A Case Study: Ground Yarding Operations in Mountainous Terrain[a]

by *Raffaele Cavalli[1] and Dzhamal Amishev[2]*

[1] Dept. TESAF, University of Padova, Italy

[2] Forest Operations, FPInnovations, Canada

1. Introduction

Mountain forests cover over 9 million square kilometres of the Earth's surface and represent a remarkable 23 per cent of the Earth's forest cover. They play a key role in mountain areas, offering goods and services essential to the livelihood of both highland and lowland communities. Mountain forests provide a range of ecosystem services that may be divided into three main categories: provisioning services (e.g., timber and fuel wood extraction); regulating and supporting services (e.g., carbon sequestration, hydrological cycles maintenance, soil stabilization); and cultural services (e.g., recreational opportunities, the role of forests in local belief systems and customs) [1]. In such a perspective it is strategic to develop and maintain forest management systems that provide a balance between land use and conservation of all the ecosystems services offered by the mountain forests.

2. Mechanization of forest operations

One important tool through which forest management systems can be applied are forest operations that develop sound engineering practices for different terrain and stand characteristics; such practices must be technically feasible, economically viable, environmentally sound and institutional feasible [2]. Around the world the forest industry is facing similar challenges in accessing wood fibre on steep terrain. Steeper slopes require alternate harvesting systems such as cable yarding, helicopter, and hand falling but these options are more expensive and much more hazardous relative to mechanized ground-based harvesting operations [3]. New machines available today can often exceed the upper slope limits established in safety codes in many countries throughout the world [4]. Current regulations in British Columbia, for example, restrict the use of ground based logging equipment to slopes not exceeding 35 to 40% without obtaining specific approval for stability and safety concerns. Various steep-slope harvesting machines with specialized undercarriages and carriers have been shown to safely access and operate on terrain up to 70% slope (**Table 1**) without external support or anchoring [5].

Slope is not the only limiting factor, however, and while modern fully mechanised ground-based systems are a default option for safe and productive harvesting, they have always been limited by other terrain factors as well such as soil strength and/or roughness [6]. There is a limit with regard to the physical feasibility of operating machines on steep slopes [7] that is continuously being tested by the various stakeholders – operators, contractors, supervisors, regulators, researchers, manufacturers, etc. Continuously increasing information provides for improved knowledge and understanding, however, there has been little quantitative framework with which to evaluate the relationship between tether tension, stability, ground pressures, and slip, especially in the context of machine specifications and site operative conditions [8]. Most forestry machines have relatively low Center of Gravity (CoG) and are technically very stable in their intended direction of drive, being uphill and downhill. Both the weight and also the force from the momentum created during traction loss can affect stability [9].

[a] Paper presented at the Joint Regional Meeting of IUFRO RG3.03.00 and RG3.06.00 in Asia "Productivity and Safety of Final Cutting on Mountain Forests", Matsuyama and Kochi, Japan: 24th-28th July 2017

3. Winch-assist developments

3.1 Winch-assist systems

There is a huge interest and recent worldwide effort to improve traction of harvesting machines when operating on steep slopes [10]. One way to improve traction and stability on steep slopes is through assisting harvesting machines by winch and cable to anchor locations such as tree stumps or stationary equipment. Options for extending mechanized equipment forestry operations to steep terrain were examined as early as the 1970's through a feasibility study of a self-contained cable tether system [11]. Steep terrain winch-assist machinery for forestry have been commercially available in Europe since the 1990's and initially they were mainly used on forwarders, but since the early 2000's numerous commercial options have been developed for harvesters [12]. In New Zealand, the first winch-assist system was pioneered in 2006. The subsequent developments in purpose built winch-assist machines over the last decade have led to strong growth in the application of this concept as a true harvesting system. Terms such as winch-assist, traction-assist, cable-assist and tethering all refer to technology that helps a harvesting machine climb a steep slope. Machines are not suspended from the cables and primary machines should be able to stop in full control at all times without reliance on the cable. Most winch-assist systems utilize alert devices which sounds an alarm in the operator's cab when the anchor moves.

While the concept of winch-assist is relatively simple, integrating winches and cables to machines is quite complicated and has generated different design options. Depending on various characteristics such as the location of the winch and its power source relative to the assisted (primary) machine, there are several categories that winch-assist systems can fall into [10]:

- Integrated winch systems: these systems have winches that are built into or bolted onto the primary assisted machines. This category includes most European-type traction-assist systems and the New Zealand-made ClimbMAX.
- Anchor machine winch systems: dedicated anchor machines are used to house and power winches that are tethered to primary assisted machines. Examples include the Remote Operated Bulldozer (ROB), EMS Tractionline, T-Mar Rhino and EcoForst T-Winch. Recently a winch mounted on a tractor has been introduced (HAAS "Three Point Winch"), providing a different solution in the category of anchor machine winch systems. Locating the winch assembly and electro-hydraulic components on a separate anchor machine has several advantages and disadvantages.

Major international equipment manufacturers that do not manufacture winch-assist systems but produce and supply forestry equipment have recently presented factory solutions to accommodate winch-assist systems for their equipment [13]. Some of these include: operator station enhancements: front escape hatch for improved steep slope safety; four-point seat belt operator comfort and support while operating on steep slopes; enhanced engine and hydraulics system (reservoirs, oil tanks, sumps) grade capabilities designed for continuous 100% grade operation and intermittent 125% grade operation; engineered attachment points (hitches) that are rated at 150% of total machine mass; extended roller frames for enhance stability of the rigid track machines on steep slopes.

3.2 Benefits of winch-assist implementation

Winch-assist technology offers potential for improving the safety, productivity, and efficiency of a harvesting operation [14], as well as for improving felling-machine mobility and reducing soil disturbance through the reduction of slip [12]. When properly implemented, winch-assist technology can provide benefits such as:

1. Safety: most contractors and users of winch-assist systems claim safety is their leading priority when implementing this technology. Mechanization of felling, bunching, shoveling, processing,

skidding, etc., provides the platform for a safe and protected environment for forestry workers. Exposure to hazards is greatly reduced and the number of workers required for the same amount of harvested volume is substantially lowered.

2. Productivity: when properly planned and laid out for winch-assist implementation, productivity gains are also usually achieved. Despite the substantially higher productivity of a felling machine compared to a manual faller, the cost for the felling phase with this technology would most likely be higher. However, increased productivity during extraction phase and overall improved value recovery usually results in improved harvesting system productivity, anecdotally reported as 20% increase overall. In addition to efficiency gains, previously non-economical stands could now be viable for harvesting through the use of winch-assist steep slope machines. These gains could have cascading effects which might improve company profile and performance.
3. Adaptability: there are a few aspects of winch-assisted technology that could improve contractor and company financial sustainability and competitiveness.
   - Quality: both delivered product quality as well as environmental performance quality. Mechanized felling and bunching provides for better directional felling and reduced tangling and breakage. Track spinning and soil disturbance (even on moderate terrain) is reduced to a minimum due to improved assisted traction, thus minimizing erosion potential. Yarding from bunched piles also results in less breakage and operator effort.
   - Worker attraction and retention: working in comfortable, air-conditioned protected modern ergonomic cabs could attract younger workers to consider a career in forestry harvesting. Improved safety, and reduced fatigue and stress have the potential to play a crucial role in retaining such workers. Improved working methods would require less effort and result in less fatigue.
   - Versatility: winch-assist technology can be used in a variety of equipment configurations that fit a contractor's suite of equipment, terrain type, piece size, labor availability (e.g. less yarder operator training required).
   - Sustainability: improved plantability and reduced planting costs will result from reduced breakage during mechanized directional felling and better tree and log positioning for yarder extraction. Less breakage will contribute to higher stand utilization and value recovery. The possibility of on-site delimbing and processing will result in less road side debris disposal and minimizing the need to burn piles.

3.3 Safety measures for winch-assist technology

There have been several international developments in safety measures for winch-assist technology based on recent learning derived from fatalities and failures occurred in recent years:

1. Rules, approved codes of practice, best practice guidelines:
   - New Zealand has winch-assist regulation within the national governmental level Approved Code of Practice.
   - Several forest management companies have developed Best Practice Guidelines, operator training competencies, and training schedules.
   - The New Zealand Forest Industry Contractors Association is developing industry-wide best practice guidelines for operation, maintenance and inspection of winch-assist equipment.
   - FPInnovations is developing Best Management Practices for BC conditions and supporting BC Forest Safety Council's operator competencies and training initiative.

- Oregon requires a special research variance for operating winch-assist equipment and will likely require winch-assist for any ground-based operation on slopes steeper than 50%.
- Equipment manufacturers' manuals and guidelines – all winch-assist equipment manufacturers provide their customers with manuals, guides, and training with varying levels of comprehensiveness. Topics may include: a) winch and cable tension monitoring and control; b) traction and stability (charts and traction coefficient identification guides; c) European winch manufacturers recommend no operation on slopes where traction cannot be maintained without the winch assistance); d) cable(s) and end connectors inspection and maintenance; e) movement sensor(s) and other safety alarms

2. Equipment manufacturers' designs:
   - Emergency back-up systems (second cable, blade or other attachment, warning devices)
   - Software solutions to spikes in tension through better synchronization between tracks and winch
   - Tension monitoring and recording
   - Lower tension in one of the two lines in twin-line systems to ensure engineering safety redundancy in case of main cable failure
   - Rated components of the whole system (2:1, 3:1, or 5:1 safety factors vary by manufacturer)
   - Controlled release vs sudden brake in case of failure.
3. Research focus:
   - Terrain and soil conditions and impacts on traction and stability
   - Use of trees to change machine direction (catching)
   - Anchor types and use of blocks
   - Cable tension behaviour in relation to machine activity
   - Extreme temperatures and the effects of snow and ice
   - Planning and layout for winch-assist harvesting
   - Remote control and teleoperation

4. Teleoperation and autonomous robotic forest operations

The forest industry worldwide has been, and will be, aspiring to completely eliminate incidents during forest operations. There are several international research agencies as well as manufacturers already focusing on the mechanization of steep slope operations with visions similar to that adopted by the New Zealand Forest Owners Association's Steep Land Harvesting Program: No worker on the slope, no hand on the chainsaw [5]. With the exponential development of technology, an integrated approach must be developed for conducting productive and injury-free mechanical harvesting operations on steep slopes that draws on the skills and accountabilities of the working team [15]. Various developments have been achieved and field-tested in the area of remote-controlled forestry equipment on challenging terrain (**Figure 1**) as a necessary first step, often in conjunction with winch-assist applications [16]. Obvious advantages of using remote control is removing the operator from hazards and also providing options for getting the machine out of a difficult situation; disadvantages would be reduced productivity and operator ergonomic comfort level in order to maintain line of site.

One of the most relevant points could be the possibility to introduce the concept of teleoperation using unmanned ground vehicles [17]. Teleoperation extends the concept of remote control even further where a machine is controlled by an operator at a remote location (no line-of-sight) with the use of cameras, sensors, and possibly additional positioning software. Benefits of teleoperation include safe and comfortable working environment, maintained productivity and extended work-shifts, cables machines with reduced weight and lower center of gravity, opportunity to introduce semi-automation and/or multiple machine operation by a single operator [16]. It is important to note that teleoperation of forestry machinery is a difficult problem, primarily due to the unstructured and uncontrolled environment in which forestry harvesting takes place [18]. Milne [18] also reported that autonomous control using Robot Operating System (ROS) and Minimal modelling based system identification techniques were useful for retrofitting excavator based forestry harvesters and removing the requirement of operators to operate all the hydraulic rams of the machines. Initial prototypes have already been developed (**Figure 2**) and prepared for field testing in New Zealand [16].

Beyond a certain physical threshold of the operational site, however, the only feasible and achievable solution providing some intelligent behaviour to machines and systems would be the role of mechatronics application [2]. Autonomous robotic forestry operations, particularly tree felling, have received significant attention and achieved advancements in recent years [19]. To successfully navigate its environment, semi-autonomous robotic devices must be capable of identifying the position, size and orientation of trees and other obstacles in the forest. Kolb *et al*. [20] proposed an approach to identify trees using data gathered from a LiDAR scanner. Such developments will speed up the implementation of teleoperated, semi-autonomous and fully autonomous forestry equipment and, in conjunction with constantly improving winch-assist technology, will provide a platform for safely extending the range of ground-based equipment to previously infeasible terrain conditions.

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TABLES

Table 1 - Ground steepness (%) limits for various types of forestry equipment. *Source: [5]*

Traction devices and the undercarriage	Ground steepness (%)		
	Harvesting	*Skidding*	*Forwarding*
Wheel with chains and band tracks	35-45	35-45	30-35
Triangular tracks	50-70	n.c.	n.c.
Integral tracks	45-60	45-55	35-45
Walking carriers (e.g. Menzi Muck)	60-80	n.c.	n.c.
Ground carriage (e.g. Konrad Pully)	n.c.	80-100	n.c.

FIGURES

Figure 1 - Field testing of remotely controlled winch-assist felling machine in New Zealand *Source: [16]*.

Figure 2 - Initial prototype of a teleoperation forest harvesting console in New Zealand *Source: [16]*.