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Steep Slope Feller Buncher:
A Feasibility Study

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The primary purpose of the Future Forests Research (FFR) Harvesting theme's Objective 1 is to reduce the cost of harvesting on steep country by improving the capability of machines to fell and bunch trees on steep terrain. The aim of this project (Task 1.1) is to further develop the tractive capacity of ground-based machinery on steep terrain.

Felling and breaking out are two of the most dangerous harvesting tasks. To a large extent, removal of people from the hazardous working environment has been accomplished on flatter sites due to the introduction of mechanised felling machines and grapple skidders. However, the inability to use such machines on steeper slopes has largely meant that these dangerous tasks are still carried out manually in cable logging. A key focus of the FFR Harvesting research programme has been improving health and safety, and the financial viability of harvesting in steep country in New Zealand with existing harvesting systems.

Worldwide, considerable effort has been put into the development of a suitable and versatile steep terrain logging system. As a result, several steep terrain harvesters have been developed and trialled with varying success – walking excavators, quad-track crawler harvesters, self-levelling dual track feller-bunchers, teleoperated harvesters and ground carriages. This report summarises some of these developments and investigates the feasibility of a traction assist winch system into harvesting machines such as wheeled harvesters and forwarders. A recent development in New Zealand (less than five years in commercial use) has been the implementation of a winch system into dual track feller-bunchers and excavators.

This project aims to further develop the prototype steep terrain feller buncher developed by FFR Programme co-investors Kelly Logging Ltd and Trinder Engineers. The purpose of this prototype is to minimise safety risks for the tree faller/operator, to achieve increased production volumes and provide the opportunity for bunching of the felled stems. The ultimate goal of bunching is to increase hauler payload and reduce grapple/hook-on element time. This will achieve increased total logging system productivity, and improve profitability of the operation.

The first prototype steep terrain harvester (the alpha prototype) showed a 60% increase in the number of trees hauled per cycle with mechanically felled and bunched wood versus unbunched wood. There was a 26% increase in daily productivity over the system with manual fallers. At the estimated total steep terrain harvester cost value ($900 K), the system would have to be used for more than 59% of the equipment lifetime to justify its purchase and implementation. Substantial gains are achieved by increasing the proportion of time that the system is used effectively, and can amount to almost $\$3/m^3$ savings if used 100% of operating time.

One of the benefits of the mechanised system was in increasing the number of productive machine hours of the yarder to 7 PMH/day resulting in a 47% productivity gain compared to a manual faller/breaker out system. With this productivity increase, the break even usage for the steep slope harvester was only 37% of the time. The system has the potential to reduce the effective logging rate by more than 20% (or more than $\$5/m^3$) if the system is effectively used on 100% of the harvest area. System profitability was sensitive to purchase price of the steep slope harvester, as well as to the productivity gains that resulted from effectively implementing the technology.

INTRODUCTION

The forest industry has identified harvesting on steep country as a priority, to reduce costs by improving productivity, and improve the safety of harvesting by reducing workers' exposure to harm. This requires a concerted collaborative research effort between industry and government to improve the profitability of forestry. As harvesting moves to steeper land (>20% slope) and smaller more isolated forests across New Zealand, the challenges of maintaining international competitiveness using existing logging methods that have changed little in 50 years will mount.

Overseas harvesting research and equipment development is focused primarily on mechanised operations on flat terrain. New Zealand's unique combination of soils, terrain, climate, forest type and infrastructure means we cannot rely on overseas research to solve our problems. A further reason for undertaking this programme is to address the current shortage of skilled people to work in physically demanding, difficult and dangerous situations that occur in harvesting on steep terrain. Our aim is to find ways of eliminating the most dangerous and physically demanding jobs and making the work more attractive to new entrants to the forest industry.

The Programme has been divided into three interrelated objectives:

1. Mechanisation on steep terrain.
2. Increased productivity of cable extraction.
3. Development of operational efficiencies.

The primary purpose of FFR's Harvesting theme Objective 1 is to reduce the cost of harvesting on steep country by improving the capability of machines to fell and bunch trees on such terrain. This can be achieved by accumulation of felled stems or logs and their presentation for attachment to the hauler grapple/carriage. FFR project Task 1.1, Steep Slope Feller Buncher, is a component of Objective 1 which addresses the capability of ground-based machinery to operate on steep terrain. The prototype steep slope feller buncher system (the "Kelly Logging System"), designed by Programme co-investors Kelly Logging Ltd and Trinder Engineers, is capable of operating safely on slopes over 45 degrees on a range of soil types. The specific aim of this project (Task 1.1) is to further develop the tractive capacity of the steep terrain feller buncher.

This report summarises developments in steep slope harvesting and investigates the feasibility of a traction assist winch system integrated into harvesting machines.

METHODS

The first stage of this project was an economic and technical feasibility study of a technological solution, namely a further-developed steep slope feller buncher. A feasibility study is an investigation into whether or not a proposed development is possible, and how successful it is likely to be [1]. In this feasibility study, titles and approach, are based on comprehensive feasibility study guidelines issued by the US Department of Energy [2].

Engineering developments often follow five distinct stages:

1. **Feasibility** – brainstorming what's out there that can be adapted, development of concepts.

2. **Simulation** – computer modelling to test if it can deliver the expected benefits, identify the flaws, and ability to develop some very early stage prototype.

3. **Alpha prototype** – development of a lab prototype to test the concept and develop the specifications for a working model.

4. **Beta prototype** – development of a working prototype that can be field tested under carefully monitored conditions and used as the basis for a commercial design.

5. **Commercialisation** – going from the Beta prototype to production of the commercial unit, and securing uptake of the unit by industry through technology transfer.

This report covers stages one to three of the development process outlined above from initial feasibility to development of the alpha prototype model. The design of the beta prototype is also presented.

The feasibility study methodology used in this report comprises the following areas:

- Current Systems and Processes
- Description of Improved System
- Comparison of Some Alternatives
- Expected Benefits and Costs
- Assumptions and Constraints
- Analysis of Benefits and Costs
- Potential Markets and Scale-up Issues

CURRENT SYSTEMS AND PROCESSES

A key focus of the FFR Harvesting research programme to date has been to address the issues around steep country harvesting, with the primary areas of concern being the health and safety of workers and the economics of existing harvesting systems.

Felling and breaking out are two of the most dangerous occupations as highlighted through ACC/Department of Labour and industry sources. While there has been considerable effort put in by industry to address this situation, removal of people from the working environment is seen as the best long-term solution. To a large extent this has been accomplished on flatter sites, with the introduction of mechanised felling machines and grapple skidders eliminating the need for breaker-outs in such a situation.

Mechanisation on flatter slopes and in processing areas has also allowed for improvements in productivity in these areas (in terms of volume production per day). However, the inability to use such machines on steeper slopes has to date largely meant that these dangerous tasks are still carried out manually. Therefore while manual felling may continue to be cost-effective in comparison to mechanisation it has constrained New Zealand harvesting systems in terms of production, additional value recovery benefits (directional felling, less breakage and lower stump height) and the opportunities to improve extraction productivity through bunching and presentation of bunched wood to the hauler grapple/carriage.

The availability of a range of mechanised systems, both in New Zealand and overseas, has been reviewed since the start of the FFR programme, including self-levelling feller bunchers, quad-track harvesters, excavator-based harvesters with wheels and legs (“Walking” Excavators), cut-to-length harvester-forwarder systems as used widely in Europe, and teleoperated harvesters. These systems are summarised below.

Dual-track Self-levelling Feller Bunchers

These machines have the capability to level the turntable when operating on a slope, and have an undercarriage with two tracks. Since the 1980s several models have been developed and used internationally (Table 1).

Table 1: Examples of some steep terrain level-swing feller-bunchers/harvesters[3]

Machine	Mass (kg)	Boom reach (m)	Max working[1] slope (degrees)
Valmet 911 (Snake)	16,900	9.5	39
Timbco 445C	27,500	6.5	27
Impex Konigstiger T30	28,000	15.0	35
Tigercat L870C	35,600	8.4	20
John Deere 909K	35,670	8.4	26
Caterpillar 552	36,015	11.3 (harvester)	N/A
Valmet 475FXL	37,195	7.3	22

[1]Maximum value for different possible machine orientations with respect to the terrain slope.

The use of self-levelling cabs on steeper slopes has been observed both in New Zealand and in Australia over the last 15 years. Their potential for New Zealand conditions in terms of the slopes worked on and the impact on productivity has been studied [4].

One example is a study of a Valmet 445 EXL self-levelling feller buncher working in a cable yarder operation in Australia (Figure 1). Total fell and bunch cycle time per tree averaged about 19 seconds, resulting in productivity per productive machine hour (PMH) of 186 trees, or 149 m^3/PMH (based on tree size of 0.8 m^3). Maximum slopes were about 25^o and the dry soil conditions enabled maximum traction. It was concluded that a high production rate could be achieved by the tracked self-levelling feller-buncher in relatively small tree size (32 cm average DBH) clearfell operations and favourable terrain conditions.

Figure 1: Use of a Valmet 445 EXL Feller buncher in a cable logging setting in Australia.

Such operations are particularly advantageous with smaller tree sizes because extraction efficiency can be improved through bunching optimal haul sizes. It was recommended that more research into mechanised felling be directed towards the performance of such steep terrain feller-bunchers working in larger (1.8 – 2.6 m^3) tree size, their advantages to cable extraction and the overall system productivity in New Zealand conditions.

Quad-Track Harvesters

Depending on the soil conditions, tracked harvesters can cope with slopes up to 60%[5, 6] but one of the disadvantages is that in heavily stocked stands operating limits are reached relatively quickly. Taking into account the disadvantages of one-piece track, the Valmet Harvester 911 X3M harvester was designed with four independent tracks which provided substantial climbing ability and increased stability of the machine (Figure 2). Under favourable soil conditions this track harvester can work on up to 70% steep slopes[5].

Figure 2: Valmet 911 X3M Harvester

With its 140 kW engine and telescoping boom it may be quite suitable for New Zealand conditions both in clearfell and thinning operations. The machine can work both uphill and downhill, and because of its improved manoeuvrability its use in highly stocked stands is possible.

Another machine with a similar design, the Allied Tree Harvester ATH28 (Figure 3), was the only model in its class back in the 90s [7]. Manufactured by Allied Systems Company of Sherwood, Oregon (manufacturer of Wagner log loaders, Allied and Hyster winches and Ranger skidders) the ATH28 was designed specifically for steep terrain. It had an undercarriage with four independent tracks with Cat D6D track components and hydrostatic transmission. The engine was a Caterpillar V-3208 rated at 157 kW (210 hp). The suspension system permitted all four tracks to maintain contact with uneven ground or over obstacles. The upper works were self-levelling on slopes up to 70% (35^{o}). The maximum speed of the harvester was 1.9 km / hr. The felling head was equipped with either a saw or a shear of up to 70 cm capacity, with a maximum reach of 7.6 m.

Figure 3: The ATH28 Allied Tree Harvester reportedly worked comfortably on relatively steep slopes

According to several international experts in the field (Brian Tuor, Rafaelle Spinelli and Loren Kellogg, pers. comm.), the ATH harvester was very capable of working on steep terrain. On suitable soils, the machine operated well on sustained slopes of 70% (35^{o}). However, productivity dropped off on slopes over about 40% (22^{o}) and operators felt that the machine was probably not competitive with chainsaw cutting on slopes over 50-55% ($27\text{-}29^{o}$) where soils were dry. In wet clayey soils, the machine may have been limited to 40-45% ($22\text{-}24^{o}$) slopes.

Only five ATH machines were sold worldwide[7]. User opinion was that the concept was outstanding but that additional mechanical modifications were necessary to achieve acceptable utilisation. All units sold were used in clearfell logging, in average tree size ranging from less than about 0.5 m^3 to over 2.0 m^3. Unfortunately this machine is no longer being offered by the manufacturer. No reason has been stated by the company for the discontinuation of the ATH harvester but it may have been a combination of tightened safety and environmental constraints and poor economic competitiveness due to high capital cost, and maintenance costs.

“Walking” Excavators

A Kaiser Spyder S2 “walking” excavator (manufactured in 1995) was observed working in the Waikato region, and the opportunity was taken to study the machine operating on slopes and clearing slash and bunching trees for extraction in a farm woodlot. [8] A similar machine, a Menzi Muck walking excavator is known to be working in the Wellington region in a civil engineering capacity, but there are no machines in New Zealand working specifically in steep country logging. During the study of the Kaiser Spyder, the machine was observed lifting and slewing trees of estimated piece size of 1.5 t. It was also observed pushing / moving a tree of an estimated 2.0 – 2.5 t (Figure 4). The Spyder was equipped with a bunching grapple on a fixed rotator rather than a rotating grapple. This allowed the machine to use its standard method of pushing itself uphill supported by two wheels and the extended boom. Travel speed up a 25 to 30 degree slope on an uneven surface was approx. 0.7 km/hour (25 m in 8 pushes).

Figure 4: Side view of Kaiser Spyder showing degree of cab levelling possible. Note stabiliser angle which illustrates the reliance on the stabiliser penetration for stability.

The New Zealand operator of the Kaiser (Karl Schwitzer, pers. com.) felt that the newer models are potentially 40% more powerful than the S2 and capable of working in tree size up to 1.5 m^3. The opportunities to upsize the machine to the point that it was capable of dealing with larger trees may be limited due to the larger, heavier machine having difficulty remaining stable on slopes because of the extra pressure applied to the ground through the stabilising legs which are required to prevent the machine sliding downhill.

A study of a similar Italian-made machine, Euromach 9000 Forester, had revealed that these machines could be a viable option, able to reach good production levels[9]. The idea of using these types of machines to clear the chute under the hauler was also discussed, especially on size limited skids, as they have the advantage over regular excavators of being able to position themselves safely on a wide variety of terrain features.

Some examples of machine costs were sourced. Estimated cost of a Menzi Muck machine landed in New Zealand is of the order of NZ$500,000. Many similar machines are available second hand and prices are available, a second-hand used Menzi Muck A91 in the US being quoted at US$156,225.

Cut-to-length Tracked Harvester-Forwarder Systems

A very successfully implemented steep terrain harvesting system in Southwest Germany was observed by the author in 2010. The harvesting system consisted of an Impex-Königstiger excavator-based harvester and a steep slope forwarder, the Herzog Forcar FC200.

The Impex Königstiger T30 harvester is manufactured by Impex Forstmaschinen GmbH of Germany (http://www.impex-forstmaschinen.de/) Technical specifications are given in Table 2.

Table 2. Technical specifications of the Impex Königstiger T30 tracked harvester

Weight	30.5 – 32.5 tonnes
Dimensions	Length 11.1m x Width 3.0m
Engine	6-cylinder Deutz turbodiesel with rated power 165 kW
Drive	2 hydrostatic single drive crawler tracks
Slope capabilities	0 to 50% (maximum 70% depending on terrain conditions)
Rotating superstructure	360° rotation, tilt to 25° forward, 12° lateral and 6° rear
Crane	Range 15 m with single telescopic boom
Lifting power	174 kNm (10 kNm at full range)
Track dimensions	400 cm length and 60 cm width.
Harvester head	Lako-Impex VV 786 (max diameter 63cm) or Lako-Impex VV 1118 (max diameter 83cm)

According to the harvesting operations manager (Matthias Schmitt, pers. com.), this mechanised harvesting and processing system closes the gap between regular mechanised harvesting operations in flat areas and hauler operations in very steep slopes (Figure 5). The adapted system is more economical and causes less damage to the soil and residual standing trees than the traditionally used motor-manual felling and skidding or using a medium sized hauler.

Figure 5: Excavator-based Impex Königstiger Harvester working in a selection cutting in Southwest Germany.

In this cut-to-length operation, processed logs are transported to the storage area alongside the forest road by a forwarder that is equipped with a traction winch. Technical specifications of the Herzog Forcar forwarder are given in Table 3.
(http://www.herzog-forsttechnik.ch/english/pdf_e/prospekt_hangforwarder_e.pdf)

Table 3: Technical specifications of Herzog Forcar FC200 8x8 steep slope forwarder

Weight	17 tonnes
Engine	Cummins 6-Cylinder turbodiesel with 142 kW
Drive	Hydrostatic, shiftable all-wheel-drive, bogie-lift on front axle
Wheel Size	Front: 600/50x22.5 LS2; Rear: 720/45x26.5 LS2
Loading Capacity	12 tonne load suitable for lengths from 2 to 6 m (on slopes 3 to 5 m)
Loading Crane	Loglift F91FT100 with 81 kNm lifting power and 10 m range
Traction Winch	Proportional speed control, hydraulic winch drive with safety brake Rope capacity 250 m (diameter 16 mm). Synchronised forwarder and winch.
Cabin	Operator seat with tilt
Loading platform	Hydraulic platform tilt (25% laterally), and moveable loading grid (500 mm)
Loading Crane	23° tilt towards loading grid
Other Features	Cameras in the rear and within the winch

The winch is able to provide more than 50% of the traction power when moving upslope, and serves as an efficient brake when moving downhill. Wheel slip is eliminated, which also reduces the amount of site impact. The winch enables the forwarder to work on slopes over 50%, both up and down slope (Figure 6). Wet underfoot conditions are also less of a problem when using the traction winch.

Figure 6: Herzog Forcar FC200 8x8 winch-assisted steep slope forwarder working in southwest Germany.

Teleoperated Harvesters

Gremo Besten

An unmanned teleoperated harvester was developed from 2002 by Fiberpac AB of Vislanda in southern Sweden. It is now manufactured by another Swedish company, Gremo AB This new method of operation requires two forwarders alternately operating the driverless harvester Besten 106RH (Figure 7). During the processing, the timber is loaded directly on the deck of the first forwarder. When the loading operation is finished the second forwarder takes over harvesting and loading itself while the first forwarder travels to the truck road for unloading. Technical specifications are given in Table 4.

Table 4: Technical specifications of Gremo Besten 106 RH Harvester

Weight/Dimensions	21.2 tonnes, 8.8 m long and 3.1 m wide.
Engine	John Deere 6-Cylinder turbo diesel with 275hp (202 kW)
Drive	6 bogie wheels on pendulum arms, two of which are driving
Tyres	600 x 26.5 with band tracks
Brake system	Brake valve in driving engines
Crane	Cranab with 2.2 tonnes capacity at 8.3m reach.
Control system	Dasa5 – digital and analogue safety function prevents interference.
Harvester head	SP 661LF harvester head is standard but can be supplied with other harvester for thinning or final felling.

Figure 7: Teleoperated harvester Gremo Besten 106 RH

Advantages of the system include:

- Less labour (with three machines and only two operators)
- Fuel consumption is reduced as for each forwarder cycle (load/unload) the forwarder crane is redundant for loading
- Lower capital cost of harvester (no operator cab) and lower operating cost per productive hour than conventional harvester
- As there is no person in the harvester machine, the felling phase is much safer for the operator.
- Diversification of operator tasks (more interesting job, possibly higher motivation)
- Direct loading prevents double handling of stems
- No timber is placed on the ground (clean wood)
- All logs are accounted for as they are loaded (no waste and no stock left in the forest)
- Shorter lead times (all wood is loaded to roadside allowing faster loadout)

Disadvantages of the system include:

- Lower forwarder productivity as direct loading (one stem at a time) is slower than loading bunched wood in the forest
- Lower harvester utilisation (and productivity per productive hour) as it is operated only when a forwarder is present, otherwise it is idle.
- Forwarder cycles must be de-phased to prevent waiting time for use of the harvester (measured in one study at 6-9 minutes per load [14]).
- Requires more skilled operators (must be competent in both harvester and forwarder operation)

According to the manufacturer's website (www.gremo.se) these machines are commercially available. No costing information has been provided however one study by Skogforsk indicated hourly costs of US$55 per PMH for the Besten and hourly productivity in 0.94 m^3 tree size of 31.3 m^3/PMH [10]. Information regarding the transferability and compatibility of the control system with other harvesting equipment is being investigated.

Konrad Pully

Another European development is a remotely operated ground skidder, the Pully from the Austrian manufacturer Konrad Forsttechnik GmbH (Figure 8). Konrad Forsttechnik manufactures the Woody harvester heads, the Highlander 6-wheeled clambunk harvester, the Mounty 5000 cable hauler, and the Woodliner 3000 and Liftliner 4000 skyline carriages. The focus in Europe is on soil conservation and safe downhill hauling on steep slopes. The Pully is basically a carriage with wheels, with its own engine, running on a skyline fitted to the front and rear. Technical specifications are given in Table 5.

Table 5: Technical specifications of Konrad Pully attachment carrier

Weight/Dimensions	3.55 tonnes, 3.2 m long and 2.5 m wide.
Engine	Volkswagen diesel engine with 75 kW rated power
Drive	Winch driving the cable at 3 m/sec
Guidance cable	18 mm steel wire
Winch pulling capacity	4 tonnes
Crane	Reach 6.0m with 44 kN pulling force
Control system	Konrad FS 12 – prevents interference.
Winch cable	80 m of 12 mm wire rope or 14 mm Dyneema synthetic rope.

Figure 8: Teleoperated ground carriage Pully by Konrad.

The Pully works downhill only, in conjunction with the Highlander harvester, picking up the processed logs and loading them into its bunk using the remote-controlled crane. Stems that are out of reach can be pulled laterally using the fitted winch. The ground carriage then transports the stems, similar to a skidder, to the forest road or processing site (Figure 9). On wet and loose ground, the carriage can move freely without causing soil damage because the machine is pulled by cable as opposed to driven by the wheels.

Some of the advantages noted by the manufacturer include the remote control option of the machine, providing for safer and more versatile use of this carriage on wet ground and various soil and terrain conditions. The relatively low tension on the cable is another advantage since the wheels of the machine supports the greater part of the combined machine/payload weight; because of this it has high loading capacity. There are no special skills required to set up the system as opposed to long-span cable systems requiring complicated intermediate supports.

Figure 9: Operation of the Konrad Pully.

DESCRIPTION OF IMPROVED SYSTEM

Assessment of Mechanised Harvesting on Steep Slopes

With all the described existing systems there are three basic drivers for their development and adaptation to steep terrain work – health and safety, productivity and quality/environmental issues.

Health and Safety

Advantages:
- With full mechanisation of the harvesting process, risk for workers is reduced significantly as their exposure to harm is reduced. Up to 3 manual fallers are replaced by one machine operator.
- With teleoperation, worker risk and ergonomic benefits are improved further, with less operator fatigue from whole-body vibration, noise, heat, dust etc.
- Increased motivation through improved working conditions.

Disadvantages:
- Increased stress rate for machine operators while working on steep slopes.
- Operators and harvesting supervisors must respect limitation of use in terms of slope.
- Some terrain conditions still not accessible by heavy equipment (wet and fragile soils, rocky terrain), therefore the crew will need access to a manual faller.

Productivity

Advantages:
- Felling and processing machines can produce a lot more wood than manual operators.
- A machine can provide the opportunity of bunching on steep terrain, shown to increase overall system productivity.
- Provides continuous harvesting process for longer working hours with less dependence on weather conditions.
- Opportunity for reduced haul distances for the yarder and fewer line shifts due to areas bunched or shovel logged with bunching machine.
- Slope-adapted machines can also be used on flat terrain (flexibility).

Disadvantages:
- Higher capital cost and operating cost (than manual operations), hence need for higher production to offset.
- May not be cost-competitive with manual felling
- Requirement for system balancing (e.g. a feller buncher can produce twice as much wood as a yarder can extract in one day).
- Operator training will be required for new technology as productivity is known to vary by as much as 100% between different operators.
- Increased need for planning of operations to ensure safe and productive operations.

Quality and Environmental Management

Advantages:
- Mechanised harvesting reduces tree breakage and protects remaining tree stands better than motor-manual due to better control of tree during felling.
- Lower stump height improves value recovery
- Traction winches improve machine gradeability and reduce track slippage, hence reducing rill and gully erosion.
- Ability to place slash in specific locations to act as a soil/sediment trap or runoff diversion.

Disadvantages:
- Possible increased soil compaction due to the equipment weight on the slope.

The Cable Assisted Excavator Concept

There are two known examples of excavators using a system to tether the machine to a tail hold to allow work on steep slopes. Both machines are in New Zealand and were studied as part of the FFR programme, and the findings were released in two separate FFR reports[11, 12]. Detailed descriptions of these systems can be obtained from these reports. While the two examples used different methods to tether the cable hold, the outcome of allowing a machine to work safely on slopes previously thought too steep justified a study of the implications of these machines on steep slopes.

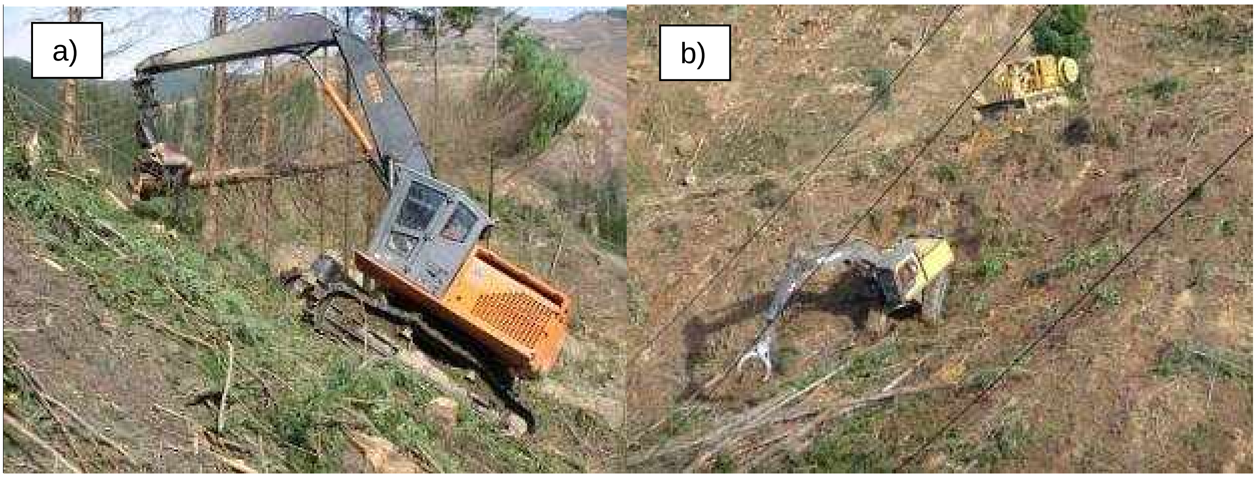

Figure 10: a) Kelly Logging's steep slope harvester working in clearfell near Nelson; and b) Ross Wood's cable secured excavator working in clearfell near Nelson.

The first machine (Figure 10 a) was operating with a felling head, and falling was observed to be significantly slower when the machine was tethered than when felling on flatter slopes without the cable. The resulting wood was bunched. The study showed an average 60% increase in number of trees hauled per cycle with mechanically felled and bunched wood versus unbunched wood.

The second machine (Figure 10 b) was working with a grapple and was utilised both in bunching the wood for the hauler and to feed the grapple, allowing for a faster cycle time for the hauler. Significant increases in the number of pieces hauled per cycle (up 33% compared to spotter controlled cycles) were observed in this operation. The concept of presenting to the grapple is also a good example of the potential for process change when it is possible to have a machine operating under the hauler.

Development of the Kelly Logging System

This project aims to achieve the further development to commercialisation stage of the "alpha prototype" steep slope feller buncher developed by Kelly Logging Ltd and Trinder Engineers of Nelson, New Zealand.

The main development involved the design and construction of the integrated winch and fitting it to the track frame on the lower (downhill) side with the rope running under the chassis and out a fairlead at the front of the machine (Figure 11). The hydraulic winch along with the fittings required added approximately 4 tonnes in weight to the 29-tonne Hitachi ZX280 upper/ZX 330LC track base.

As at June 2011, the "alpha prototype" had been working for more than two years and there has been no indication of compromised engine durability or performance due to working on steep slopes (Trinder Engineering, pers. comm.).

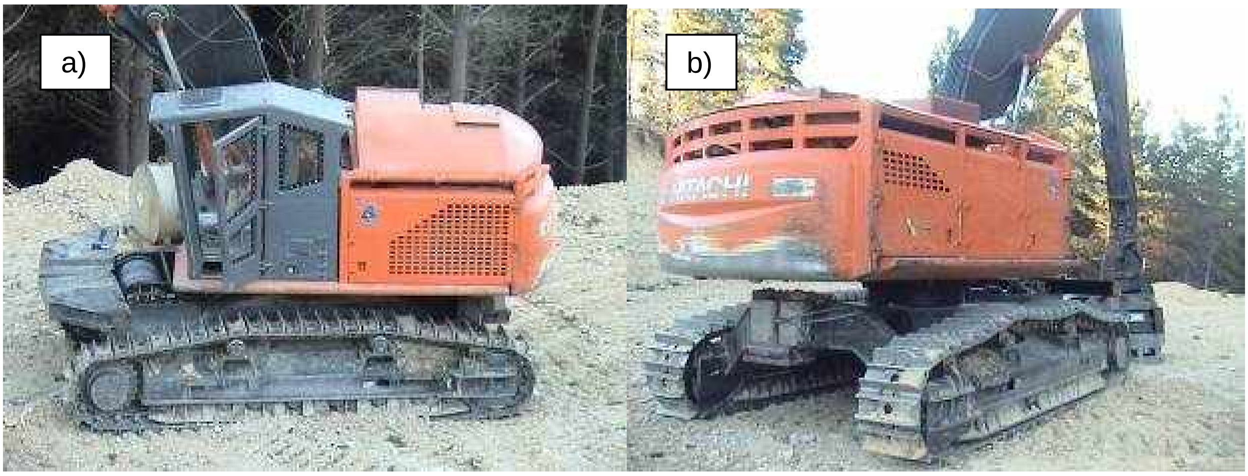

Figure 11: The steep slope harvester with a) the protective winch cover open revealing the winched rope on the lower side of the tracks, and b) rope coming out through the fair lead on the upper side of the tracks.

In addition to manufacturing and fitting the hydraulic winch several substantial modifications have been performed on the machine over this period:

- Purpose built operator cab with integrated side guarding; one piece catwalk and independent hydraulically opening bonnet system.
- Hydraulically powered slack pull rollers were fitted. These are located just inside the fair lead. They continuously hold 200 kg of load on the rope on the drum to stop bird nesting.
- An extra external horizontal tail roller was fitted to the fair lead to decrease rope deflection as the excavator operates downhill of the anchor point.
- Track power was increased to maximum by Hitachi engineers to enable the excavator to climb uphill on steep slopes. To prevent any engine damage, extra oil cooling and engine compartment venting were added.
- Track frame was lengthened and 74mm grouser bar extensions fitted
- Substantial strengthening of factory heavy duty track guards was required due to increased loads working on steep slopes.
- Under body protection with drop down turret plate.
- Counterweight rear overhang was reduced about 250 mm to aid dropping over banks and general clearance when slewing on steep terrain.
- Weight of the counterweight was reduced by about 80% to 1.5 tonnes to reduce overall machine weight. The new machine weight is now 40.6 tonnes. With zero counterweight, the slew power on steep slopes was reduced too much and the machine could not fell and bunch efficiently.
- The stick was shortened by 950 mm to allow felling head operation range closer to the base of the machine. This reduced overall weight and helped with required slew power on steep slopes and reduced machine tipsiness on steep slopes when at full reach.

Through the process the design engineers and the operating crew learned a lot about steep slope harvesting machines. The design engineer and the logging contractor travelled to the U.S. to investigate self-levelling functionality. A self-levelling machine was purchased and trialled to assess its suitability for fitting the winch system. One of the objectives was to assess the improvement in operator comfort and possibly steep slope stability. This further development of the alpha prototype was not proceeded with as the design of the levelling base did not fit the winch and there would have been additional associated costs. The designers also considered the future vision that teleoperation/robotics would likely be the way forward with steep terrain equipment, thus a self-levelling operator cab would become redundant.

Development of the Beta Prototype Steep Slope Feller Buncher

Improvements that would further enhance the tractive and lifting/slewing capacities have been considered for the next model steep slope harvester (the "Beta prototype"). The base machine chosen by the engineering company for the next model is a dual tracked excavator Hitachi ZX400, and actual modifications commenced in July 2011. This model was chosen as it was felt that the slew ring of the first prototype (Hitachi ZX280) was too small to withstand the stresses encountered harvesting larger trees on steep slopes. With the bigger base this problem will be addressed.

The similar 4-tonne hydraulic winch will be placed on the upper side of the machine (as opposed to previously being installed on the lower side), thus resulting in a better balance on steep slopes. A blade will be installed on the lower end of the track frame to enhance stability while working on slopes. It can also be used to level the ground for machine positioning, filling ground holes from uprooted trees etc.

This prototype will include a new Trinder-designed felling head, specifically made to work smoothly on steep terrain and also handle wind thrown trees without compromising the capabilities of the head. It was expected that this machine would be available for field trials before the end of 2011.

Considering subsequent custom-built steep slope harvesters, Trinder representatives have contacted the excavator manufacturers, Hitachi, and investigations made into whether an excavator that incorporates some of the changes necessary for integrating the hydraulic winch could be manufactured. This would avoid the breaking down of the machine once out of the factory and then reconstructing it to install the winch and other modifications necessary. This would also streamline the production of these harvesters and may be beneficial in terms of capital cost.

Other improvements that have been discussed with the engineering company and could potentially be integrated in subsequent models include improved control and monitoring of the winch through integrating a camera within the winch to monitor rope and winch conditions, as well as a camera showing the rope as it is released through the fair lead on the steep slope.

Alternative Winch Systems

One option for further development is for the winch to be detachable and mountable on more than one machine. Similar examples exist on the European market, where traction winches can be mounted on different machines, even on different types of machines (harvesters and forwarders) in a cut-to-length harvesting systems (Figure 12).

All of these are specific winches designed for steep slope applications. The HSM-15 harnesses up to 150 kN constant pulling force independent of the cable layer on the drum; it employs a heavy duty planetary gearbox with hydraulically actuated wet disc brake, it is wirelessly remotely controlled, and the force between the wheel-drive and the winch is synchronised. It is mounted on the rear of the machine, and is tiltable and quick-coupling (detachable) to allow use with multiple machines. Prices that could be sourced from the internet ranged from €100,000 to €120,000.

Figure 12: CAD drawing a) and photo d) of the HSM Slope Terrain Winch (HSW-15). Photo b) of traction winch manufactured by Ritter; Photo c) Alpine Synchrowinch manufactured by Herzog Forsttechnik.

Another possible modification is to alter the track construction to achieve improved manoeuvrability and flexibility of the track base. Some examples are the WFW SoftTrack Drive (Figure 13 a), manufactured in Germany (www.wfw.net) and the Street Rubbers flexible track concept introduced by Impex Königstiger (Figure 13 b).

The SoftTrack drive is interchangeable with bogie wheels and the change is done in a few hours; it is suitable for most wheel-based harvesters and achieves improved traction and performance in steep and wet slopes with minimum ground pressure. The flexible track (Street Rubbers - http://www.street-rubbers.de) development combines the advantages of wheels and belts and is capable of traversing over obstacles up to 50 cm in height without compromising the stability of the tracked machine. Due to the additional supporting roller between the wheels, the pressure distribution on the ground is improved, minimizing ground pressure.

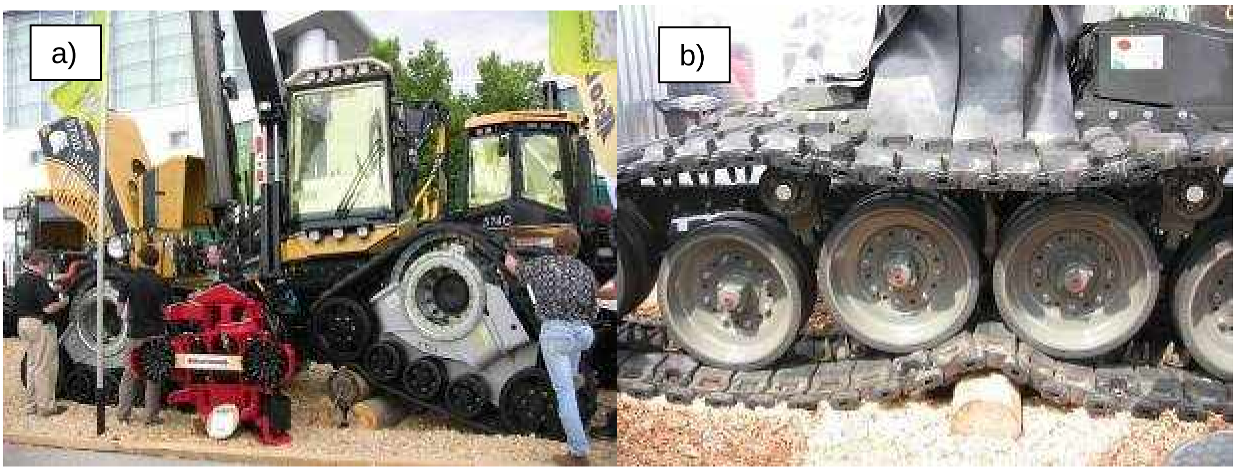

Figure 13: Available options for improved track performance: a) the WFW's SoftTrack drive and b) flexible track concept (Street Rubbers) by Impex Königstiger.

EXPECTED BENEFITS AND COSTS

Apart from the obvious health and safety benefits of mechanisation, there are two main productivity benefits from implementing the steep slope harvester in a harvesting operation:

1. benefits from bunching the harvested wood, and
2. benefits from being able to work longer hours.

Bunching wood by the harvester increases the number of hooked trees per strop/choker and also improves hook-on time, which results in increased yarder productivity in strop/carriage cable system operations. In a grapple yarder operation the number of grappled trees per cycle is increased and the grapple load element time is improved, both factors resulting in increased yarder productivity.

Manual tree fallers and breaker outs are limited in terms of the work hours they can operate. Ergonomically, working in a protected excavator cab with improved lighting and audio-visual conditions may lead to reduced fatigue and allow longer working hours. Working longer hours (with less dependence on weather conditions) leads to improved profitability by reducing the daily fixed costs spread over the volume of wood produced, thus reducing the effective logging cost.

Costs are based on estimates of machinery/supplies prices as well as currency exchange rates current as at June 2011. The cost of the chosen base machine, Hitachi Zaxis 400 LCH excavator, is estimated at $350,000. The following modifications and improvements are estimated to cost $450,000:

- purpose built winch with 375 m 7/8 swaged rope;
- purpose built high and wide undercarriage chassis;
- full hydraulic bonnet, incorporating a 1100-litre fuel tank and a 800-litre rear mounted hydraulic tank;
- straightening the boom and altering the stick;
- adding a purpose built cab and incorporating a blade, a high flow oil cooler with reversing fan;
- fire suppression;
- stump safety movement monitor; and
- painting and other miscellaneous costs.

Additional to these costs of the modified machine is the Trinder purpose-built felling grapple estimated at $100,000. This felling grapple is equipped with high powered clamping force for wind throw and features a retractable saw box that is designed to fell on slopes greater than 26°, and for shovel logging on slopes. The total estimated cost for the steep terrain harvester used in this analysis is $900,000.

ASSUMPTIONS AND CONSTRAINTS

All costings and the economic analysis were carried out using findings from the detailed time study of the alpha prototype steep terrain harvester[12]. The system consisted of a yarder, chute clearing excavator, guy line and tail hold excavator, processor and two loaders (one tracked and one wheeled loader). Crew members consisted of one foreman, five machine operators, two tree fallers and one quality controller. The mechanised system used the feller buncher (steep terrain harvester). No additional crew member was included in the costings for the mechanised system; rather one of the two manual fallers was assumed to operate the steep terrain harvester.

System costs were estimated using calculated productivity and representative costs from the INFORME forestry equipment survey[13]. Assumptions included 9.0 scheduled working hours for all machines, and maximum machine utilisation levels of 85% for the processor, 80% for the feller buncher and yarder.

Estimated system cost for manual felling and yarding unbunched wood based on daily production of 351 m^3/day was $25.34/$m^3$ (48.8 m^3/PMH * 7.2 Yarder PMH/day). In this scenario yarder productivity limited the system production, requiring a maximum 80% machine utilisation over 9 scheduled hours per day to achieve 7.2 PMH). System balance for this scenario required 6.1 Processor PMH (at 57.7 m^3/PMH) resulting in machine utilisation of 68%.

A comparable estimated system cost for the mechanised felling and bunching system was based on daily production of 444 m^3/day and was estimated at $22.42/$m^3$ (74.1 m^3/PMH * 6.0 Yarder PMH/day). Machine utilisation for the yarder was a conservative 67% (6.0 PMH/day out of 9.0 scheduled hours).The processor was the limiting factor to system production. To balance system production and avoid creating bottlenecks on the landing required 7.65 processor hours (at 58 m^3/PMH giving 85% utilisation). The feller buncher was required for 7.0 PMH/day (at 64.7 m^3/PMH, based on 100% usage of the winch), resulting in machine utilisation of 77%.

Some additional assumptions and constraints were considered:

- Steep terrain harvester use may be limited operationally, depending on the type of terrain and soil as well as specific operational harvest plans. Tracked equipment cannot work in areas featuring large rocky outcrops or bluffs, extremely loose or wet soils or very broken terrain. Machine utilisation rates may vary depending on conditions.
- The productivity of the alpha prototype steep terrain harvester felling and bunching without the cable assist was measured at 75.8 m^3/PMH. Using the winch system productivity was measured at 64.7 m^3/PMH. Given the estimated productivity of the mechanised system described above (444 m^3/day), the required minimum machine utilisation of the steep slope harvester was 65% (assuming use without the winch).
- Tree size may also be limiting to steep terrain harvester use beyond about 4.0 tonnes per stem (>70cm butt diameter).
- With some of the improvements intended for the beta prototype steep slope harvester, additional gains in productivity and economic life could be achievable. Further field studies as part of the evaluation of this system will determine the magnitude of these gains.
- According to the manufacturer, the system is expected to have an economic life of at least 5000 productive machine hours. As improvements are implemented in subsequent models it is expected that the harvester life will be extended.
- A draft best practice guideline is under development by the manufacturer in consultation with the Department of Labour and is expected to be incorporated into the revision of the Approved Code of Practice for Safety and Health in Forest Operations in 2012. While there are no machinery manufacturers' specifications for slope steepness, in general steep terrain forestry equipment manufacturers suggest that for safety reasons, no machine should be operated on slopes where it cannot be stopped safely without winch assistance. The winch is not meant to replace traction control, but to assist traction and machine mobility to improve machine performance.

RESULTS

Initial Productivity Study

The results of the detailed time study of the alpha prototype steep terrain harvester[12] showed a 26% increase in daily productivity over the described system with manual fallers (444 m^3/day vs. 351 m^3/day). The base rate for the manual system with no steep slope harvester was calculated at $25.34/$m^3$.The effective logging rate of the steep slope harvester system (based on this improved production rate) was calculated for different usage rates and machine capital costs as shown in Figure 14.

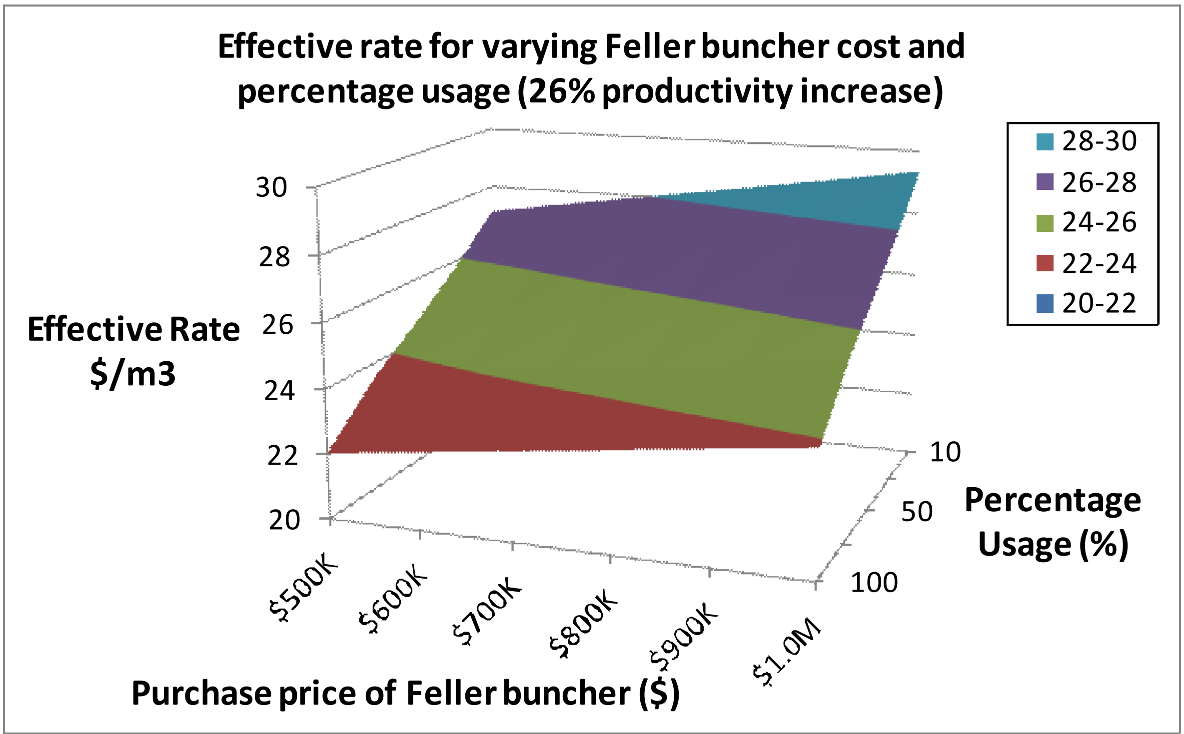

Figure 14: Effective rate for a range of machine costs and varying use of the steep slope harvester assuming 26% gain in system daily productivity.

At the estimated total capital cost of $900,000, the break even usage rate for the steep slope harvester was 59%. As usage increases to 100%, the productivity advantage of the steep slope harvester system over the manual system results in substantial gains of almost $3.00/$m^3$ compared to the manual system (down to $22.42/$m^3$).

Further Analysis

A sensitivity analysis table was constructed showing the break even usage with varying capital costs across the range of expected productivity gains achievable through effectively implementing the system (Table 6).

If the capital cost can be reduced to $800,000 through engineering or procurement improvements, and the estimated productivity increase of 26% is achieved, the harvester would only need to be used for 53% of operating time to break even with the manual faller system.

Alternatively, at the maximum capital cost calculated of one million dollars, system productivity gains in excess of the measured 26% would be required to keep the break even usage rate less than the required machine utilisation (around 65%). If these productivity gains cannot be achieved then, using the assumptions in this costing model, purchase of the harvester is not justified in comparison with the manual faller system.

Table 6: Required percentage use of the steep slope harvester to break even with the manual felling system at varying harvester capital costs and assumed productivity gains.

Total Cost	Range of productivity gains achievable using the Steep Slope Harvester				
	20 %	26 %	35 %	40 %	47%
	Percentage use to break even with manual felling system				
$1,000,000	95%	65%	55%	48%	40%
$900,000	87%	59%	50%	43%	37%
$800,000	77%	53%	44%	38%	33%
$700,000	69%	46%	39%	34%	29%
$600,000	59%	40%	34%	30%	25%
$500,000	50%	34%	30%	25%	21%

Because of the improvements that have been built into the beta prototype, higher average productivity gains may be achieved over the life of the machine. A cost-productivity surface was created assuming a 40% increase in productivity (Figure 15).

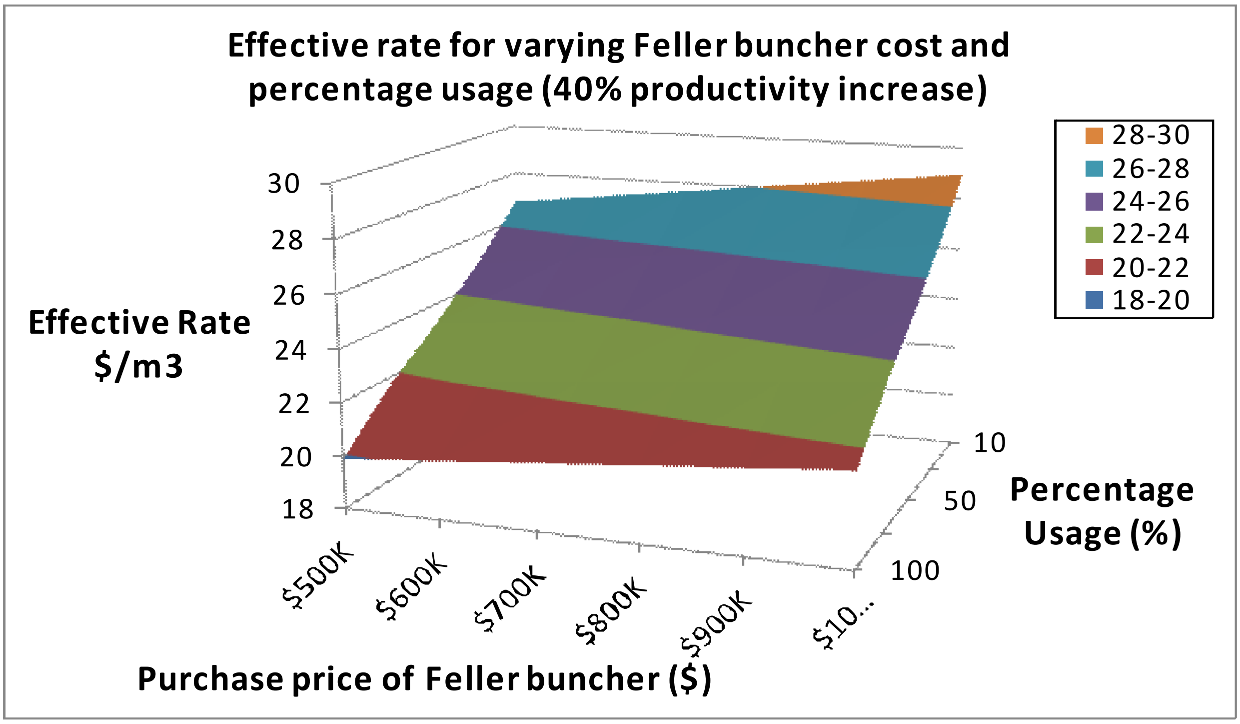

Figure 15: Effective rate for a range of machine costs and varying use of the steep slope harvester assuming 40% gain in system daily productivity.

At the estimated capital cost of $900,000 and a productivity increase of 40%, the harvester would need to be operated for 43% of operating time to break even with the manual faller system. Such productivity gains may be achieved by either working the yarder longer hours (6.6 PMH) or even double shifting it. Dramatic differences can be noted between these scenarios where if the increase in system daily productivity is doubled from 20% to 40% the break even usage of the steep slope harvester would be halved (Table 6).

The potential gains in terms of reduced effective logging rate were more than $4.00/m^3$ if the system was effectively used on 100% of the harvest area at the estimated harvester cost of $900K (Figure 15).

DISCUSSION

Is a harvesting system productivity gain of 40% over and above a manual faller system realistic? Maximising the yarder hours beyond that used in the system balancing exercise (6.0PMH) as suggested above, to similar to that of the manual system (7.0 PMH at 77% machine utilisation) seems reasonable. Balanced system productivity of 518 m^3/day would require double shifting the processor (2 x 7 SMH shifts at 65% machine utilisation). In order to balance the system this would require the feller buncher to operate 6.8 PMH (76% machine utilisation), assuming operation without the cable assist (at 75.8 m^3/PMH) or 8.0 PMH using the winch system all the time (89% machine utilisation at 64.7 m^3/PMH). A feasible maximum machine utilisation of 85% for the feller buncher could be achieved if the proportion of time using cable assisted felling and bunching did not exceed 73% (as opposed to felling and bunching without the winch operation). If higher use of the winch was required to fell and bunch more of the harvest area then the scheduled hours of the feller buncher would have to be extended also.

Given the increased daily system cost of double shifting the processor (another operator and a vehicle) and the additional production to 518 m^3/day, the estimated effective logging rate in this scenario reduced from \$22.42/m^3 to \$20.00/m^3 (a reduction of a further \$2.42/m^3).

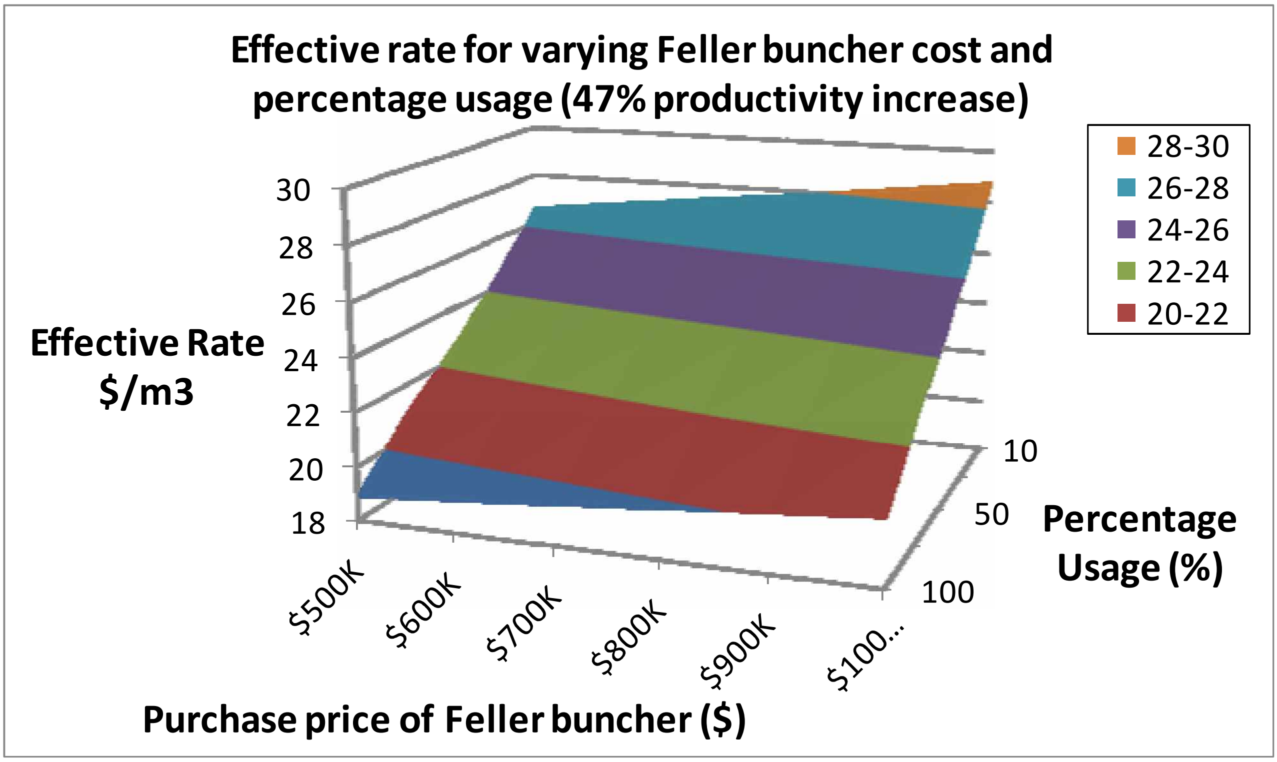

Figure 16: Effective rate for a range of machine costs and varying use of the steep slope harvester assuming 47% gain in system daily productivity.

Compared to the manual faller system with a similar working time (7.2 yarder PMH) producing 351 m^3/day, this is a 47% productivity gain. At the estimated capital cost of \$900k, the steep slope harvester must operate for more than 37% of operating time to break even with the manual faller system, which is more than achievable. This productivity gain results in reduced effective logging rate of more than \$5/m^3 (20% reduction) if the system was used effectively for 100% of the time (Figure 16).

These calculations indicate that the potential for economic gains that can be achieved with the steep slope harvester is large. This system does not require additional operators and can be balanced by carefully planning and scheduling of existing crew time. Mechanisation allows longer working hours than manual operation in suboptimal lighting and poor weather conditions. Good maintenance of equipment is however required to prevent breakdowns and production delays, hence keeping machine utilisation at the high levels required for maximum production.

POTENTIAL MARKETS AND SCALE-UP ISSUES

The steep terrain harvester is compatible with all cable logging systems where steep terrain is the limiting factor for using conventional ground-based equipment. There are an estimated 220 haulers working in New Zealand[14]. Ground-based harvesting crews may also benefit from such a machine on steeper slopes. Internationally, similar ground and stand conditions exist in the Pacific Northwest region of North America (Canada and USA), so with successful implementation and uptake by the NZ industry the potential opportunities for export to other forestry countries may be significant.

One of the scale-up issues to be considered is the relatively small size of the manufacturer (Trinder Engineering), which may create limitations in sourcing skilled technicians for large scale manufacture of the steep slope harvester.

CONCLUSION

The difficulties, and in many cases, the inability to use mechanised feller-bunchers on steeper slopes has meant that the health and safety of workers and the economics of existing harvesting systems are primary areas of concern for the forest industry. Several different alternative steep terrain machines exist worldwide, and a recent New Zealand development has incorporated a supporting winch into an excavator-based feller buncher. The purpose of this prototype steep terrain harvester is to achieve increased volumes and provide the opportunity for bunching of the felled stems while eliminating the need for manual tree fallers. The ultimate goal of bunching is the resulting increase of hauler productivity and the total logging system productivity, thus improving the economics of the operation. Effectively, larger payload and reduced grapple/hook-on time is achieved by the accumulation of felled stems for hauling.

A detailed study of the first prototype steep terrain harvester showed an average 50% increase in number of trees hauled per cycle with mechanically felled and bunched wood versus unbunched wood. Productivity gains reported amounted to a 26% increase in balanced system daily productivity over the described system with manual fallers. At the estimated total steep terrain harvester cost ($900,000), the system would have to be used for more than 59% of the time to justify its purchase and implementation. Once the break even point ($25.34/m^3) is reached, substantial profitability gains are expected to be achieved with increasing the proportion of the time that the system is used effectively. These cost gains amounted to almost $3.00/m^3 if the machine was used for 100% of operating time (reducing the logging rate to $22.42/m^3).

Rebalancing the system by increasing the number of yarder productive machine hours to 7.0 PMH/day resulted in a 47% productivity gain compared to the manual faller system. With this productivity increase achieved, the break even usage of the steep slope harvester reduced to 37% of operating time. The system showed the potential to achieve a reduced effective logging rate of more than $5.00/m^3 (20%) over the manual system if it was used effectively for 100% of operating time.

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