Advantage

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Evaluation of supported and unsupported grapple skidding in winter conditions in the central interior of British Columbia

Contents

Abstract

The Forest Engineering Research Institute of Canada (FERIC), in cooperation with Winton Global Lumber Ltd. in Prince George, B.C., studied supported and unsupported winter skidding operations with conventional rubber-tired grapple skidders. In supported operations, skidders worked with track skidders and loaders that assisted with loading and decking, respectively. In unsupported operations, skidders worked alone. This report presents the study results, and discusses factors that influenced the productivities and costs of both skidding systems.

Keywords

Harvesting systems, Grapple skidders, Extraction, Winter operations, Productivity, Costs, Interior British Columbia.

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Introduction

Woodlands managers often modify existing techniques and introduce new ones in an attempt to improve the efficiency of harvest operations. One such modification is a supported harvesting system, in which the main machine is assisted by one or more auxiliary machines. Past FERIC studies of Caterpillar 535B and Trans-Gesco TG88 skidding operations supported by loaders decking the stems demonstrated that this was a feasible alternative to traditional operations in which all skidding phases—including decking—were performed by the skidder (Kosicki 2005a, b).

In the winter of 2005/06, Winton Global Lumber Ltd. proposed the evaluation of supported and unsupported winter skidding operations using conventional wheel grapple skidders working in three blocks north of Prince George, B.C. FERIC monitored the study and the results are presented in this report.

Objectives

The goal of the study was to assess the economic and operational aspects of winter skidding with conventional wheel grapple skidders working alone or in teams with track skidders and loaders assisting with loading and decking, respectively. The following specific objectives were established to address this goal:

- Determine overall productivity and cost for the supported and unsupported grapple skidding systems.
- Identify factors that influence the performance of the grapple skidders and develop productivity and cost functions.
- Suggest strategies to optimize performance of the studied skidding systems.

Site description

Grapple skidding operations were observed in three study blocks located in Winton Global's Merton and Caine operating areas.

In all blocks, the harvesting prescription specified clearcutting with reserves. Table 1 summarizes the site and stand conditions.

All three blocks were classified as Mossvale Moist Cool Sub-Boreal Spruce (SBSmk1)[1] biogeoclimatic units (DeLong et al. 1993). Elevations ranged from 720 to 890 m. Topography of the blocks was generally gentle to steep with average slopes ranging from 10 to 15%.

Forest cover consisted of old-growth lodgepole pine (*Pinus contorta* var. *latifolia*), hybrid white spruce (*Picea glauca* x *engelmannii*), and subalpine fir (*Abies lasiocarpa*). Merchantable stand and tree volumes ranged from 321 to 414 m^3/ha and 0.58 to 0.72 m^3/tree, respectively.

Skidding equipment and operations

Harvest blocks, harvesting equipment, and skidding systems for this study were selected by Winton Global. Relatively high road densities in the study blocks (Table 1), and hence short skidding distances, provided favourable conditions for supported systems.[2] The study blocks were harvested in the winter of 2005/06 by three full-phase contractors using fully mechanized roadside systems (MacDonald 1999). Study blocks were felled before the skidding phase began

[1] Formerly SBSe2.

[2] Supported systems are suitable for short skidding distances because the benefits of reduced or eliminated loading and decking times on productivity and cost decrease with increasing skidding distance.

Table 1. Site and stand descriptions

	Block A	Block B	Block C
Total area under prescription (ha)	114.3	103.3	107.7
Site characteristics [a]			
Ecological classification [b]	SBSmk1	SBSmk1	SBSmk1
Elevation range (m)	720 to 780	800 to 890	790 to 870
Terrain	level to steep	gentle to steep	level to moderate
Average slope (%)	10	14	15
Road density (m/ha)	39	35	20
CPPA terrain classification [c]	1.3.2	1.3.2	1.3.2
Species composition (%)			
Lodgepole pine	49	61	65
White spruce	41	31	25
Subalpine fir	8	5	7
Other	2	3	3
Net merchantable volume (m^3)			
Per hectare	321	414	342
Per tree	0.72	0.58	0.66

[a] From Silviculture Plan.
[b] DeLong et al. 1993.
[c] Mellgren 1980.

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and were accessible to skidding equipment from in-block spur road systems. Skidding operations were performed with four models of wheel grapple skidders with net power ratings of 134 to 155 kW (Appendix I).

In the conventional unsupported system, all functions in the skidding cycle, including loading and decking, were performed exclusively by the wheel skidder. In the supported system, a track skidder prepared bunches for skidding by moving them, usually over short distances, to locations more accessible to a wheel skidder. At the roadside, the wheel skidder's payload was unloaded by opening the grapple, and the skidder did not attempt to deck extracted loads. A loader was dedicated full-time to decking the skidded stems. Unsupported systems were employed throughout Block C and in a portion of Block A. Supported systems were used in Block B and in a portion of Block A. A more detailed description of the harvesting systems and equipment applied in the study blocks is given in Table 2. Figures 1–6 illustrate several of the machines used.

Study methods

Skidding cycles were detail-timed at frequent intervals throughout the study period, with each timed cycle divided into seven elements: travel unloaded, load, travel loaded, unload, deck, in-cycle delays, and interaction. The seventh cycle element—interaction—identifies situations where two machines in a skidding system affected each other's performance to a degree that the activity of one had to be temporarily suspended. In this study, interactions occurred between wheel skidders (e.g., two skidders at the same section of a narrow skidding trail), a wheel skidder and a supporting track skidder (e.g., a wheel skidder waiting to intercept a load still being extracted by a track skidder), and a wheel skidder and a loader (e.g., a loaded skidder arriving at the roadside before the loader completed decking stems from the previous cycle).

For each cycle that was timed, the following were also recorded: the skidding distance, number of bunches and stems per cycle, and reasons for observed delays. The average piece volumes in cubic metres were determined by scaling individual unprocessed stems in bunches or decks, and cycle volume was calculated as a product of an average piece volume and an average number of stems per cycle.

Single regression analysis with a .05 significance level was performed to search for

Table 2. Description of the harvesting systems

Study block	Skidding system	Description
A	unsupported	Skidding with a Caterpillar 535B wheel grapple skidder (Figure 1). Loading and decking unsupported.
	supported	Skidding with a Caterpillar 545 wheel grapple skidder. Loading supported by a Caterpillar 527 track grapple skidder with a swing boom (Figure 2). Decking of skidded stems performed by a Caterpillar 330C track heel-boom loader (Figure 3).
B	supported	Skidding with two Ranger F68G wheel grapple skidders. Loading of both skidders supported by a Caterpillar D5H TSK track grapple skidder with a swing boom (Figure 4). Decking of skidded stems performed by a Link-Belt 3400 track loader with a butt-and-top grapple (Figure 5).
C	unsupported	Skidding with two Tigercat 630B wheel grapple skidders (Figure 6). Loading and decking unsupported.

Figure 1. Caterpillar 535B wheel grapple skidder.

Figure 2. Caterpillar 527 track grapple skidder preparing bunches for the Caterpillar 545 wheel grapple skidder.

Figure 3. Caterpillar 330C track heel-boom loader decking stems skidded by the Caterpillar 545 wheel grapple skidder.

Figure 4. Caterpillar D5H TSK track grapple skidder preparing bunches for the Ranger F68G wheel grapple skidders.

Figure 5. Link-Belt 3400 track loader decking stems skidded by the Ranger F68G wheel grapple skidders.

Figure 6. Tigercat 630B wheel grapple skidder.

potential relationships between skidder travelling times and distances. A covariance analysis was used to detect differences between loaded and unloaded travelling speeds. To test whether cycle elements independent of skidding distances (loading, unloading, decking, and interaction) are equal for all skidders, one-way analysis of variance (ANOVA) was carried out. Equations were then developed to predict delay-free cycle time and to derive productivity and cost functions.

Production functions in this report were developed to predict skidding productivity in cubic metres per productive machine hour (m^3/PMH) and per scheduled machine hour (m^3/SMH). Hourly costs for the machines used in unsupported and supported systems were calculated using FERIC's standard methods (Appendix II). Skidding cost per cubic metre ($/$m^3$) for each system was determined by dividing the total hourly cost of all machines in each system by its skidding productivity in m^3/SMH.

Results and discussion

Detailed-timing study

Results of the detailed-timing study for the four skidders are summarized in Table 3. Because of the relatively high densities of in-block roads (see Table 1), the corresponding average skidding distances were short and, except for the Ranger F68G, did not exceed 100 m. Overall, about 90% of cycles for the four skidders consisted of a single bunch. Except for the Tigercat 630B, the average payloads in m^3/cycle were less than would be expected for skidders of 135- and 150-kW power ratings. Skidded payload sizes are discussed in the section, "Potential payloads, productivities, and costs," presented later in this report.

Cycle time, productivity, and cost of skidding

Cycle time elements

Single regression analysis of the detailed-timing data found a significant relationship between travelling times and distances (Equations 1 to 4 for travelling unloaded, and Equations 5 to 8 for travelling loaded, Appendix III).

The regression lines showing the relationship between skidding distance and unloaded and loaded travelling times (Figures 7 and 8, respectively) were almost parallel, which suggests that there were no differences in the skidders' travelling speeds; this was confirmed by covariance analysis. The similarity of travelling speeds resulted from similar terrain and work conditions. For the four skidders, the average loaded and unloaded travelling speeds were 86 and 92 m/min, respectively.

Table 4 summarizes the average times for loading, unloading, decking, delay, and interaction elements for unsupported and supported skidding systems.

Table 3. Detailed timing for the grapple skidders

Description	Supported Caterpillar 545	Unsupported Caterpillar 535B	Supported Ranger F68G	Unsupported Tigercat 630B
Productive time (min)	305	89	367	276
Productive machine hours (PMH)	5.08	1.49	6.11	4.60
Total cycles (no.)	123	23	78	65
Average cycle time (min)	2.5	3.9	4.7	4.3
Average skidding distance (m)	50	73	120	100
Average bunches/cycle (no.)	1.2	1.2	1.1	1.2
Average stems/cycle (no.)	7.5	6.8	5.8	10.4
Average stem volume (m^3) [a]	0.77	0.77	0.60	0.70
Average load (m^3/cycle)	5.74	5.21	3.52	7.27
Average productivity (m^3/PMH)	139	80	45	103

[a] Based on scaling results.

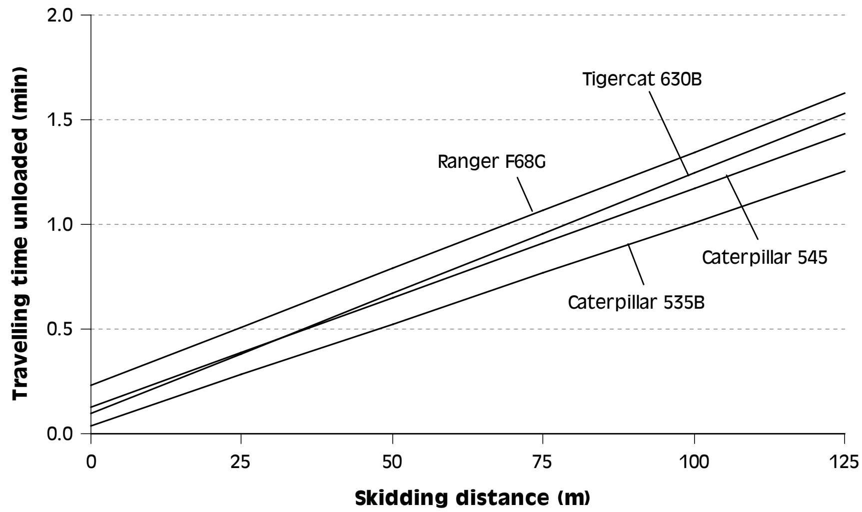


Figure 7. Calculated unloaded travelling time as a function of the skidding distance.

Figure 8. Calculated loaded travelling time as a function of the skidding distance.

Table 4. Terminal, interaction, and delay times for unsupported and supported skidding systems

	Average time (min/cycle)			
Cycle element	Supported Caterpillar 545	Unsupported Caterpillar 535B	Supported Ranger F68G	Unsupported Tigercat 630B
Loading	0.56	0.95	0.64	0.49
Unloading	0.25	0.16	0.31	0.12
Decking	-	1.10	-	1.02
Total terminal	0.81	2.12	0.95	1.63
Delays	0.06	0.16	0.25	0.14
Interaction	0.20	-	0.41	-
Total	1.07	2.37	1.61	1.77

In unsupported systems, the most time-consuming cycle element was decking which averaged about 1 min/cycle. In supported systems, the gain resulting from elimination of decking from the cycle time was moderate because a portion of the saved time was consumed by the interaction between machines working in the system. Loading times for both supported systems were significantly less than for the unsupported system with the Caterpillar 535B. The very short loading time in the unsupported system with the Tigercat 630B is attributed to the correct alignment of bunches with properly squared butts. Generally, the total of terminal, interaction, and delay times was less for supported systems than for unsupported systems.

Table 5 summarizes interaction times for the two supported systems. The interaction "wheel skidder – track skidder" represented the time a wheel skidder waited to intercept a load being moved by the track skidder. "Wheel skidder – wheel skidder" interaction occurred when one of the skidders had to stop to allow the other to continue its action (i.e., two skidders moving on the same section of a narrow skidding trail, or arriving at the same time at the roadside to unload the skidded turn for decking with the loader). "Wheel skidder – loader" interaction occurred when a loaded skidder had to wait at the roadside because the loader had not completed decking the previous turn.

Table 5. Interaction times for supported skidding systems

	Interaction (min/cycle)	
Interacting machines	Caterpillar 545B [a]	Ranger F68G [b]
Wheel skidder – track skidder	0.15	0.06
Wheel skidder – wheel skidder	-	0.26
Wheel skidder – loader	0.05	0.09
Total	0.20	0.41

[a] One wheel skidder in the system.
[b] Two wheel skidders in the system.

Cycle time

Regression equations for unloaded and loaded travelling times (Appendix III) combined with terminal, interaction, and delay times were used to produce equations for calculated cycle times as a function of skidding distances (Equations 9 to 12, Appendix III). The graphical representation of cycle times is shown in Figure 9. Differences in cycle times resulted exclusively from differences in terminal, interaction, and in-cycle delay times.

Payloads

Table 6 shows the average stem and payload volumes skidded in the study blocks. The largest payloads were skidded by the Tigercat 630B in an unsupported system and averaged 7.27 m^3/cycle. For the Ranger F68G working in a supported system, cycle payloads averaged only 3.52 m^3. The large difference in payloads for these two 150-kW

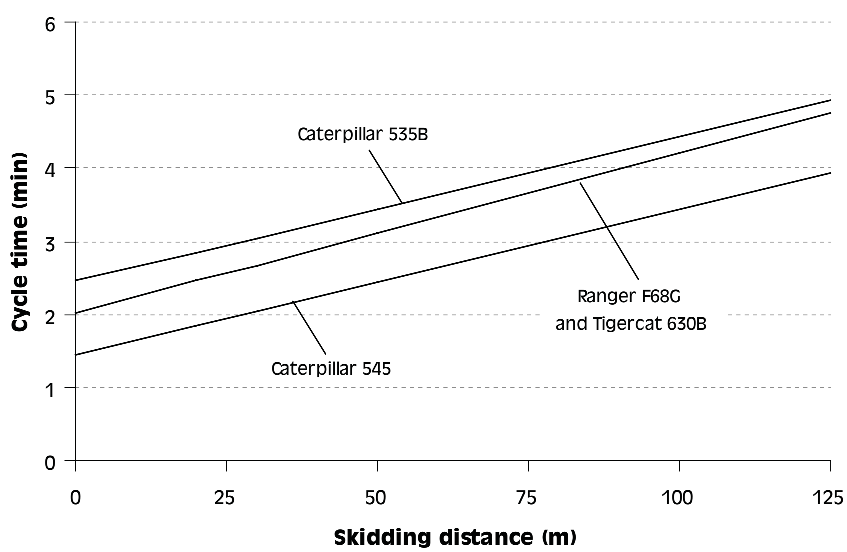


Figure 9. Cycle times as a function of skidding distance.

Table 6. Payload characteristics for grapple skidders and skidding systems

Description	Unsupported Caterpillar 535B	Supported Caterpillar 545	Supported Ranger F68G	Unsupported Tigercat 630B
Payload (stems/cycle)	6.8	7.5	5.8	10.4
Volume (m³/stem)	0.77	0.77	0.60	0.70
Volume (m³/cycle)	5.21	5.74	3.52	7.27

power class skidders is attributed to the bunch sizes prepared by the feller-bunchers. Also, the Caterpillar D5H TSK track skidder did not prepare bunches with volumes matching the capabilities of the Ranger F68G.

There was relatively small difference between cycle payloads for the Caterpillar 535B and Caterpillar 545 working in the same study block but in different skidding systems (unsupported and supported). The Caterpillar 527 track skidder mostly limited its supporting action to moving bunches from steep sections of the block to locations more accessible to the Caterpillar 545, and placed little emphasis on building larger payloads for the skidder by accumulating bunches left by the feller-buncher.

Generally, the payload volumes for skidders, with the exception of the Tigercat 630B, were less than would be expected for skidders of these power classes (Kosicki 2000, 2002a, 2002b, 2003, and 2005a; Gingras and Godin 2001). Payload volumes for the four skidders are discussed in the later section, "Potential payloads, productivities, and costs."

Skidding productivity

Figure 10 shows skidding productivities in m³/PMH (left-hand y-axis) and in m³/SMH (right-hand y-axis)[3] calculated using Equation 13 (Appendix III). The highest (and almost identical) productivities were achieved by the unsupported Tigercat 630B and the supported Caterpillar 545. The Caterpillar's high productivity is attributed to the elimination of the decking component from skidding cycles. The Tigercat's cycle times, longer than that of the Caterpillar 545

[3] For the skidding productivity per SMH, the shift time utilization of 85% was assumed (Kosicki 2002b).

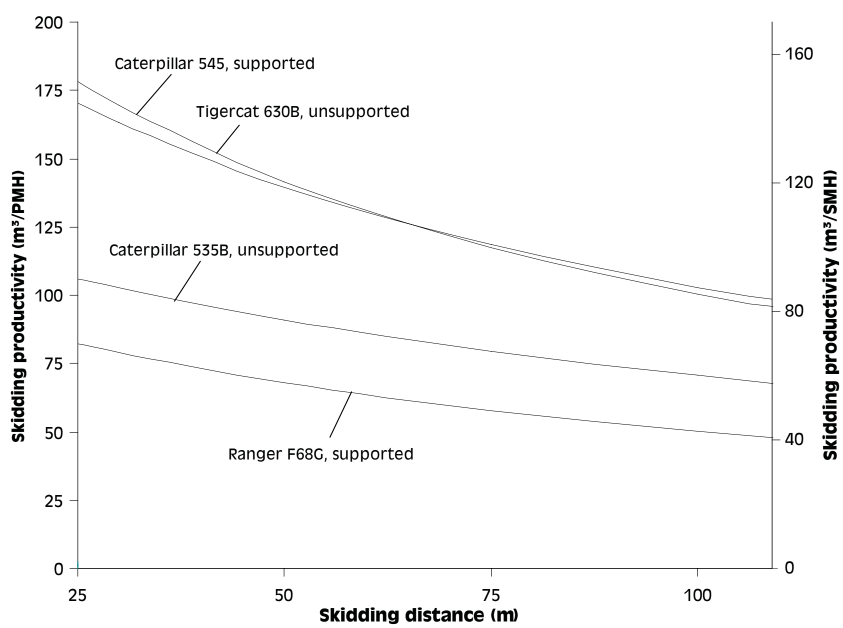


Figure 10. Calculated skidding productivities in m³/PMH and in m³/SMH (at 85% utilization) as functions of skidding distance for the four skidders and the unsupported and supported skidding systems.

(see Figure 9), were easily offset by its larger payload (7.27 m^3/cycle). The 155-kW Ranger F68G working in a supported system achieved a productivity that was even less than that of the 134-kW Caterpillar 535B working in an unsupported skidding system as a result of its low average payload of 3.52 m^3/cycle. The Ranger's productivity with expected payloads is discussed in the later section, "Potential payloads, productivities, and costs."

Skidding cost

Skidding system costs in $/SMH were calculated as the sum of the hourly costs of associated machines (Table 7) (see Appendix II for hourly machine cost calculations).

The hourly cost of the supporting machines (track skidder and loader) constituted a considerable portion of the total system costs. The sum of the track skidder's and loader's costs, as a percentage of the total system cost, was 52% for the skidding system with two Ranger F68Gs, and 70% for the system with one Caterpillar 545.

Unit skidding cost in $/$m^3$ was calculated by dividing the system cost in $/SMH (Table 7) by the skidding productivity in m^3/SMH achieved by the skidding system (Figure 10). The resulting skidding costs as a function of the skidding distance are shown in Figure 11. For the unsupported skidding systems with low hourly costs in $/SMH, the unit skidding costs in $/$m^3$ were less than those for supported systems. The low skidding productivity of the Ranger skidders (Figure 10) combined with the hourly costs of the supported system (Table 7) resulted in a high skidding unit cost. In the supported skidding system with one Caterpillar 545, the high productivity was unable to compensate for the high hourly system cost, and the resulting cost in $/$m^3$ was greater than that for unsupported systems. The expected skidding costs for supported systems are discussed in the following section, "Potential payloads, productivities, and costs."

Potential payloads, productivities, and costs

The average cycle payloads in this study underwent a critical evaluation by comparing them to earlier FERIC studies on grapple skidders of similar sizes and power ranges working in unsupported systems (Kosicki 2000, 2002a, 2002b, 2003, and 2005a; Gingras and Godin 2001). For these skidders, the following indices were calculated:

- Payload in cubic metres per 1000 kg of skidder mass
- Payload in cubic metres per kilowatt of engine power
- Payload in cubic metres per 1 m^2 of the cross-sectional area of grapple

The results of calculations in Table 8 show that, except for the Tigercat 630B, indices for the skidders in the current study were less than those for skidders in previous FERIC studies. For the Ranger F68G, the indices were much lower than those for all other skidders in previous and in current studies.

For the four skidders in this study, potential loads in cubic metres were computed as products of the appropriate engine power in kilowatts and the average index of 0.049 m^3/kW established in earlier FERIC studies (Figure 12). For the Tigercat 630B, the difference between calculated and potential payloads was very small (about 3%). For

Table 7. Machine and skidding system costs in $/SMH

Machine	Cost ($/SMH) Unsupported Caterpillar 535B	Supported Caterpillar 545	Supported Ranger F68G	Unsupported Tigercat 630B
1st skidder	123	129	129	127
2nd skidder	-	-	129	-
Track skidder	-	155	155	-
Loader	-	139	125	-
Total	123	423	538	127

Figure 11. Calculated skidding cost in unsupported and supported systems.

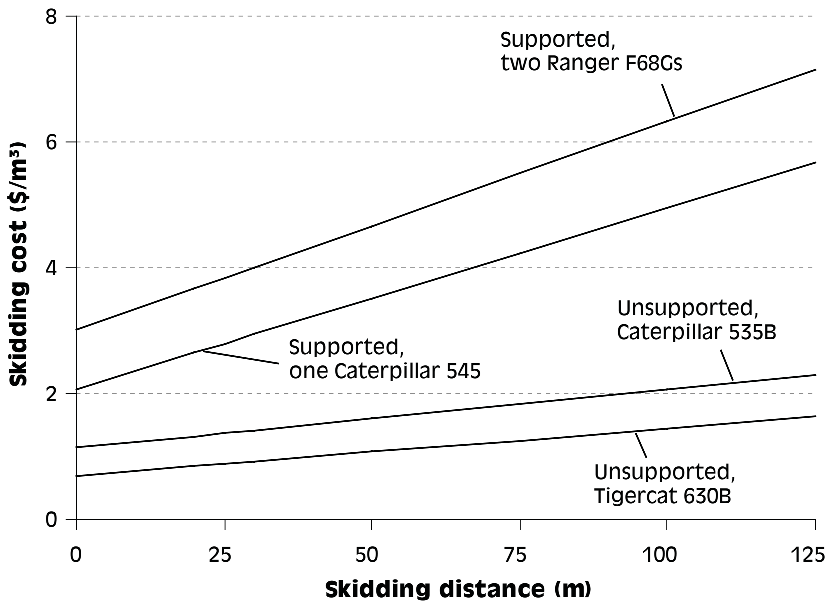
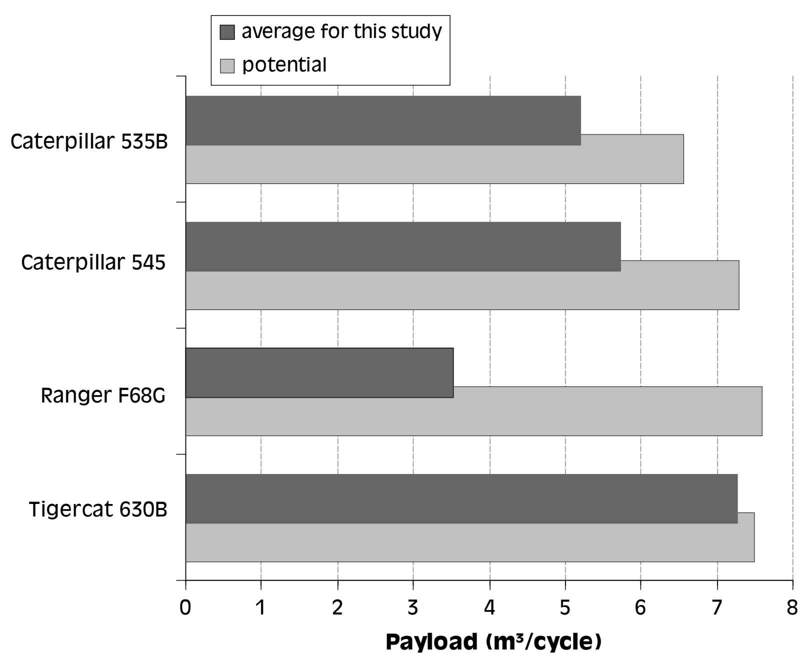


Table 8. Indices for grapple skidders in this and previous FERIC studies

		Current study			
Description	Average from earlier studies	Caterpillar 535B	Caterpillar 545	Ranger F68G	Tigercat 630B
Skidder mass (kg)	15 400	16 920	20 230	17 220	17 000
Net engine power (kW)	128	134	149	155	153
Grapple area (m^2)	1.16	1.34	1.54	1.44	1.35
Payload (m^3/cycle)	6.29	5.21	5.74	3.52	7.27
Load in m^3 per					
1000 kg of skidder mass	0.41	0.31	0.28	0.20	0.43
1 kW of engine power	0.049	0.039	0.039	0.023	0.048
1 m^2 of grapple area	5.4	3.9	3.7	2.4	5.4

Figure 12. Average payloads for this study and potential payloads in m^3/cycle.



both Caterpillar skidders, the calculated payloads were about 80% of expected payloads. The Ranger F68G's average payload of 3.52 m^3/cycle was only 46% of the payload expected for a 155-kW skidder.

The effect of the average payload in this study and the potential payload on the Ranger F68G's productivities and skidding costs are shown in Figures 13 and 14, respectively. An increase in payload from 3.52 m^3/cycle to the potential 7.60 m^3/cycle would increase the Ranger's skidding productivity by 116% and reduce the skidding cost by 54%.

The skidding productivity achieved by one Caterpillar 545 in a supported system was satisfactory (Figure 10) but, because of high hourly system costs (Table 7), the skidding costs in $/$m^3$ were greater than those for unsupported systems (Figure 11). A considerable reduction in skidding cost could be achieved if the supported system employed two Caterpillar 545 skidders (Figure 15).[4]

[4] Productivity and cost calculations included an allowance for interaction between machines in the system.

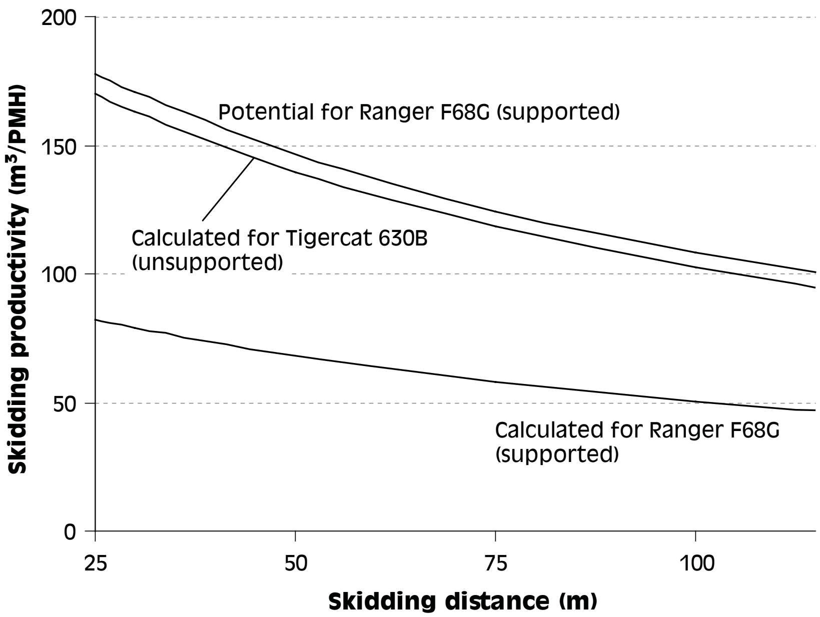


Figure 13. Calculated and potential skidding productivity for the Ranger F68G working in a supported skidding system. The production line for the Tigercat 630B was added for comparison purposes.

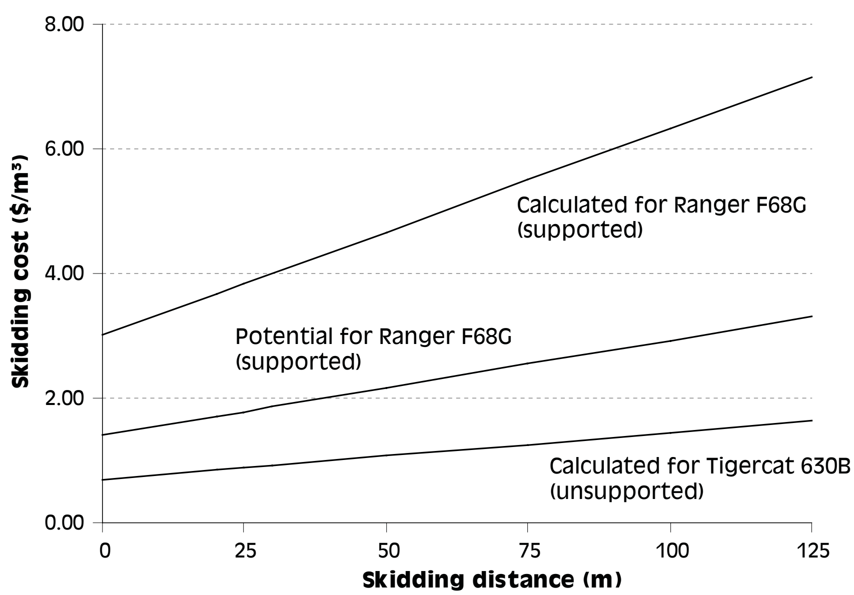
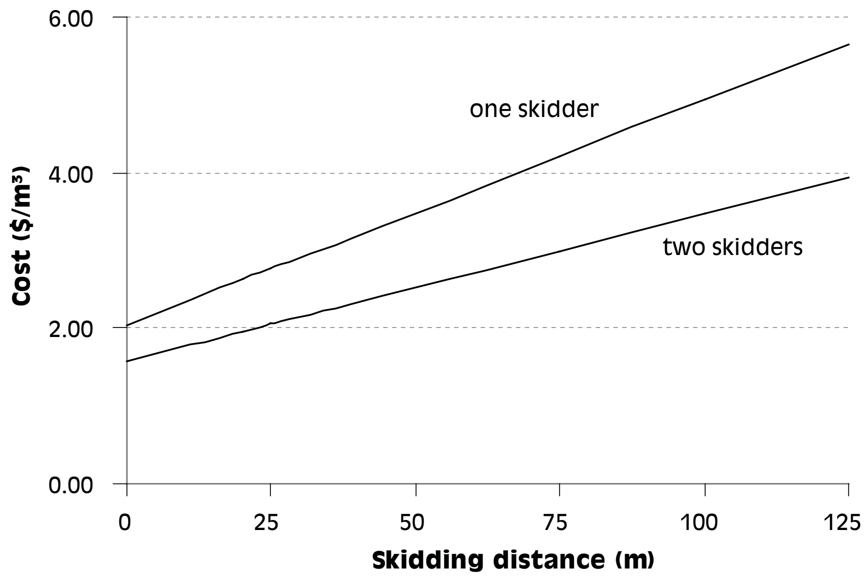


Figure 14. Calculated and potential skidding costs for two Ranger F68G skidders working in a supported skidding system. The cost line for the Tigercat 630B was added for comparison purposes.

Figure 15. Skidding cost for a single Caterpillar 545 and two Caterpillar 535s working in a supported skidding system.



Conclusions

This study highlighted several advantages and disadvantages of supported and unsupported skidding systems with wheel grapple skidders.

The advantages of an unsupported skidding system are as follows:

- The skidder works independent of other machines, and there are no interactions in the skidding cycle. The skidder's operator has high flexibility in selecting skidding routes, payload sizes, and loading and unloading sites.
- The hourly cost of the harvesting system is limited to the skidder's cost and the unit skidding cost is lower than in supported systems.

The disadvantages of unsupported systems are as follows:

- If the bunch sizes are below the skidder's capacity, multiple bunches have to be grappled to complete an adequate payload; consequently, the loading time increases. A considerable portion of the cycle time is spent decking skidded stems. Time-consuming loading and decking result in productivities that are less than those in supported systems.
- In terms of safety and cost, decking by the skidder is desirable but it requires ample room to maneuver which is not always available. To prepare higher decks, the skidder has to travel over stems or push the deck up with its blade, but these practices may result in stem breakage.
- The skidder has to extract stems from the entire block, including difficult and less accessible areas (e.g., steep portions of the block).
- Preparation of the decking area with a wheel skidder is usually difficult.
- Increased soil disturbance at the roadside can be expected.

The advantages of supported grapple skidding are as follows:

- A track skidder moves bunches to locations more accessible to a wheel skidder. Stem breakage, loading time, and skidding distance with a wheel skidder are reduced.
- If the bunch sizes are below the wheel skidder's capacity, a track skidder may optimize the wheel skidder's payload by moving appropriate numbers of bunches to a new location.
- Decking with a loader reduces cycle time, improves skidding productivity, fully utilizes the available decking area, and reduces stem breakage. Decks of appropriate height and properly placed, untangled stems with squared butts improve productivity of the processing phase.

- A loader and/or track skidder can be used to prepare the decking area and maintain skidding trails.
- If the bunch sizes are properly matched to the load capacity of the skidder, skidder productivity is greater than in unsupported systems.

The disadvantages of supported grapple skidding are as follows:

- Capital investment and hourly cost of a supported skidding operation are high. Unit skidding cost, even if multiple skidders with high skidding productivity are employed, are greater than that of an unsupported system.
- Interaction between machines increases skidding cycle times and might limit the number of skidders employed in a supported system.
- Because of the fixed location of the loader, the skidding direction may not be optimal.
- A break-down of any of the associated machines can disrupt the efficiency of the entire system.
- Landing congestion can increase safety hazards.

Implementation

The following recommendations should improve the efficiency and productivity of grapple skidding performed with unsupported and supported systems:

- In both skidding systems, the feller-buncher should prepare correctly placed and indexed bunches with volumes matching the capabilities of the grapple skidders. Felling heads with a lateral tilt of 340° or 360° allow the feller-buncher operator to prepare large bunches without reducing felling productivity.
- Wherever possible, the skidder should work independent of the auxiliary machines. An unsupported skidding system, although less productive, is more cost-effective than a supported system. Lay out and harvest blocks to minimize situations where a track skidder and a loader are required to assist the skidder.
- When contemplating skidding with supported loading and decking, take into account that supported systems are suitable for short skidding distances because the benefits of reduced terminal times (loading, unloading, and decking) on productivity and cost decrease with increasing skidding distance.
- To increase productivity and reduce skidding cost, the supporting track skidder should not only move bunches to locations more accessible to a wheel skidder, but also produce payloads that match the wheel skidder's capabilities.
- To reduce unit skidding cost in supported systems, consider the feasibility of having the track skidder and loader assist more than one grapple skidder.
- Try to employ the auxiliary machines on a part-time basis. A track skidder, instead of assisting the wheel skidder throughout all shifts, can pre-skid bunches before the grapple skidding starts. Interaction between track and wheel skidders will be eliminated, and the track skidder will have more flexibility in preparing bunches for grapple skidding.
- In difficult terrain, an early field reconnaissance of the block by the contractor, equipment operators, and supervisor will give the opportunity for all involved to analyze working conditions, strategize, and establish cooperation essential for efficient skidding with supported systems.

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Appendix I

Technical specifications for the wheel grapple skidders

Description	Caterpillar 545	Caterpillar 535B	Ranger F58G	Tigercat 630B
Engine	Cat 3306 DITA	Cat 3126 DITA	Cummins 6CTA 8.3	Cummins 6CTA 8.3
Net power (kW)	149	134	155	153
Length (m)	7.23	6.2	7.24	7.14
Width (m)	3.39	3.39	3.7	3.23
Wheelbase (m)	3.84	3.53	3.76	4.09
Ground clearance (m)	0.61	0.58	0.53	0.62
Operating mass (kg)	20 230	16 920	17 510	17 000
Travel speed (km/h)	6.2–27.5	6.2–27.5	4.3–26.9	0–17.7

Appendix II

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

	Caterpillar 535B	Caterpillar 545	Ranger F68G	Tigercat 630B	Caterpillar D5H TSK & Caterpillar 527 [b]	Link-Belt 3400 loader [c]	Caterpillar 330C loader
OWNERSHIP COST							
Total purchase price (P) $	325 000	356 000	356 000 [d]	345 000	495 000	420 000	520 000
Expected life (H) h	10 000	10 000	10 000	10 000	12 600	16 000	16 000
Scheduled hours/year (h)=(H/Y) h	2 000	2 000	2 000	2 000	1 800	2 000	2 000
Expected life (Y) y	5	5	5	5	7	8	8
Salvage value as % of (P) (s) %	20	20	20	20	25	30	30
Interest rate (Int) %	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Insurance rate (Ins) %	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Salvage value (S)=((P•s)/100) $	65 000	71 200	71 200	69 000	123 750	126 000	156 000
Average investment (AVI)=((P+S)/2) $	195 000	213 600	213 600	207 000	309 375	273 000	338 000
Loss in resale value ((P-S)/H) $/h	26	28.48	28.48	27.6	29.46	18.38	22.75
Interest ((Int•AVI)/h) $/h	6.83	7.48	7.48	7.25	12.03	9.56	11.83
Insurance ((Ins•AVI)/h) $/h	2.93	3.20	3.20	3.11	5.16	4.10	5.07
Total ownership costs (OW) $/h	35.75	39.16	39.16	37.95	46.65	32.03	39.65
OPERATING COST							
Fuel consumption (F) L/h	25	25	25	25	32	30	30
Fuel (fc) $/L	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Lube & oil as % of fuel (fp) %	10	10	10	10	15	15	15
Annual tire consumption (t) no.	1	1	1	1	-	-	-
Tire replacement (tc) $	5 200	5 200	5 200	5 200	-	-	-
Track & undercarriage replacement (Tc) $	-	-	-	-	49 500	42 000	52 000
Lifetime repair & maintenance cost as % of purchase price (P)	80	80	80	80	80	80	80
Track & undercarriage life (Th) h	-	-	-	-	5 000	8 000	8 000
Regular shift length (rsl) h	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Shift length (sl) h	10	10	10	10	10	10	10
Operator wages (W) $/h	25.83	25.83	25.83	25.83	25.83	27.32	27.32
Lifetime repair and maintenance cost (Rp) $	260 000	284 800	284 800	276 000	396 000	336 000	416 000
Wage benefit loading (WBL) %	20	20	20	20	20	20	20
Fuel (F•fc) $/h	22.50	22.50	22.50	22.50	28.80	27.00	27.00
Lube & oil ((fp/100)•(F•fc)) $/h	2.25	2.25	2.25	2.25	4.32	4.05	4.05
Track & undercarriage (Tc/Th) $/h	-	-	-	-	9.90	5.25	6.5
Tires (t•tc/h)	2.60	2.60	2.60	2.60	-	-	-
Repair & maintenance (Rp/h) $/h	26	28.48	28.48	27.6	31.43	21.00	26.00
Wages & benefits (W•(1+WBL/100)) $/h	31.00	31.00	31.00	31.00	31.00	32.78	32.78
Overtime (0.5W(sl-rsl)(1+WBL/100)/sl) $/h	3.10	3.10	3.10	3.10	3.10	3.28	3.28
Total operating costs (OP) $/h	87.45	89.93	89.93	89.05	108.54	93.36	99.61
TOTAL OWNERSHIP AND OPERATING COST (OW+OP) $/h	123.20	129.09	129.09	127.00	155.20	125.39	139.26

[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 Caterpillar D5H TSK is no longer commercially available. Purchase price used in the cost analysis is based on the Caterpillar 527.
[c] Link-Belt 3400 is no longer commercially available. Purchase price used in the cost analysis is based on the Link-Belt 249 TL.
[d] Actual purchase price for the Ranger F68G was not available. Price used in the cost analysis is based on the Caterpillar 545.

Appendix III

Regression, cycle time, productivity, and cost equations

Linear equations for travel unloaded and loaded

Equation 1: Caterpillar 545, travel unloaded		
$TE = 0.130 + 0.0105(SD)$	$n = 124$	$r^2 = 0.64$
Equation 2: Caterpillar 535B, travel unloaded		
$TE = 0.039 + 0.0097(SD)$	$n = 23$	$r^2 = 0.85$
Equation 3: Ranger F68G, travel unloaded		
$TE = 0.231 + 0.0110(SD)$	$n = 77$	$r^2 = 0.94$
Equation 4: Tigercat 630B, travel unloaded		
$TE = 0.093 + 0.0112(SD)$	$n = 64$	$r^2 = 0.96$
Equation 5: Caterpillar 545, travel loaded		
$TL = 0.214 + 0.0095(SD)$	$n = 122$	$r^2 = 0.64$
Equation 6: Caterpillar 535B, travel loaded		
$TL = 0.046 + 0.0100(SD)$	$n = 23$	$r^2 = 0.81$
Equation 7: Ranger F68G, travel loaded		
$TL = 0.168 + 0.0108(SD)$	$n = 76$	$r^2 = 0.97$
Equation 8: Tigercat 630B, travel loaded		
$TL = 0.137 + 0.0110(SD)$	$n = 60$	$r^2 = 0.98$

Where:

TE = travelling time unloaded (min)
TL = travelling time loaded (min)
SD = skidding distance (m)
n = number of observations
r^2 = coefficient of determination

Cycle time equations

Equation 9:	Caterpillar 545	$CT = 1.44 + 0.0199(SD)$
Equation 10:	Caterpillar 535B	$CT = 2.45 + 0.0197(SD)$
Equation 11:	Ranger F68G	$CT = 2.01 + 0.0220(SD)$
Equation 12:	Tigercat 630B	$CT = 2.00 + 0.0225(SD)$

Where:

CT = cycle time including in-cycle delays (min)
SD = skidding distance (m)

Productivity and cost equations

Equation 13: $SP = \frac{60(CV)(U)}{CT}$

Where:

SP = skidding productivity in m^3/SMH
CV = average volume per skidding cycle (m^3)
U = utilization (%/100)
CT = cycle time from appropriate time equation (min)

Equation 14: $C = \frac{SSC}{(SP)(n)}$

Where:

C = skidding cost in applied system ($/$m^3$)
SSC = skidding system cost ($/SMH)
SP = skidding productivity from Equation 13 (m^3/SMH)
n = wheel skidders working in the skidding system (no.)