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Assessment of a winch-assisted skidder in Castle Downs Forest, New Zealand

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EXECUTIVE SUMMARY

Winch-assist technology to enable ground-based harvesting machines to operate on steep terrain is now well-established in New Zealand. The most common configuration is an excavator or bulldozer-mounted winch or dual winch, to support a steep slope felling machine. More recently such winch-assist systems have been used to extend the operating range of grapple skidders. Objectives of this study were to evaluate the benefits of a winch-assisted skidder operation on slopes that challenge conventional skidding, to assess the impact of these operations on ground disturbance on slopes, and to determine the productivity of this system.

A winch-assisted skidder operation, using a Tigercat 632E skidder and a TimberMax winch-assist machine was studied in Castle Downs Forest, 90km north of Invercargill, New Zealand. A short follow-up study was also completed in Blackmount Forest to add additional data. The study compared the performance of the skidder with and without winch assistance. The skidder system was supported on the slope by an excavator with a grapple that pre-bunched the stems to the main extraction trail.

Productivity in cubic metres (m^3) per hour was measured over 114 skidder extraction cycles using time study methods on three extraction trails. On the lower slope in Castle Downs Forest (Path 1, 16 degrees slope) skidder productivity was compared with and without winch-assist, however on the steeper slope (Path 2, 21 degrees slope) the skidder extracted without winch-assist only. Time study data was also collected over a third extraction trail (Path 3, 23 degrees) in Blackmount Forest with winch assist on a steeper slope.

As the extraction distance increased, the cycle time of the skidder increased, and productivity decreased. There was little difference in delay-free skidder productivity between Path 1 and Path 2, at approximately 95 m^3/hr over 100m haul distance, reducing to 40m^3/hr at 300m haul distance. The slower skidder speed when using the winch on Path 1 was offset by higher average payloads and overall showed an 8% gain. However, the Tigercat / TimberMax communication system, which under loaded conditions is essential for effective operation, had problems during the study and resulted in significant delays. On Path 3, where the skidder was winch-assisted on the steepest slope, the average delay-free productivity dropped significantly to about 50 m^3/hour at 100m haul distance, due to very low skidder speeds when loaded (well below 1 metre/sec).

Assessment of soil disturbance was carried out using a line transect method. No disturbance, or slight mixing of topsoil, covered 50% of the area, and a further 40% was covered in slash. As such the site would be well protected from excessive erosion during rain events. A further 6% by area was disturbed greater than 5cm in depth and less than 15cm in depth, and this was both on the extraction trail and on tracks left in the cutover from the felling or shovelling machine. The level of deep disturbance (being greater than 15cm in depth) was low, covering less than 2% of the overall site. Deep disturbance was mainly restricted to the primary extraction trails that would be rehabilitated post-harvest by pulling slash back over the trails.

Benefits of using this winch-assisted skidding system included increasing the area of the terrain accessible with ground-based systems. In this specific case the forest owner (Rayonier Matariki Forests) and the contractor (King One Ltd) was able to change from harvesting the area with a swing yarder to harvesting with a winch-assist cable-skidder, at significant cost reduction.

INTRODUCTION

The volume of steep slope harvesting in the New Zealand forest industry is increasing in order to access plantation forest harvest areas planted on steep and difficult terrain (Visser, Raymond and Harrill, 2015). Until recently, steep terrain harvesting required significant manual input, which introduces worker safety issues. The need to eliminate, isolate, minimise, and mitigate manual harvesting hazards has motivated a major drive to full mechanisation, even on steep terrain. Over the last decade, technological progress has enabled ground-based operations to expand onto steeper slopes and for jobs to become safer (Visser & Stampfer, 2015). This has largely been achieved through the development and widespread implementation of winch-assisted harvesting - a work technique based on connecting the ground-based felling or extraction machine to a winch that gives it greater stability and climbing ability. On steep slopes, the winch provides greater traction to the assisted machine to safely traverse steeper terrain and reduces machine impacts in poor soil conditions, such as weak or saturated soils, or soils with higher clay content (Koszman, 2018; Cavalli & Amishev, 2017).

Literature has shown that winch-assist operations have resulted in improved terrain access, increased slope limit for ground-based operations, reduced length of haul roads necessary and, when used correctly have decreased soil disturbance (Visser & Stampfer, 2015; Chase *et al.* 2019; Holzfeind, 2020).

Establishing slope limits for ground-based operations has proven difficult. A study by Berkett and Visser (2012) showed that harvesting machinery working on slopes commonly exceeded the recommended maximum slopes of 30% for wheeled machines and 40% for tracked machines that were in place at the time. Since then the New Zealand Approved Code of Practice (ACOP) has modified the requirement stating that mobile plant “shall not be operated on slopes that exceed the maximums in accordance with the manufacturer’s specifications” (ACOP, 2012). The Code also states that when the stability of mobile plant is compromised by slope, weather or ground conditions then a specific hazard management plan shall be developed, implemented and monitored. This clearly places the responsibility for safe operation on the company/contractor/operator. However, few manufacturers actually specify operating limits for purpose-built harvesting machinery.

Until quite recently, winch-assist technology was used mainly for felling and bunching. Winch-assisted feller-bunchers and shovel loaders were used to prepare loads for conventional cable yarding. The need to remove the manual component from cable yarding (that is, manual hooking on the loads, known as breaking out) was achieved by equipping yarders with mechanical grapples and hydraulic grapple carriages. However, recently skidders have also been equipped with winch-assist and this configuration may offer several advantages over cable yarders. Winch-assisted skidders can operate productively on convex terrain, where there is limited deflection (or sag in the skyline), limiting the payload capability for skyline systems (Berkett, 2012), where it would be difficult for cable yarding to be productive.

Winch-assist skidders offer cost advantages over cable yarders and may offer advantages over conventional skidders without winch-assist, such as reduced soil disturbance, sustained productivity in uphill hauling, and over longer haul distances.

Some studies report that winch-assisted machines may cause less soil disturbance than other steep-terrain machines without winch-assist (Holzfeind *et al.* 2020). When operating on steep terrain, a machine without winch assist needs turning and repositioning to achieve better stability, whereas a winch-assisted machine can move straight up and down the hill and still maintain traction with the ground, thus disturbing less ground (Thompson & Hunt, 2016). Furthermore, winch-assist minimises the spinning of wheels or tracks, which is a main cause of rutting and soil compaction (Kozman, 2018). Iarocci (2017) observed this in an operation in Chile where a Tigercat 635E Skidder tethered to an Ecoforst T-Winch with approximately an eight-tonne load operating on a grade of 40-45% showed little to no ground disturbance from wheel spin. In Europe this benefit when working on sensitive soils or protected areas is a major driver for use of winch-assisted technology (Holzfeind *et al.* 2020).

Figure 1: Tigercat 632E skidder hauling logs to landing.

Use of winch-assist technology to improve access may also help to reduce the number and length of skid trails required in a harvest area, for example where trails are necessary for accessing small pockets of wood on steep slopes (Koszman, 2018). Winch-assist technology, combined with appropriate road layout, may provide more cost-effective forwarding distances, and offer an opportunity for reducing large scale haul road construction (Thompson & Hunt 2016). A study by Strimbu & Boswell (2018) of an operation in Alberta, Canada, comprising a Tigercat 635E skidder attached to a T-Winch 10.1, compared the productivity of the skidder with and without assistance from the T-Winch. The use of the T-Winch in that operation indicated savings of 1.1km of road construction. Overall, with adequate block layout and road engineering combined with the use of winch-assisted extraction systems the study indicated that road construction efforts could be reduced by half over that required for a conventional cable yarding system.

Setting up a winch-assist skidder operation requires much less time and effort than setting up a yarder operation. Even in marginal sites, when skidding uphill or in snowy conditions, a winch-assist system will be more productive and reliable than a conventional skidder system. For instance, the productivity of a winch-assist skidder may double that of a conventional skidder without winch-assist (Strimbu and Boswell 2018). Furthermore, downtime due to weather disturbance is reduced, as the traction assistance helps keep the equipment working when conventional equipment would have to stop. Koszman (2018) considered winch-assisted systems to have great application when harvesting areas during winter months, when traction issues are created from heavy snow or when extracting heavy wood.

Despite these potential advantages, most available studies of winch-assist technology have been conducted on felling machines, and there is limited information available on winch-assisted skidders. There are very few independent studies (Strimbu and Boswell 2018, Pedofsky and Visser 2019) and the studies available are essentially case studies that offer information on one machine working in one site. Ideally, with a number of such studies, the forest industry's knowledge of this new technology can be increased and a reference system provided that can help better gauge the potential of this new technology and estimate with more assurance the performance expected of a given system under stated conditions.

PROJECT OBJECTIVES

The goal of this study is to contribute to building such knowledge, by producing objective, fact-based performance data of a winch-assist skidder used in a typical New Zealand operation. In particular, the study aims to determine the impact of winch-assist on skidder productivity and soil disturbance by testing the same machine, driven by the same operator on the same trails, with and without winch-assistance.

The objectives of this study are to undertake an experimental study of an existing winch-assist skidder operation in New Zealand to improve our knowledge of the system, including:

- Examining the effect of slope, extraction distance and winch assistance on skidder performance.
- A survey to assess the ground disturbance as a function of slope gradient and winch assistance.

SITE AND SYSTEM DESCRIPTION

Forest Site

The case study was carried out in Castle Downs Forest, 90km north of Invercargill. The harvest area was 33.5 ha., of *Pinus radiata* at a stocking of approximately 725 stems/ha. Trees had an average stem volume of 0.79 m^3 with a mean tree height of 28.9m. The total recoverable volume was 530 m^3/ha.

Most of the harvest area was on slopes of less than 18 degrees (Figure 2), however there were significant areas of 22-28 slope (40-50%), which was the focus of the study. Initially the steeper area was planned for cable yarder extraction, but poor deflection in similar settings had resulted in low cable production. The other alternative was to create extensive skid trails for skidder extraction across the slopes, but this would have had detrimental environmental impacts. The use of winch-assisted skidding provided the opportunity to extract stems straight up the hill to the landing.

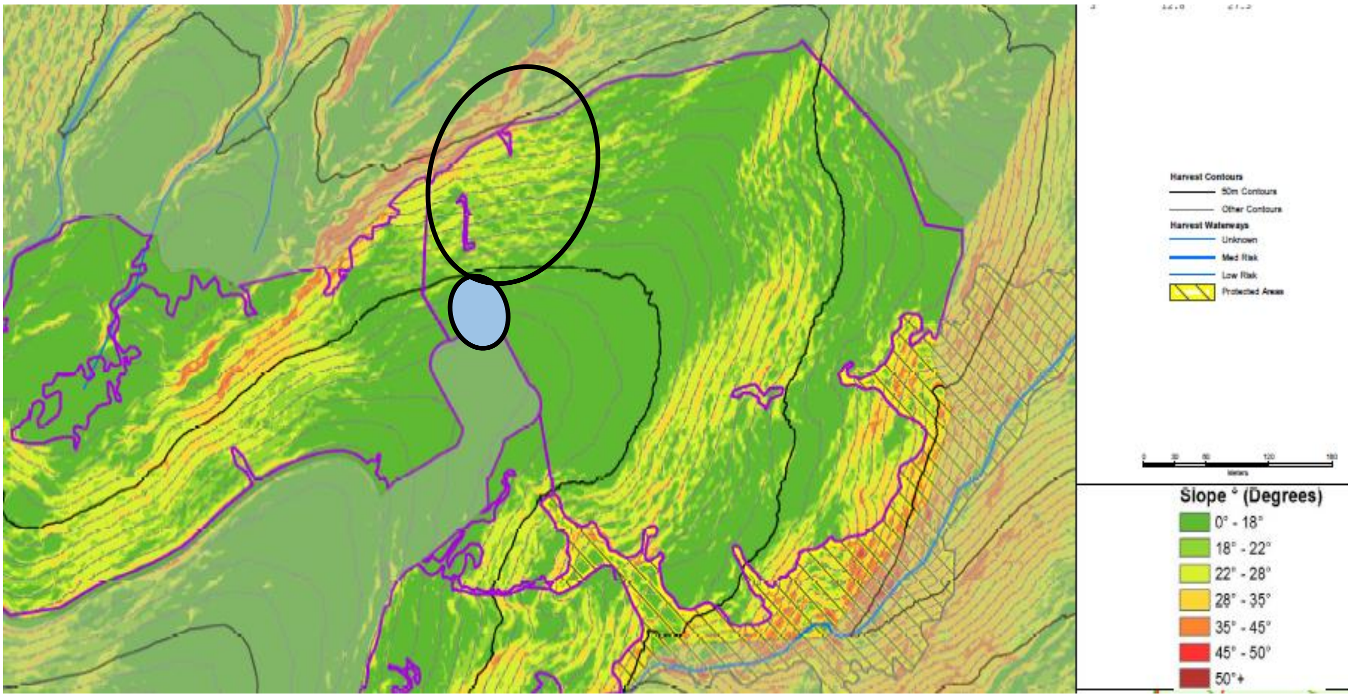

Figure 2: Section of harvest area showing slope by category. The blue circle shows location of the landing, the area circled was the skidder study.

A second site in Blackmount Forest (Path 3, 23 degrees slope) was included in the study because there was a communication system breakdown between the TimberMax winch-assist machine and the Tigercat 632E Skidder, preventing data collection with winch assist on the steeper slope (Path 2, 21 degrees, in Castle Downs Forest), which was an integral part of the study. This additional location in Blackmount Forest was chosen as the stand was similar in terms of tree size and the terrain was similar to Path 2 in terms of both slope (23 degrees) and soil type. Most importantly for the study, the same machine combination and operator was used.

Harvesting Crew Description

King One Ltd is a harvesting crew which uses mechanised felling, both winch-assisted felling and extraction, and mechanised log processing. The operation includes seven harvesting machines:

- One Tigercat 855 self-levelling felling machine
- One excavator used for shovelling/bunching
- One Tigercat 632E wheeled skidder
- One Tigercat 880 base with a Waratah 625 processor head
- Two excavator loaders with grapples for sorting and stacking logs and loading trucks
- One TimberMAX T20 traction-winch package comprising the winch unit, hydraulic components and the iWinch Control System. Unlike New Zealand made units that mount on the back of an excavator or dozer, this unit attaches to the boom of the excavator. It has a 'spike' at the base that is driven into the ground to anchor it.

The skidder operator, Brad Hammond, was very experienced with more than 10 years in forest operations and 6 years with King One operating a range of machines (Figure 3).

Figure 3: Skidder operator, Brad Hammond of King One Ltd, with the TimberMax T-20 winch assist unit

Study Site Layout

The landing that was used during the initial study at Castle Downs Forest is shown in Figure 4 (overleaf). During unloading, the skidder typically hauled the logs towards the surge pile then dropped its load, and then picked up the top end of the stems, and pulled them into the surge pile to align them with the other stems. If the skidder was able to drop the stems into the surge pile in one movement without having to double-handle then it was much quicker. However in order to keep the surge pile tidy some movement of stems was required, adding additional time to the skidder cycle. The form of the trees was poor resulting in a large volume of harvest residues.

Figure 4: Landing used during the initial study at Castle Downs Forest. The skidder was lined up with the TimberMax winch assist unit (centre). The stems were dropped to the left of the processer (shown on the right).

During the study two primary extraction paths were being used (Figure 5).

- **Path 1** (blue line in centre of Fig 5) was used for the first day's study and was about 280m in length. It had a convex profile, with the slope coming off the landing about 5 degrees slope for the first 50 m, then descending at 11 degrees slope for approximately 80m, then down the slope for an additional 150 m at 16 degrees.
- **Path 2** (red line to left of blue line in Fig 5) was used on Day Two of the study, using the same first 130m as Path 1 and then dropping off at, initially 14 degrees, then up to 21 degrees slope.

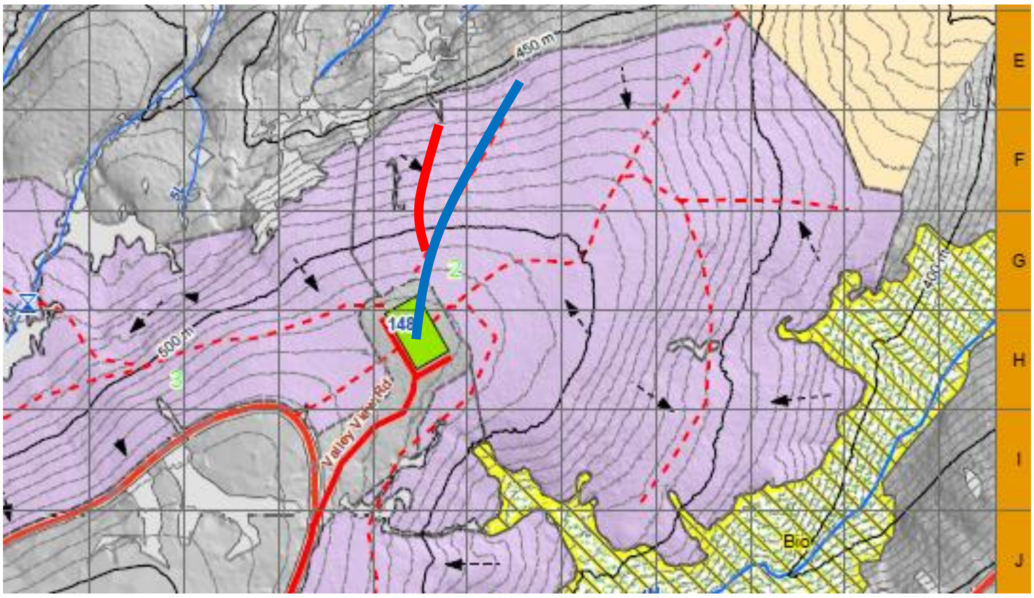

Figure 5: Harvest Plan showing the intended study area. The approximate locations of the extraction paths are shown (Path 1-blue and Path 2-red).

In Blackmount Forest, an additional extraction path (**Path 3**) was studied as it was steeper than the other two paths, being 40%, or 22 degrees slope. This path is shown on the contour map, and photo in Figure 6.

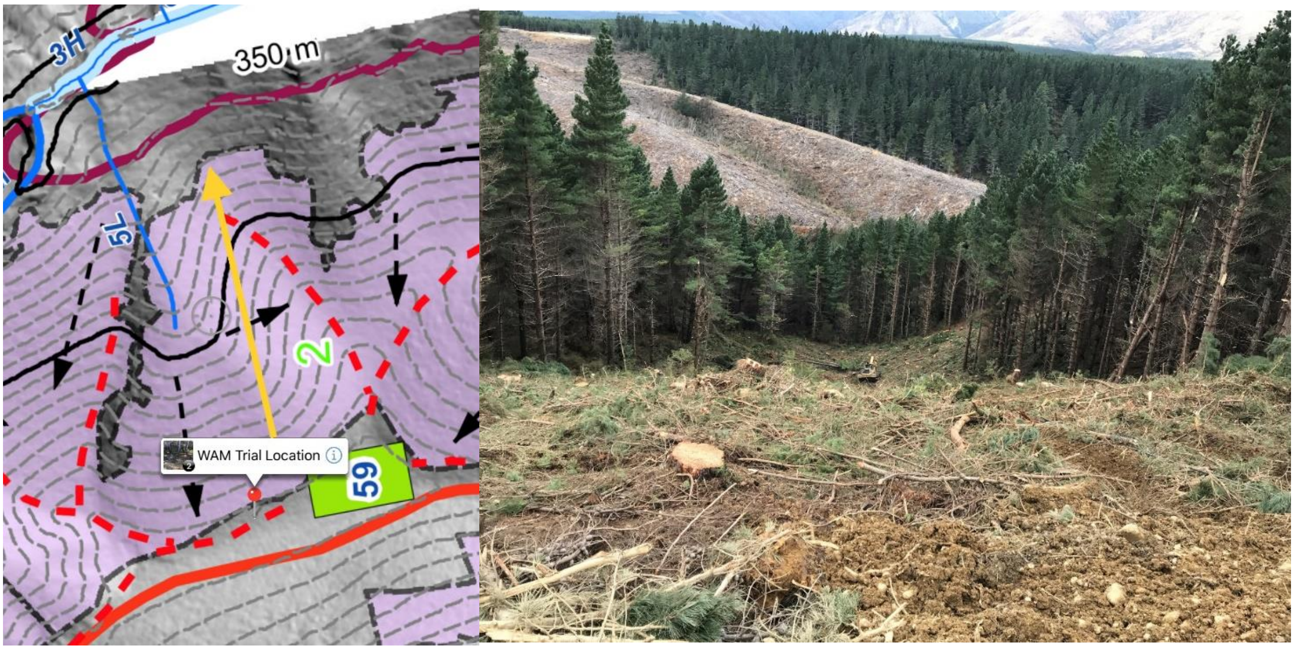

Figure 6: Section of map showing the intended harvest plan. The approximate locations of the study extraction paths are shown (1-blue and 2-red).

The TimberMax winch assist machine was set up next to the landing and directly on the edge of the slope. The excavator loader on the slope both pre-bunched the stems and helped the grapple skidder accumulate the load (Figure 7).

Figure 7: System set-up in Blackmount Forest, with the TimberMax winch-assist on the edge of the landing, and the shovel loader moving downslope to pre-bunch along the main path for the Tigercat 632E skidder.

STUDY METHODOLOGY

Time and Motion Study

A time study was carried on the winch-assist skidder to determine time consumption for each specific work element and recording the load size and extraction distance for each cycle. Each skidder work cycle was split into the following work elements:

Travel Empty: Element starts from when the skidder starts backing up after it has dropped the load and realigned its frame, and ends when the skidder stops on the cutover to pick up stems.

Load: Element starts when the skidder stops travelling, and opens its grapple and lowers its arch to reach out for a load. Element ends when the skidder begins its return journey to the landing with a full payload.

Travel Loaded: Element starts when the skidder begins its return journey to the landing with a full payload. Element ends when the skidder stops near the processor and articulates its frame to manoeuvre its load on to the surge pile.

Unload: Element starts when the skidder stops to unload stems onto the surge pile near the processor. Element ends when the empty skidder realigns its frame and starts to back up.

Delay: Delays were recorded and the reasons the operation stopped were identified. This also included operational delays such as ancillary tasks like decking or fleeting work.

Skidder Payload Volume Calculation

The number of stems in the load was recorded for each cycle. Stems were categorised as either long stems or short stems. The average volume per stem type was calculated by the processor scaling 25 stems and recording the individual merchantable volume of each stem. These stems were then ordered by descending size and the list was split based on the proportion of long and short stems in the time study counts. Then the volumes of the long and short stems were averaged separately and applied to the counts in the time study. This way, an estimate of skidder load volume was obtained without researchers needing to stop the operation at each cycle, or taking any safety risks by getting too close to the machine.

Machine Tracking

The extraction distances (m) for each cycle were measured using a laser range finder.

A GPS receiver was fitted to the skidder and recorded one data point every 5 seconds, consisting of an X, Y and Z coordinate locating position in real time. This was used to provide additional data to validate the time study data (Figure 8). The data was used to create maps of routes the skidder travelled, and cross-sectional profiles of the terrain negotiated.

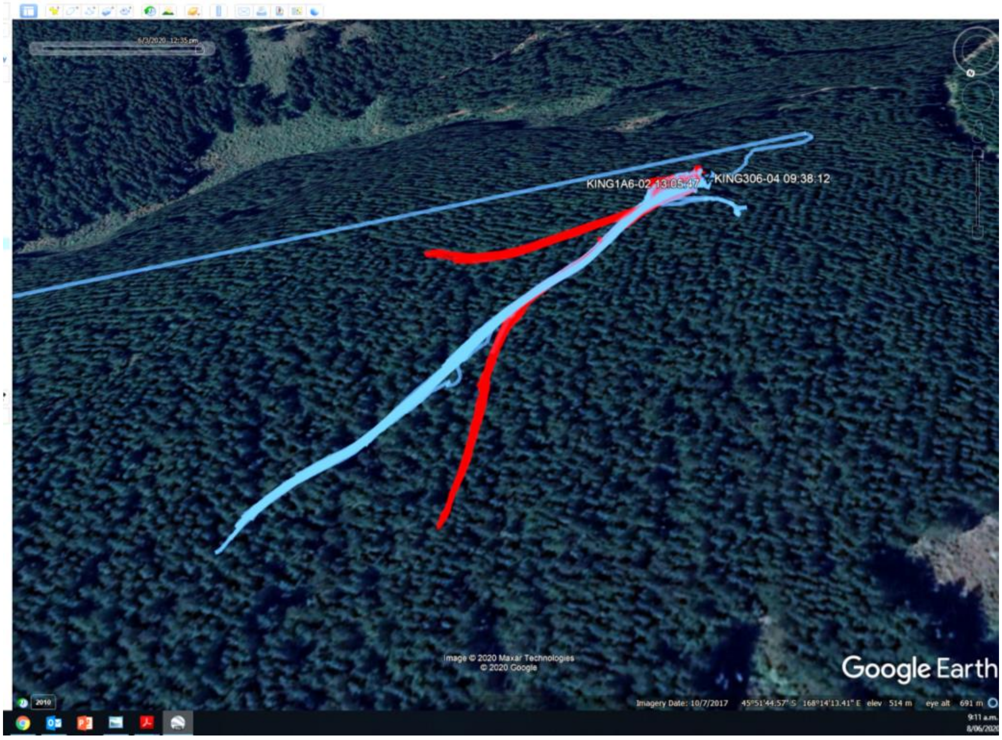

Figure 8: Winch-assisted Tigercat 632E skidder navigating 21 degree (38%) slope, was fitted with a GPS unit to track its location, speed and change in altitude.

Ground Disturbance Survey

A survey was conducted to assess the ground disturbance from the skidder with and without winch assistance. The survey was completed using the line transect method, representative of the whole study area. Visual classes were used to simplify and standardise the assessment of soil disturbance as the degree of change from natural conditions (Page-Dumroese *et al*., 2009; McMahon 1995).

The sample process involves laying out transect lines perpendicular to the main skidding direction spaced at approximately 40m. Survey points were taken at 1m intervals along the transect lines along two parallel survey lines 5m apart. The visual classes of soil disturbance were categorised into the following categories (Table 1).

Table 1: Ground disturbance classification

Class	Category	Description
0	Undisturbed	Soil remains intact and original litter still in place.
1	Shallow disturbance	Litter and topsoil have mixed, visible evidence of operation
2	Disturbance >5cm	Subsoil is exposed and deeper than 5cm compared to surrounding soil.
3	Deep disturbance >15cm	Subsoil is exposed and deeper than 15cm compared to surrounding soil.
4	Slash <30cm	Soil is covered by slash less than 30cm deep.
5	Slash >30cm	Soil is covered by slash greater than 30cm deep.
6	Non-soil	No soil, object such as tree stump or rocks.

The categories are aligned with operational considerations. Disturbance greater than 5cm is at risk of creating soil erosion, and deep disturbance, of greater than 15cm, effectively creates a gouge, or rut in the extraction trail that can readily accumulate and mobilise water flow, and hence is the category of greatest concern regarding environmental damage. As a general reference point, deep disturbance of 6% of the total area, using the greater than 15cm depth category, is considered the upper limit in Canadian forest practices on government land.

It should be noted that the ground disturbance surveys were completed before, during and straight after the extraction process. The designated skid trails were the areas where deep disturbance was most common. However, the contractor used an excavator to cover over the skid trails, including digging drainage controls (cutouts) and raking slash back onto the trail for erosion protection.

RESULTS

Productivity Calculation

Time study and skidder payload data were collected by observing 114 skidder cycles over 3 days, distributed as follows: Path 1, winch assist = 18 cycles; Path 1, no winch assist = 39 cycles; Path 2 no winch assist = 23 cycles; Path C, winch assist = 34 cycles. Mean descriptive statistics are shown in Table 2.

Table 2: Descriptive statistics: mean data

Path	No.	1	1	2	3
Gradient	Degrees	16	16	21	23
Winch assist	Y/N	Yes	No	No	Yes
Observations	Cycles	18	39	23	34
Distance	Metres	159[a]	224[b]	192[c]	94[d]
Travel empty	Sec (s)	90[a]	74[b]	67[c]	62[c]
Load	Sec (s)	9[a]	15[b]	9[a]	17[b]
Travel loaded	Sec (s)	114[a]	194[b]	164[c]	192[b]
Unload	Sec (s)	28[a]	13[b]	12[b]	42[c]
Total Cycle	Sec (s)	241	296	252	407
Load size	Pieces	7.1[a]	5.4[b]	4.9[b]	3.3[c]
Load size	m3	5.8[a]	4.3[b]	3.9[c]	4.7[b]
Productivity	m3/PMH	86.6	52.3	55.7	41.6

Note: if denoted by different superscript letters, the mean values in the same row are statistically different

Table 2 shows that the skidder covered different distances over different paths, and these differences introduce a significant bias when trying to compare cycle time and productivity figures across treatments. Load volume is the only parameter among those reported in Table 2 that could be independent of the extraction distance.

The raw data were used to model skidder performance to repeat the comparison under standardised conditions. The skidder cycle was split into the following time elements:

- Travel empty
- Load
- Travel loaded
- Unload

The sum of the time used to complete these elements make up the total cycle time. Productivity in cubic metres (m^3) per productive machine hour (PMH) is then calculated as:

$$(3600/\text{Cycle time in seconds}) * \text{Load in } m^3$$

This represents productivity, excluding all delays, expressed as m^3 /PMH_0

To standardise the comparison for equal extraction distances, travel speed was calculated separately for the travel empty elements and the travel loaded elements.

Therefore, data analysis consisted of finding the relationship (if any) between cycle time, load size, slope gradient and winch assist treatment (Yes or No). This was tested using the General Linear Model technique, which is especially robust against violations of the parametric assumptions and can deal with uneven number of observations (unbalanced datasets).

Travel speed

The results for travel speed are shown in Table 3.

Table 3: Descriptive statistics: skidder travel speed

Path	No.	1	1	2	3
Gradient	Type	Moderate	Moderate	Steep	Steep
Winch	Y/N	Yes	No	No	Yes
Travel empty	m/s	1.78[a]	3.05[b]	2.90[b]	1.53[c]
Travel empty	km/h	6.4	11.0	10.4	5.5
Travel loaded	m/s	1.39[a]	1.17[b]	1.18[b]	0.51[c]
Travel loaded	km/h	5.0	4.2	4.2	1.8

Note: if denoted by different superscript letters, the mean values in the same row are statistically different

Essentially, skidder travel empty speed (downhill) was 71-90% faster without winch-assist, regardless of slope gradient. The interaction factor “winch assist” x “slope gradient” is not significant and the winch-assist treatment alone explains over 80% of the variability in the data (Table 3).

Conversely, skidder travel loaded speed (uphill) is significantly affected by both the winch-assist treatment and slope gradient, and by their interaction. In particular, when working on the moderate slope, winch assist allows a significant increase of both travel speed (from 4.2 km/h to 5.0 km/h) and load size from 4.3 m^3 to 5.8 m^3 (evidenced by the high significance of the interaction factor).

On the steeper slopes, winch assist allows an increase of load size (from 3.9 m^3 to 4.7 m^3) but cannot prevent a severe drop of travel loaded speed (from 4.2 km/h to 1.8 km/h). Conversely, without winch assist, travel loaded speed remains relatively high on both the moderate and the steep slope (4.2 km/h) – but load size also drops (from 4.3m^3 to 3.9m^3). Therefore, under the conditions of this study, winch assist appears to have a specific impact on payload capacity more than on mobility.

Table 4: General Linear Model statistics for travel speed

	Effects	DF	SS	Eta	F	P
Empty Speed	Winch assist	1	53.7	81%	445	0.000
	Slope	1	1.03	2%	10.6	0.001
	Winch*Slope	1	0.078	0%	0.77	0.384
	Error	110	11.1	17%		
Loaded Speed	Winch assist	1	4.53	32%	56.4	0.000
	Slope	1	3.10	22%	337	0.000
	Winch*Slope	1	5.01	36%	379	0.000
	Load size	1	0.00	0%	3.49	0.064
	Error	109	1.44	10%		

Loading, unloading and load size

The results for loading, unloading and load size are shown in Table 5.

.

Table 5: Descriptive statistics: loading, unloading and load size

Path	No.	1	1	2	3
Gradient	type	Moderate	Moderate	Steep	Steep
Winch assist	Y/N	Yes	No	No	Yes
Load	Sec (s)	9^a	15^b	9^a	17^b
Unload	Sec (s)	28^a	13^b	12^b	42^c
Pieces	No.	7.1^a	5.4^b	4.9^b	3.3^c
Volume	m^3	5.7^a	4.3^b	3.9^{bc}	4.7^c

Note: if denoted by different superscript letters, the mean values in the same row are statistically different

Loading time is not affected by slope gradient or winch assist treatment, and only the number of pieces per load had an effect on loading time (Table 5).

Regression analysis indicated that loading time decreased, not increased, with the number of pieces in a load – although its effect is very small:

Loading time (s) = 14.1 – 0.37 No. pieces (R^2 = 0.01). The most likely explanation is that when the loading time was shortest, that was because the skidder was being fed by the shovel, which was bunching the stems on the slope.

In contrast, unloading time is only affected by the winch assist treatment, explaining over 50% of the variability in the dataset. The explanation is the different arrangement at the landing once the winch is installed, with the need not to run over the cable and the presence of an anchor machine. This likely leads to more manoeuvring on the way in and/or out of the unloading place. Therefore, for the purpose of modelling, two levels of unloading time were selected, corresponding to the average values under the winch and no-winch treatments: these are, respectively 37s and 13s.

Finally, load size was affected by winch assist treatment, slope gradient and their interaction – as expected. The results are logical and indicate that using the winch assist always resulted in a significant increase in load size, both on moderate slope (from 4.3m^3 to 5.7 m^3, a 33% increase) and on steep slope (from 3.9m^3 to 4.7m^3, a 20% increase). In contrast, moving without winch assist from a moderate to a steep slope resulted in a drop in load size – from 4.3m^3 to 3.9m^3 almost a 10% reduction.

Table 6: General Linear Model statistics for loading, unloading and load size

	Effects	DF	SS	Eta	F	P
Loading	Winch assist	1	28.0	0%	0.01	0.921
Time	Slope	1	5.98	0%	3.01	0.085
	No. pieces	1	700.1	8%	9.8	0.002
	m^3	1	45.3	1%	0.65	0.424
	Error	109	7658	91%		
Unloading	Winch assist	1	17286	52%	65.85	0.000
Time	Slope	1	877.3	3%	3.1	0.081
	No. pieces	1	12.8	0%	0.09	0.979
	m^3	1	3.00	0%	0	0.761
	Error	109	15105	45%		
Load	Winch assist	1	21.9	19%	43.25	0.000
m3	Slope	1	13.3	11%	19.97	0.000
	Winch * Slope	1	2.97	3%	4.1	0.045
	Error	110	79.8	68%		

For modelling, the average load size figures in Table 5 were adopted unmodified. A caveat must be issued about the different piece size recorded for Path 3, which was in another forest, since it was not possible to test all treatments in exactly the same compartment and forest due to logistical reasons. Apparently, tree size in this second compartment was much larger than in the first one, namely: 1.5 m^3 vs. 0.8 m^3. This might have affected the results of the study, if it was not for the fact that loads were pre-bunched by a shovel that tried to build single accumulations matching the optimum for the skidder under the specific conditions. Larger trees would imply less flexibility when fine-tuning load size, since the shovel could only add or subtract 1.5 m^3 increments, as an average. Whatever the alignment between bunch size and load capacity, the effect would be reflected in the combination of load size and travel speed, both of which are included in this model. Therefore, while the model may or may not accurately represent best practice, it does accurately represent the observed practice in this study.

Standardized comparison

The simulated standardized comparison was conducted using the parameters described just above and is depicted as Figure 9.

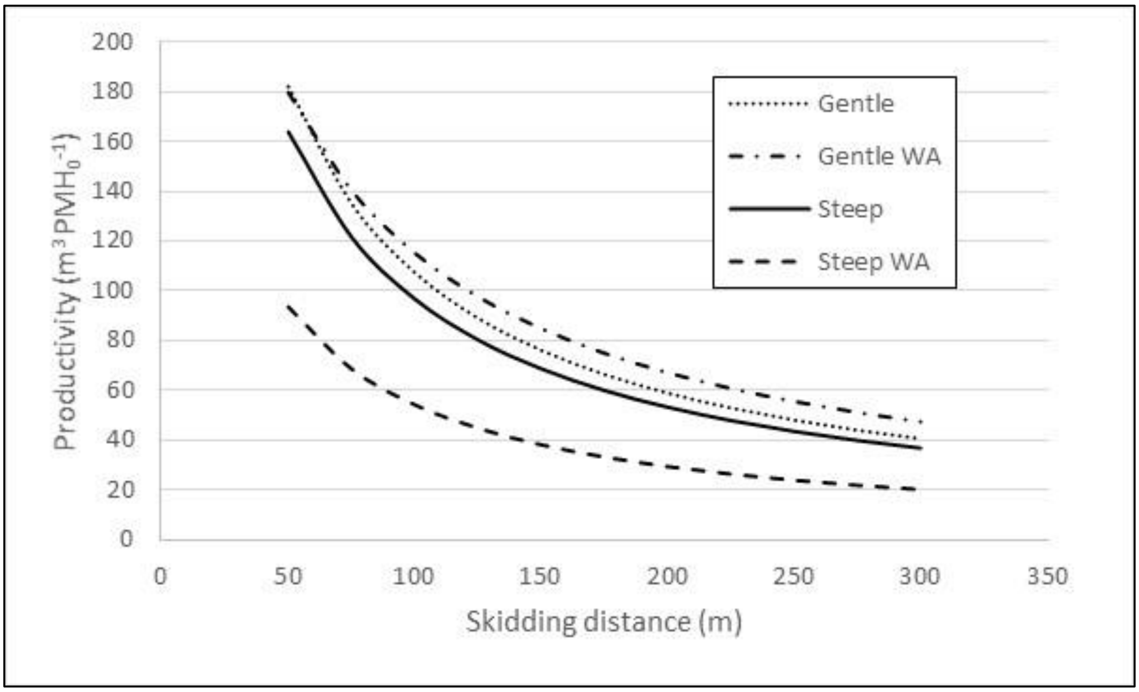

Figure 9: Delay-free productivity as a function of distance, slope gradient and winch-assistance

Winch assist seems to pay off on the gentle slope, but not on the steeper one. In both cases, winch assistance resulted in a decreased travel speed and an increased payload size: while on the gentle slope the payload increase was much larger than the speed reduction, the contrary was true on the steeper slope.

The results seemed to indicate that there is a 'sweet spot' for winch-assisted skidding, in the 15° range, where winch assist allowed for a dramatic increase in payload. As slope gradient increased, it seemed best to reduce payload than trying to maintain (or increase) it with the aid of a winch. Winch-assisted uphill skidding on slopes in the 20° range did not seem to pay off: while it allowed maintaining a large payload, it caused such an increase in cycle time that productivity dropped dramatically – productivity dropped even more than caused by a 20% reduction of payload.

Tension Monitoring

Similar to other winch-assisted machines, it was not possible to download tension data, although tensions are continuously monitored for the effective operation of the system. The TimberMax does have a feature in its operating system that allowed the operator to visualise the tension data characteristic in the form of a bar chart. For the duration of the Blackmount Forest (Path 3) part of the study, that chart is shown in Figure 10. It indicated that the downhill/unloaded phase had tensions in the range of 4 to 10 tonnes (40 to 100 kN). In the uphill/loaded phases the tension ranged between 16 and 20 tonnes (160 to 200 kN). These settings reflected contractor/operator preference of running the winch assist system at relative high tensions.

Figure 10: Tension data as recorded during the Blackmount part of the Study.

Speed and Elevation Tracking using GPS

With the skidder movement tracked by a GPS unit, it was also possible to overlay the skidder path on a GoogleEarth map (Figure 8), from which the Path 1 and Path 2 became visible. GPS also allowed elevation changes to be recorded (Figure 11). This was easily matched to the cycles in the time study. The main difference between the two measurement methods (real time GPS and time study) was that the time study made it possible to obtain a record of load size and to identify the different cycle elements. The latter could also be deduced from the speed graphs, but with more effort and uncertainty. On the other hand, GPS data offered more detailed information on speed, which could be calculated at 2-5 seconds intervals, or approximately fifteen and thirty times per trip, depending on whether the trip was unloaded or loaded.

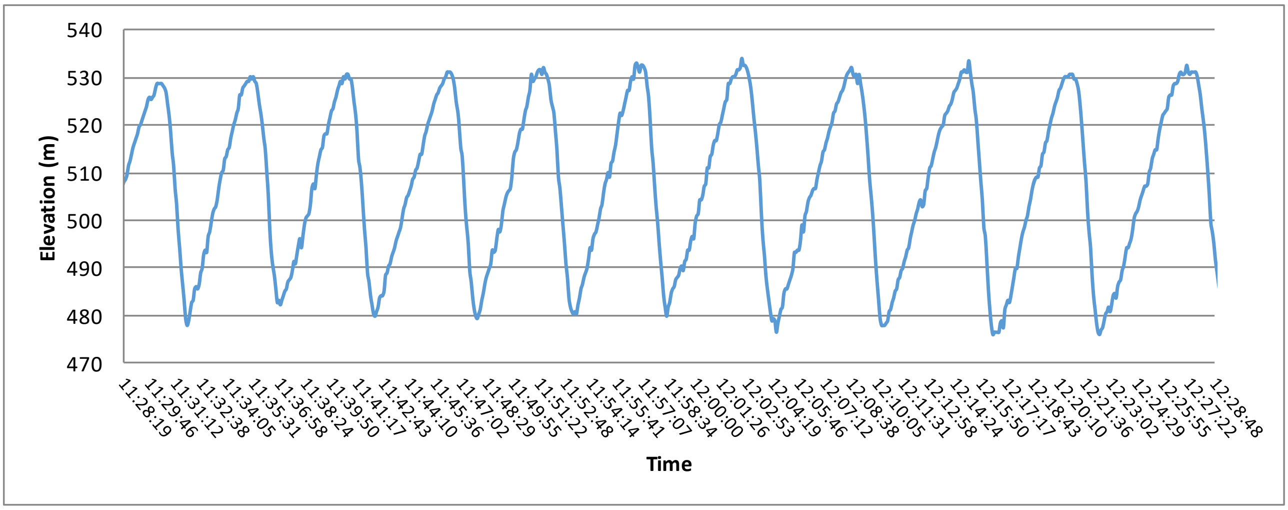

Figure 11: Skidder elevation changes of from one period on Day 1. Each sinus curve is one extraction cycle: the skidder descends to pick up the load (dip), then comes back up to take its load to the landing (peak).

The speed graphs offered a detailed insight into skidder movements (Figure 12).

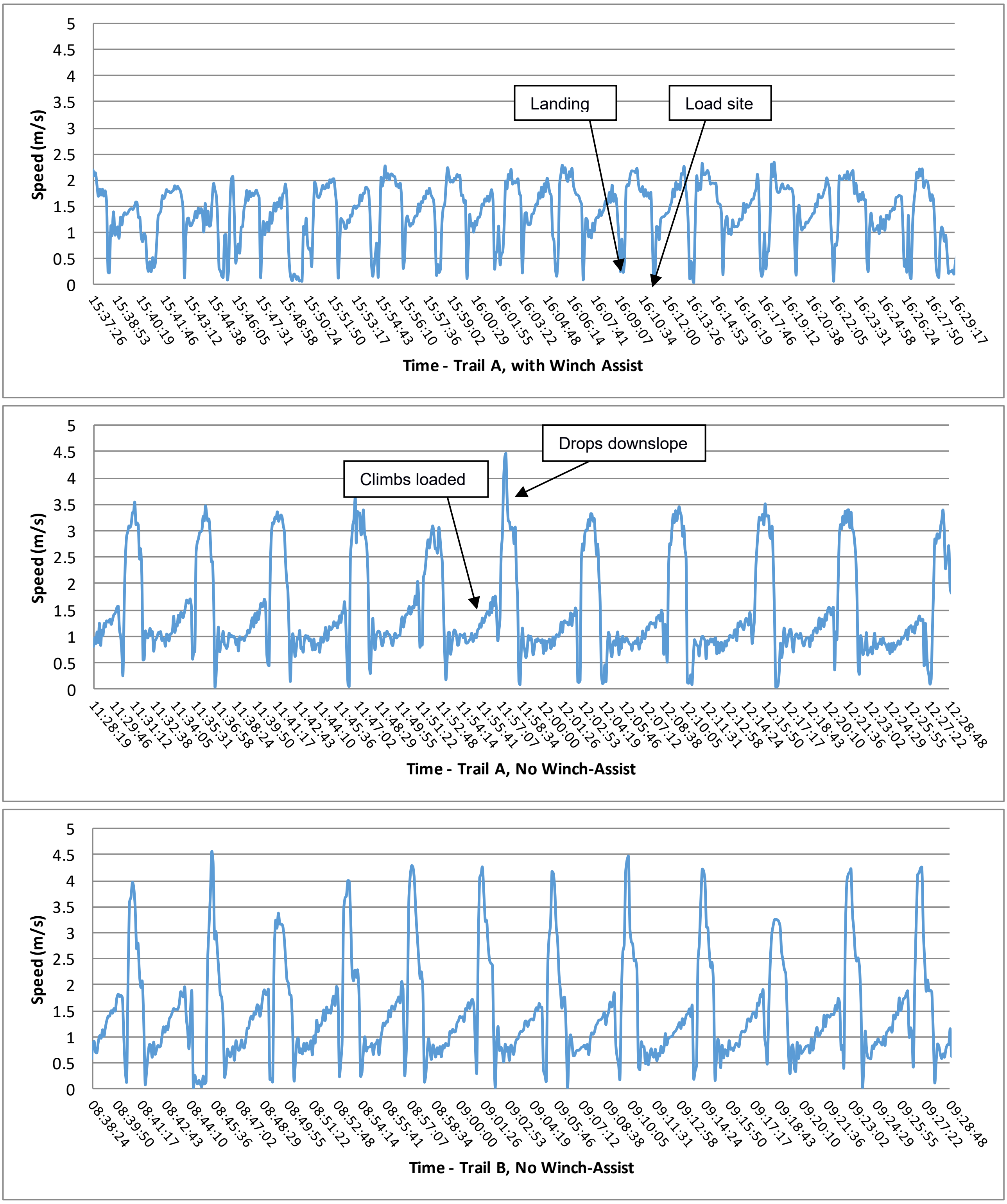

Figure 12: Skidder speed charts. They show the high peak and fast speed ramp on the travel empty down the hill and the much smaller peak and slower speed ramp as the loaded skidder struggled uphill.

The speed charts show steep speed peaks for the machine travelling fast downhill followed by a sudden halt for picking up the load and slowly increasing speed as the loaded skidder moves uphill onto an increasingly gentle slope, all the way to the surge pile.

Data collected with the GPS are generally consistent with those obtained from the time study: both find that travel empty speed is much lower under the winch assist treatment, while it does not change significantly with the gradient of the Path when the skidder worked without winch assistance (within the slope gradients explored in this study). Conversely, loaded speed was higher for the winch assist treatment (peaks at ca. 2 m/s vs. 1 m/s).

Figure 13 shows the skidder velocity chart for the Blackmount site (Path 3), where it is clearly visible that the lower travel empty (downslope) speed averaged about 1.5 m/s compared with 2 m/s, but also the very dramatic drop in loaded velocity which averaged just 0.5 m/s, compared to 1.5 m/s on the more gentle slope.

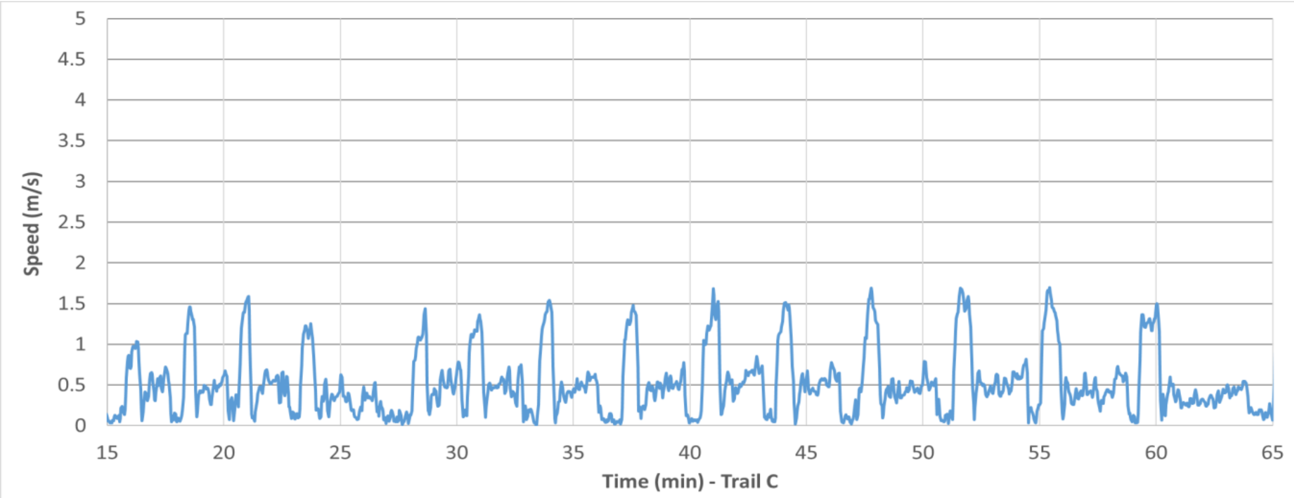

Figure 13: Skidder speed chart for Blackmount (Path 3) where the skidder was winch-assisted by the TimberMax on the steeper slope.

Delays

Unfortunately the study was plagued by repeated breakdowns of the winch assist system, which eventually prevented testing the winch-assist treatment on the steeper Path 2. Over the 2 days of the study, total delays amounted to 3.3 scheduled machine hours or 30% of total time. However, the skidder was also able to operate without the winch. Of these delays, two-thirds were represented by mechanical delays, mostly winch malfunction. During the two days the winch-assist unit was only functional for 1.3 hours, representing a mechanical availability of only 11%. Figure 14 shows the breakdown of total time as recorded over the two days of the study.

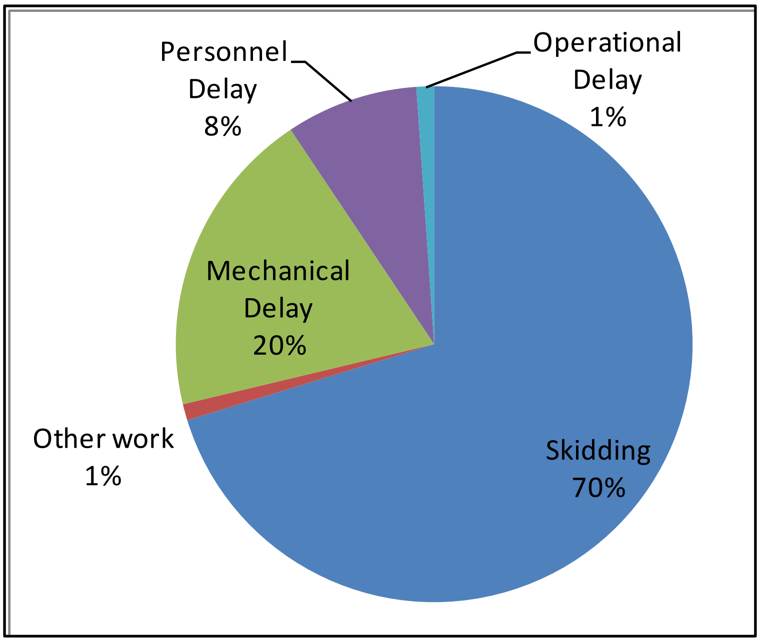

Figure 14: Breakdown of worksite time delays experienced over the study period

While "skidding" comprises skidding work only (i.e. travelling to the loading site, picking up a load and dropping it onto the surge pile), the "other work" category represents ancillary work, such as decking the stems or picking up slash for returning it to the cutover.

Operational delays were mostly represented by short waiting pauses in front of the surge pile as the processor was engaged with managing stems. The relatively long personnel delay is represented by a lunch break, which some operators include as part of the scheduled (paid) worksite time and others do not.

Soil Disturbance

The soil disturbance assessment was carried out using a line transect method. Table 7 below shows the data collected. The same data are reported graphically as Figure 15.

Table 7: Soil disturbance results collected at main study site before and after to extraction

Transect	Skidding	Not Disturbed	Mixing	>5cm rut	>15cm rut	<30cm slash	>30cm slash	No Soil
1	Before	35%	22%	6%	2%	21%	14%	2%
1	After	14%	37%	10%	2%	16%	20%	1%
2	Before	30%	15%	4%	2%	19%	28%	1%
2	After	21%	31%	6%	3%	28%	10%	2%

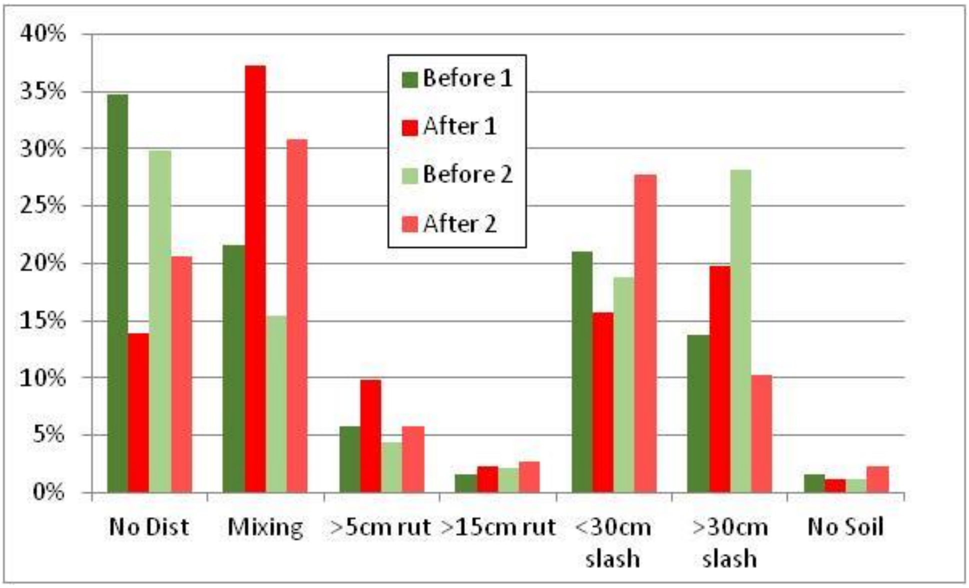

Figure 15: Soil disturbance recorded over the two transects before and after skidding

Before skidding, 'slash' accumulations and 'no disturbance' were the most represented soil state classes, whereas after skidding the most represented were 'soil mixing' and - again – 'slash' accumulation. Essentially, skidding resulted in a sharp increase of soil mixing and a small but steady increase of rutting. However, rutting was relatively infrequent and deep rutting was contained well below the 5% bar, even after skidding. The overall incidence of slash accumulations remained approximately the same before and after skidding: what varied was the thickness of the observed accumulations. However, this result was inconsistent, as the proportion of thick accumulations increased after skidding in one transect and decreased in the other, followed by a compensatory decrease (or increase) in the proportion of shallow accumulations. Overall, the surface area covered by slash remained the same.

Figure 16: example of shallow / 'mixed' disturbance.

Figure 17: Skid trail Path 1 in operation, leading down to the shovel. The deep disturbance measure was almost exclusively from the main skid trails

Figure 18: Example of slash < 30cm. The slash is thick enough to obscure the ground, but would not necessarily affect planting.

Figure 19: Soil disturbance at a location where the shovel was working and feeding the grappled skidder

For further assurance, two more transects were inspected in the adjacent area where harvesting had been completed and no further activity was being undertaken (Table 8). Again, the incidence of rutting was very small, especially regarding deep rutting (>15 cm).

Table 8: Soil disturbance results collected in the adjacent area after harvesting had been completed

	Not disturbed	Mixing	>5cm rut	>15cm rut	<30cm slash	>30cm slash	No Soil
Transect 1	22%	25%	7%	3%	35%	9%	2%
Transect 2	32%	26%	8%	4%	43%	18%	4%
Overall	23%	22%	6%	3%	33%	11%	2%

These figures match relatively well with the after-skidding figures recorded over the study area (Figure 20). In fact, the completed area show a higher incidence of shallow accumulations and on undisturbed soil, and a lower incidence of mixing and heavy accumulations, as it could logically result from cleaning and broadcasting the heaviest accumulations. So, at the end of harvest more area would be covered by slash (hence less soil mixing visible), but with a thinner mat.

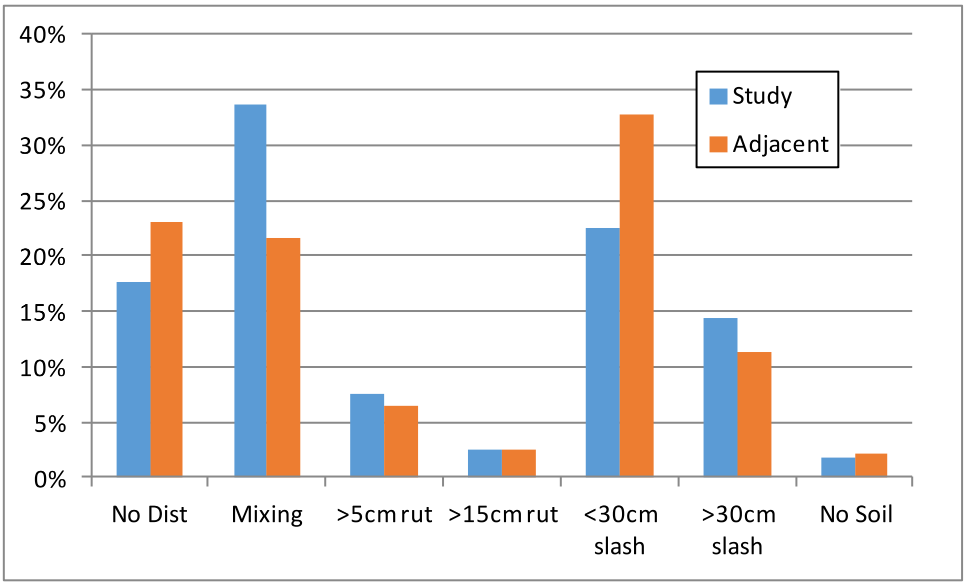

Figure 20: Overall soil disturbance on the study site (after skidding) and on the adjacent area where harvesting had been completed

Figure 21: Post-harvest next to skid trail 1 – the site is left very clean.

Figure 22: Slash is pulled back over the skid trail after extraction is complete.

DISCUSSION

The study indicated that winch-assisted skidder harvesting offers significant productivity boost of about 20% on relatively moderate slopes, despite longer total cycle time due to increased payload capacity. This result is similar to that reported by Strimbu and Boswell (24%) in a similar comparison study conducted in Canada. However, on steeper slopes this combination of machines and conditions yielded a lower productivity in m^3/PMH, due to slower travel speeds, despite increased payload. This indicates such systems perform better on easier terrain slopes (30% or 16 degrees) rather than steeper slopes (40% or 22 degrees).

In general, these results appear to corroborate previous studies. For instance, the productivity recorded in this study of 70 to 90 m^3/PMH over distances ranging from 150 to 200 m for the gentler slope fall between results of 80-100 m^3/PMH reported by Pedofsky and Visser (2019) and results reported by Strimbu and Boswell (2018) of 50-60 m^3/PMH for the same range of distances. The lower productivity of 30-40 m^3/PMH for the steeper slope was caused primarily by the very slow travel speeds both uphill loaded and downhill empty.

The results of load size estimates, ranging from 3.9-5.8 m^3, which were estimated based on stem counts, are similar to those reported by Strimbu and Boswell (2018), ranging from 4.6-5.7 m^3, however Pedofsky and Visser (2019) reported much larger payload figures (7-8 m^3).

Similar corroboration is obtained for site impact; although the studies used three slightly different soil disturbance assessment methods. All studies indicated that deep rutting is generally limited: 9% in this study vs. 12% in Pedofsky and Visser 2019, and 8-10% in Strimbu and Boswell 2018. The latter study was the only one offering a direct comparison of winch-assist vs. conventional in terms of site disturbance and indicated a reduction of ca. 25% of soil scalping and rutting when under the winch-assist treatment. Unfortunately, this study could not offer a similar comparison because both treatments - winch-assist and conventional - were tested over the same skid trails.

This study, and those quoted above, indicate that the introduction of winch-assist can produce a significant productivity increase in specific conditions. This study did not quantify the impact of operational delays associated with aspects such as relocating the winch assist anchor machine, or working with the ropes, nor did it contain a cost/benefit analysis.

At this stage, the main hurdle seems to be the limited reliability of the equipment, which presented serious interface problems during this study. Anecdotal evidence point at similar problems being experienced after this study. Similar problems of the kind have been experienced with commissioning new equipment. It is expected these problems will be solved over time.

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