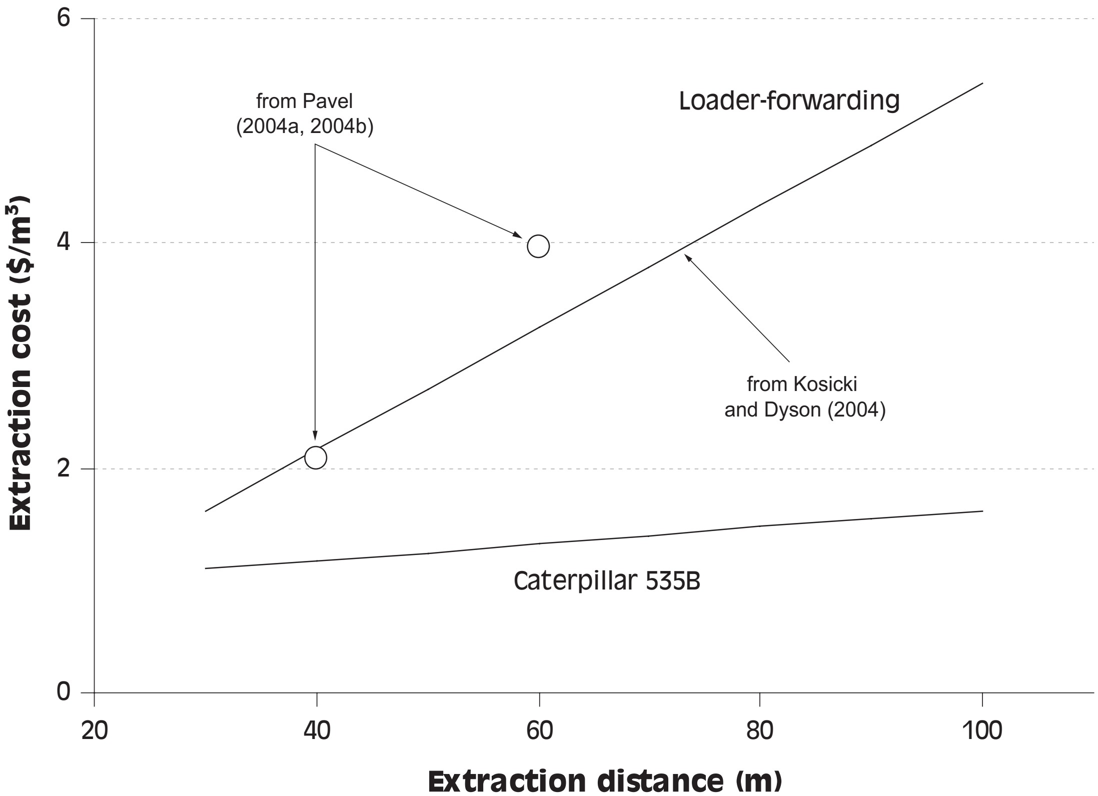


Figure 12. Estimated skidding costs in the study for the Caterpillar 535B when decking with skidder, compared to loader-forwarding estimates from previous studies.

of final costs is more complex. On the one hand, decking with a loader-forwarder reduces the skidder's cycle time (Figure 9) and increases its productivity (Figure 10), therefore reducing skidding cost. On the other hand, the use of a loader-forwarder for this purpose incurs additional cost, and this amount depends on how much of the loader-forwarder's time is spent supporting the skidder.[5] The maximum occurs when the loader-forwarder supports the skidder on a full-time basis, and the cost decreases if less supporting time is needed.

The combined costs of skidding with the Caterpillar 535B and decking with a loader-forwarder were calculated from Equation 9 (Appendix II) for an hourly loader-forwarder cost of $144.46/SMH (Appendix I) and loader forwarder-to-skidder support ratios varying from 1.0 (full-time support) to 0 (no loader-forwarder support, decking with the skidder only). Additionally, it was assumed that if the loader-forwarder supported the skidder on a part-time basis, the rest of the loader-forwarder's time was spent performing productive work (forwarding, loading hauling tracks, sorting logs, etc.). The results are shown in Figure 13 and are compared with the cost for loader-forwarding only from an earlier FERIC study (Kosicki and Dyson 2004).

Figure 13 shows that combined skidding and loader-forwarding in second-growth stands using the Caterpillar 535B grapple skidder is a cost-effective alternative to loader-forwarding alone. The lowest skidding cost in $/m³ is achieved when the decking is performed by the skidder with no support by the loader-forwarder. This scenario is represented by the cost line in Figure 13 for the support ratio of 0. This option, however, is usually not feasible in difficult terrain and in unfavourable roadside decking conditions (i.e., limited access to the road, confined decking space, roads in deep cuts, or on slopes) where some degree of loader-forwarder support for the skidding phase is necessary.

The financial consequences of this action depend on the amount of loader support required. For example, if the average skidding distance is 85 m and the loader-forwarder is

[5] Support time includes loader's travel time between work sites.

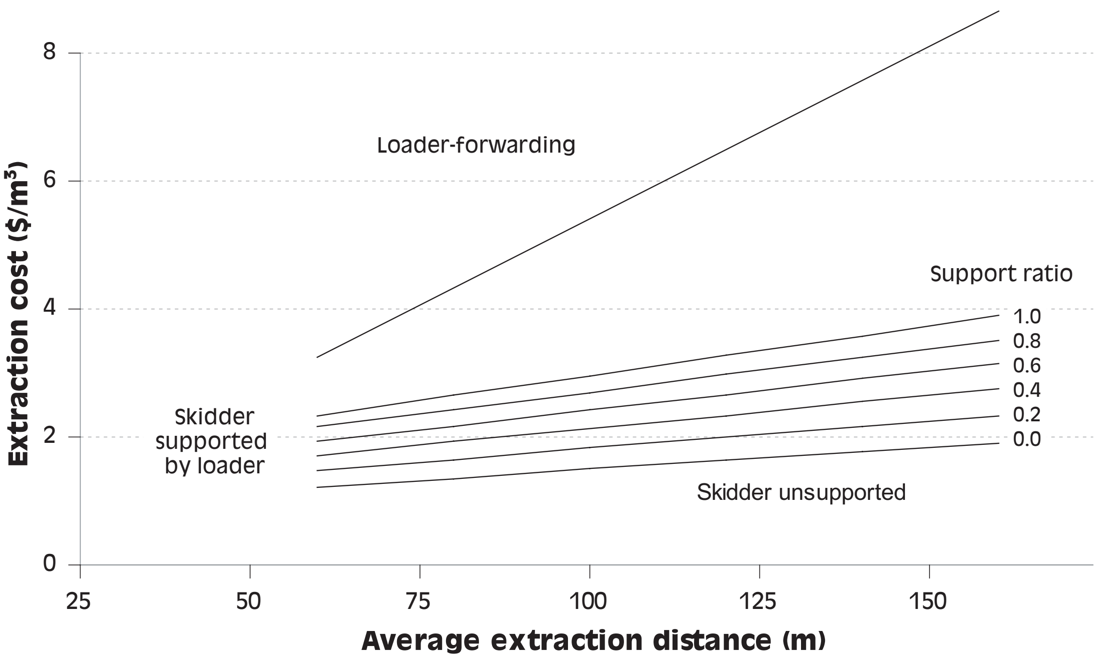


Figure 13. Estimated loader-forwarding and skidding costs as functions of extraction distance and support ratio.

expected to support the skidder for 4 h during a 10-h skidding shift, the support ratio is 0.4, and predicted skidding costs including decking costs are $1.93/m^3$. These costs are about 41% greater than the skidding and decking costs without support of a loader-forwarder. However, for the same extraction distance of 85 m, the loader-forwarding cost would be $4.38/m^3$. In some situations, the loader-forwarder may need to support the skidder on a full-time basis (support ratio = 1). Even in this case, the resulting cost of $2.67/m^3$ for a distance of 85 m is considerably less than the loader-forwarding cost of $4.38/m^3$.

A substantial reduction in combined skidding and decking costs can be achieved if one loader-forwarder can adequately support two or more grapple skidders. For example, a loader-forwarder employed on a full-time basis and supporting two skidders has a support ratio of 0.5 per skidder. For this ratio and an average skidding distance of 85 m, the predicted combined costs from Figure 13 are $2.11/m^3$ compared to $2.67/m^3$ for a one-skidder/one- loader combination. This represents a 21% cost reduction.

Figure 14 shows the ratio of total extraction cost for the Caterpillar 535B skidder supported by a loader-forwarder to the cost of loader-forwarding only, for varying levels of loader support. At an average skidding distance of 85 m and a support ratio of 1.0, the total cost of extraction including decking with a loader-forwarder is 59% of the cost of loader-forwarding only. For the same distance and support ratio of 0.4, the estimated cost reduction is 57%.

Comparison with other studies

Table 6 compares the Caterpillar 535B and four 4-wheel-drive rubber-tired grapple skidders in earlier FERIC studies (Kosicki 2000 and 2003; Gingras and Godin 2001).

The Caterpillar 535B grapple skidder's mass, engine power, and grapple area are, respectively, 14, 7, and 23% greater than for the four other skidders, while its cycle payload in this study was 29% greater than the average payloads for the other skidders in earlier FERIC studies.

Soil disturbance

The harvesting operation in this study did not use bladed skidroads, so all soil disturbance on the net area to be reforested (NAR) consisted of "dispersed disturbance" as defined in the Forest Practices Code (FPC) (BCMOF and BC Environment 2001). In accordance with FPC definitions, the sample

Figure 14. Skidding and decking cost versus loader-forwarding cost as functions of skidding distance and support ratio.

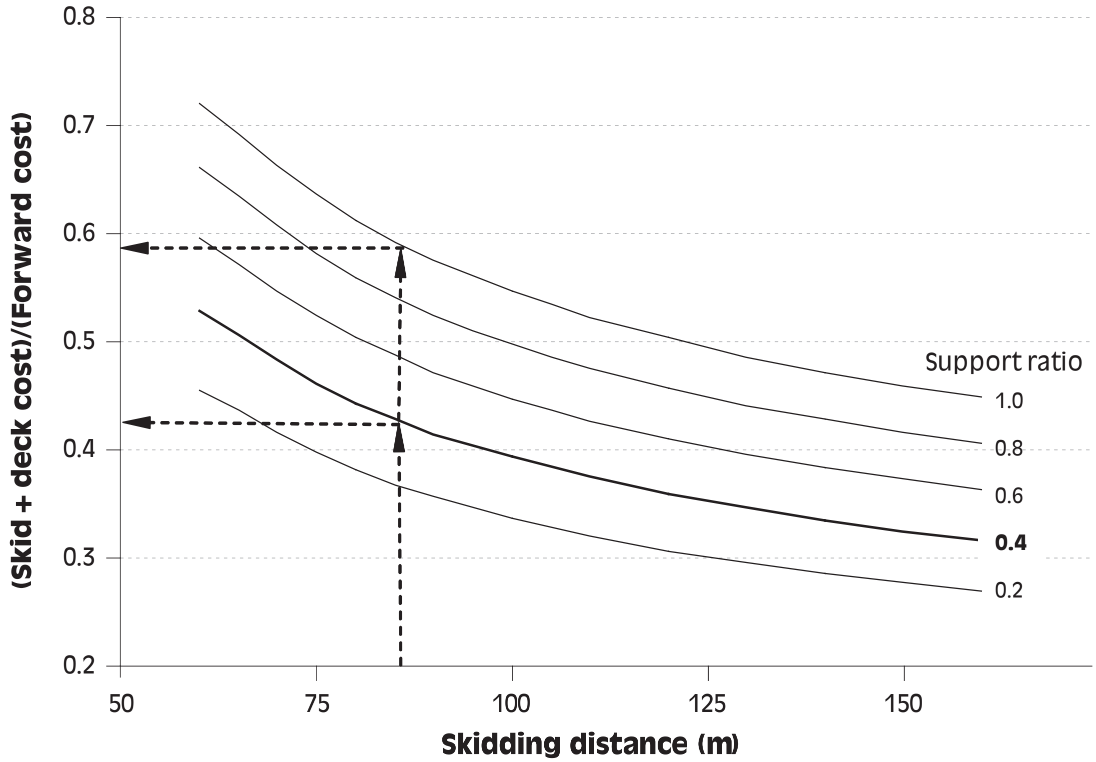


Table 6. Indices for selected models of grapple skidders

	John Deere 748E (1)	John Deere 748E (2)	Timberjack 560 (3)	Tigercat 630 (4)	Average of (1) to (4) (5)	Caterpillar 535B (6)	Caterpillar 535B vs. other skidders in % (6)/(5)
Skidder mass (kg)	14 560	14 560	15 400	14 750	14 818	16 920	114
Engine power (kW)	123	123	118	137	125	134	107
Grapple area (m^2)	1.07	1.07	0.92	1.30	1.09	1.34	123
Average volume (m^3/stem)	0.51	0.44	0.44	0.19	n/a [a]	1.52	n/a [a]
Average bunch volume (m^3)	2.21	3.64	3.64	3.37	3.21	6.46	201
Payload (bunches/cycle)	2.44	1.44	1.44	2.00	1.83	1.13	62
Payload (m^3/cycle)	5.40	5.24	5.24	6.74	5.65	7.3	129
Skidding direction [b]	F	F	F	F	F	F	A

[a] Not applicable.
[b] F = favourable (level terrain), A = adverse (upslope).

points were classified into the following categories: Wheel or Track Ruts (T), Repeated Machine Traffic (E); Wide Gouges (W), and Not Counted (undisturbed points, and disturbed points not meeting the criteria for T, W, and E). From 2375 sampling points, 98 points (i.e., 4.1%) were classified as disturbed. Within individual plots, disturbance levels ranged from 0 to 20%. Six and five plots had levels greater than 5 and 10%, respectively. Seventy-one percent of countable disturbance fell into the Wheel and Track Ruts (T) category; Repeated Machine Traffic with evidence of compaction (E) constituted 27% of all types of disturbance; and Wide Gouges (W) were rare (2% of all types of disturbance).

Total soil disturbance on the study block using this survey method was 4.1%, less than the maximum allowable level of 5% specified in Canfor's Site Plan. Moderately dry soils at the time of harvesting, the low to moderate soil compaction hazard, and use of wide tires contributed to the low disturbance. The most severe occurrences of soil disturbance were at the bottoms of large poorly drained depressions. Fine-textured soil deposits, higher soil moisture contents, and adverse skidding on frequently used trails created very deep ruts in these depressions.

Soil disturbance could have been reduced further by mapping and marking the wet areas prior to harvesting and designating them for skidding in drier weather or by using a loader-forwarder operating on mats or puncheon.

Conclusions

This study demonstrated that skidding of clearcuts in second-growth stands using a grapple skidder is a feasible and cost-effective alternative to traditional loader-forwarding under some conditions. The results and conclusions of this study are very similar to an earlier FERIC study on a grapple skidder working in similar terrain and stand conditions (Kosicki 2003).

This study also demonstrated that a grapple skidder and loader-forwarder working as a team may complement each other very well. The grapple skidder's large payload volume and high travelling speed make it efficient for long extraction distances, while the loader-forwarder is better suited for short extraction distances such as from bands adjacent to the roads. Loader-forwarders may also be more suitable in areas inaccessible to grapple skidders such as small confined pockets, steep slopes, areas where extraction would occur in an adverse direction, and areas where soils are more moist and fine-textured.

Complementing loader-forwarding with skidding may also allow a reduction of in-block roads because the productivity and cost are less sensitive to extraction distance with the skidder than with the loader-forwarder.

Cost analyses showed that the introduction of the Caterpillar 535B grapple skidder to the study block resulted in considerable time and cost savings, even if the skidder is supported on the roadside with a loader-forwarder performing decking of skidded stems. A further reduction in combined skidding and decking costs can be achieved if one loader-forwarder can adequately support more than one skidder at a time.

The study block was within the maximum allowable soil disturbance level of 5% specified by the FPC for coastal British Columbia. The most severe cases of soil disturbance occurred at the bottoms of large poorly drained depressions. These sensitive sites should be reserved for loader-forwarding or possibly for skidding during dry weather.

Implementation

This and earlier FERIC studies highlight several factors that can contribute to the successful employment of grapple skidders in roadside harvesting operations in coastal second-growth stands.

- Effective skidding with grapple skidders to realize cost reduction benefits requires careful layout of the block and detailed planning of all harvesting phases.
- Fewer roads may be needed for grapple skidding than for loader-forwarding. Skidding distances can be longer than loader-forwarding distances, but they should not exceed 250 to 300 m.[6]
- On gentle slopes (10 to 20%), skidding uphill, although technically feasible, should be avoided. Instead, to utilize the skidder's payload capacity and reduce the soil disturbance level, downhill skidding is generally recommended.
- In more difficult terrain, an early field reconnaissance of the block by contractors, equipment operators, and supervisors will give the opportunity for all involved to analyze working conditions, strategize, and establish cooperation.

[6] It is generally accepted by woodlands managers and contractors that the extraction distances for grapple skidders should not exceed 250 to 300 m.

- The feller-buncher operator should be familiar with the block layout, general direction of skidding, and capabilities of the skidder to correctly place and index bunches of appropriate sizes. To facilitate the skidder's travelling, loading, and decking, stumps of trees cut by the feller-buncher should be as low as possible.
- If the bunch sizes are below the skidder's capacity, the operator should optimize the payload size by collecting multiple bunches. This will minimize costs, especially in the case of long skidding distances.
- If the loader-forwarder removes large debris from the decking areas and extracts stems from the bands adjacent to the road, the skidder's productivity will increase. Skidder traffic adjacent to the road, and subsequent soil disturbance in the decking area, will decrease.
- In difficult terrain and roadside conditions (limited access to the full length of the road, confined decking areas, roads sections with deep cuts, hillside roads, etc.), use a loader-forwarder to deck the stems for the skidder. To minimize skidding and decking costs, use the loader to support the skidder only where it is necessary.
- When contemplating joint grapple skidding/loader-forwarding operations, consider the feasibility of having the loader-forwarder support more than one grapple skidder.
- If the loader-forwarder supports the skidder on a part-time basis, minimize the number of times the loader-forwarder travels between the extraction side and roadside. The skidder should use all available area at the roadside to drop off loads before moving the loader-forwarder in to deck the stems.
- During breaks in skidding operations, use the loader-forwarder to prepare properly oriented, well-aligned bunches matching the load capacity of the skidder. This will improve the performance of the skidder.
- If hot processing is necessary owing to lack of decking space, have the skidder extract loads alternately from short and long distances to balance skidding and processing phase productivities.
- In the case of adverse weather conditions and signs of rutting, stop skidding until conditions improve.
- The skidder should not operate on sensitive areas where soils are more moist and/or fine-textured as rutting is likely to occur. Leave these areas for loader-forwarding during dry weather.

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Appendix I

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

	Caterpillar 535B grapple skidder	John Deere 3554 loader-forwarder [b]
OWNERSHIP COST		
Total purchase price (P) $	281 000	550 000
Expected life (H) h	10 000	16 000
Scheduled hours/year (h)=(H/Y) h	2 000	2 000
Expected life (Y) y	5	8
Salvage value as % of (P) (s) %	20	30
Interest rate (Int) %	5	5
Insurance rate (Ins) %	2	2
Salvage value (S)=((P•s/100) $	56 200	165 000
Average investment (AVI)=((P+S)/2) $	168 600	357 500
Loss in resale value ((P-S)/H) $/h	22.48	24.06
Interest ((Int•AVI)/h) $/h	4.22	8.94
Insurance ((Ins•AVI)/h) $/h	1.69	3.58
Total ownership costs (OW) $/h	28.38	36.58
OPERATING COST		
Fuel consumption (F) L/h	25	30
Fuel (fc) $/L	0.90	0.90
Lube & oil as % of fuel (fp) %	10	15
Annual tire consumption (t) no.	1	n/a
Tire replacement (tc) $	5 200	n/a
Lifetime repair & maintenance cost in % of purchase price (P)	80	80
Track & undercarriage replacement (Tc) $	n/a	38 500
Track & undercarriage life (Th) h	n/a	8 000
Regular shift length (rsl) h	8.0	8.0
Shift length (sl) h	8.5	10.0
Operator wages (W) $/h	23.80	26.80
Wage benefit loading (WBL) %	51	51
Lifetime repair & maintenance cost $	224 800	440 000
Fuel (F•fc) $/h	22.50	27.00
Lube & oil ((fp/100)•(F•fc)) $/h	2.25	4.05
Tires (t•tc/h)	2.60	n/a
Track and undercarriage (Tc/Th)		4.81
Repair & maintenance (Rp/h) $/h	22.48	27.50
Wages & benefits (W•(1+WBL/100)) $/h	35.94	40.47
Overtime (0.5W(sl-rsl)(1+WBL/100)/sl) $/h	1.06	4.05
Total operating costs (OP) $/h	86.83	107.88
TOTAL OWNERSHIP AND OPERATING COST (OW+OP) $/h	115.21	144.46

[a] The costs used in the study are not the actual costs incurred by the company, and do not include indirect costs such as crew and machine transportation, overhead, profit, and risk.

[b] The John Deere 892E LC loader is no longer commercially available. Purchase price used in the cost analysis is based on the John Deere 3554 loader.

Appendix II

Regression, productivity, and cost equations for skidding

Linear equations for travel unloaded and travel loaded

Equation 1: Caterpillar 535B, travel unloaded
$TE = 0.364 + 0.0109(SD)$ n = 355 $r^2 = 0.595$

Equation 2: Caterpillar 535B, travel loaded
$TL = 0.206 + 0.0123(SD)$ n = 358 $r^2 = 0.671$

Where:
TE = travelling time unloaded (min)
TL = travelling time loaded (min)
SD = skidding distance (m), range from 15 to 170 m
n = number of observations
r^2 =coefficient of determination

Delay-free cycle time equations

Equation 3: Caterpillar 535B, decking by skidder only
$CT = 2.64 + 0.0232(SD)$

Equation 4: Caterpillar 535B, decking by skidder and loader-forwarder
$CT = 2.14 + 0.0232(SD)$

Equation 5: Caterpillar 535B, decking by loader-forwarder only
$CT = 2.02 + 0.0232(SD)$

Equation 6: Caterpillar 535B, hot processing
$CT = 2.08 + 0.0232(SD)$

Where:
CT = delay-free cycle time (min)
SD = skidding distance (m), range from 15 to 170 m

Productivity and cost equations

Equation 7: $\text{Productivity} = \dfrac{60(CV)(U)}{CT + DT}$

Where:

Productivity	=	predicted skidding productivity measured in m^3/SMH
CV	=	average volume per skidding cycle (m^3)
U	=	utilization (%/100)
CT	=	cycle time from appropriate time equation (min)
DT	=	"in-cycle" delay time per cycle (min)

$$\text{Equation 8: Cost} = \frac{HC}{\text{Productivity}}$$

Where:

Cost	=	predicted skidding cost in $/m³
HC	=	estimated skidding cost in $/SMH
Productivity	=	predicted skidding productivity in m³/SMH from Equation 7

$$\text{Equation 9: } C_{S+D} = \frac{SC + (LC)(SR)}{(SPUS)(1 - SR) + (SPS)(SR)}$$

Where:

C_{S+D}	=	combined skidding and decking cost in $/m³
SC	=	skidder cost ($/SMH)
LC	=	loader-forwarder cost ($/SMH)
SR	=	support ratio
SPUS	=	skidding productivity with decking by skidder (m³/SMH)
SPS	=	skidding productivity with decking by loader-forwarder (m³/SMH)