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Project Title: Protecting the Logging Workforce: Development of Innovative Logging Techniques for a Safer Working Environment

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List of Terms and Abbreviations

Carriage– A load-carrying device from which logs are suspended and which rides back and forth along the skyline on sheaves for yarding. Also called the “skyline carriage”.

*CHCF = Cable-assisted harvesting + cable-assisted forwarder

Choker– A short (usually less than 20 feet) noose of wire rope for hauling logs.

Choker setter- the person who puts a choker around a log and attaches it to the skidding or yarding equipment.

*Conventional = Manual timber falling and choker setting + cable logging

FAAC=Forest Activities Advisory Committee of Oregon Occupational Safety and Health Administration

Fall– See “fell”. Note: “fall” and “faller” are often used interchangeably with “fell” and “feller”.

*FBCY = Self-leveling feller-buncher + conventional yarding

*FBGY = Self-leveling feller buncher + grapple yarding

Fell-To cut down trees. Also “fall”.

Feller-buncher– See “Full-tree length harvester“.

Full-tree length harvester– A machine with a fixed-grip harvesting head which can grasp, cut, lift, swing and bunch trees for yarding. Usually this machine does not limb or buck to log lengths as a “cut-to-length” harvester can do. Also known as a “feller buncher”.

Grapple– A hinged set of jaws capable of being opened and closed, used to grip logs during yarding or loading. Can also be attached to swing or non-swinging grapple skidder.

Grapple yarding– Cable yarding with grapples instead of chokers.

Grouser- The raised steel strip the length of a crawler pad to provide traction.

Harvesting– A loose term for the removal of trees from the forest, for product utilization.

Hook– a) n. A curved member used to catch, hold, or pull something. b) v. To attach chokers to logs in the brush.

Landing– A place where logs are collected prior to further transportation. See “Spot landing” and “Continuous strip landing”

Lateral yarding– Any movement of logs toward the centerline of a yarding road.

Layout– a) a logging plan including units and roads. b) The position of the running lines in a cable yarding system.

Log– a) n. Any cut section of a felled tree. b) v. To harvest timber.

Logger– A worker employed in the woods producing wood products or in the support of such production, such as road construction.

Logging– Any or all part of converting trees into logs and transporting them to an unloading area.

Machine rate– The cost per unit of time to own and operate a piece of equipment.

MBF– Thousand board feet. Often the log rule being used is appended, such as “MBF, Scribner.”

OROSHA=Oregon Occupational Safety and Health Administration

Radio controlled carriage– A carriage that is operated by remote control with radio signals from the ground.

Rigging– The cables, blocks, and other equipment used in yarding and loading logs.

Rigging slinger– The headman on a rigging crew who is responsible for choker setters and chaser and who selects the logs to make up a turn.

ROPS– Roll Over Protection Structure. A sturdy structure built into or fitted around the operator cab on certain equipment which protect operators if the machines overturn.

Shackle– A U-shaped metal connector with a pin or threaded bolt through the ends. AKA “clevis”.

Yarder– A machine or system of winches used to haul logs into a landing. Often combined with a portable tower. Technically the yarder is just the power and winch system, but in practicality today, it is the whole machine including the tower.

Yarding– The act or process of conveying logs to a landing. In common practice, yarding is often reserved for cable logging, while skidding is used for ground based logging.

* Definitions with this symbol are project specific.

http://www.soperwheeler.com/about-us/education/logging-terminology/

Abstract

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Logging is one of the most dangerous occupations in the United States. Latest year deaths are 55 nationally (BLS) with numerous serious injuries (National injury data underreported). Adoption of technology and engineering solutions have the potential to reduce hazards workers are exposed to and to increase productivity of each individual worker. This is important in an industry having a difficult time recruiting and maintaining a younger work force.

This project examines the benefits and challenges of using tethered logging systems on steep slopes to reduce the number of workers exposed to the hazards for felling trees. Operators are in machines with "Forestry" cabs that are designed to withstand impacts from trees and other falling objects.

The most recent reporting shows that tethered systems in Oregon have operated 33,329 hours (June/2016 to June/2019) on slopes over 50%. Estimates are that tethered mechanical felling systems are, on average, two to four times more productive than hand falling. This replacement use of tethered systems equates to 97 faller years, which could have seen two deaths and numerous critical injuries. Washington has more tethered logging systems operating than Oregon and their data would be similar to Oregon. Over 200 cutter years have likely been saved in the two states. To date, there have been no serious injuries or deaths reported with tethered systems in Oregon and Washington.

In order for state and federal land managers to embrace the use of tethered systems on the ground they manage, productivity and environmental concerns need to be addressed as well as improved safety.

System productivity was studied and compared to conventional hand falling techniques. In a whole-tree harvesting comparison, machine cutting was twice as productive as manual cutting and the advantages of pre-bunching increased yarding productivity 120% over yarding after conventional cutting. A tethered harvester in a cut-to-length system had a productivity rate of 2100 cubic feet per scheduled machine hour.

Stability analysis of tethered systems was studied and compared to non-tethered systems. Tethered systems shift the effective center of gravity of machines on steep slopes, increasing the ground track contact length or wheels with the ground. This was modeled using several machines positioned in different orientations on and off tether.

Impacts to soil and water quality were investigated in case studies. Soil erosion, infiltration rate, bulk density, and compaction were measured. On the sandy, silt, clay soils of western Oregon it appears that tethered equipment may, through a tillage effect, loosen soil in some cases. Soil compaction was minimal. These findings of limited environmental impact may speed land managers acceptance of tethered operations and thereby improve safety of forest workers on steep terrain.

Project findings were documented in ten publications and disseminated in 36 presentations.

Section 1 - Overview

Significant or Key Findings

In Oregon, the logging portion of the forestry sector generates about 8,000 jobs and produces approximately $701 million in goods, and much of this employment and income is retained within rural areas of the state, which often have fewer employment options (Adams et al., 2012).

Unfortunately, logging represents one of the two most dangerous jobs in the United States with high fatality and injury rates (Figure 1, Bureau of Labor Statistics, 2018). This is due to the nature of the work that is often performed on steep ground, frequently under wet conditions with unstable footing. Large trees are severed and fall to the ground without any additional restraint. Subsequently, choker setters must climb on these potentially unstable tree stems to attach cables before they can be pulled by a yarder, a specialized crane, to a centralized landing area with a limited operating space.

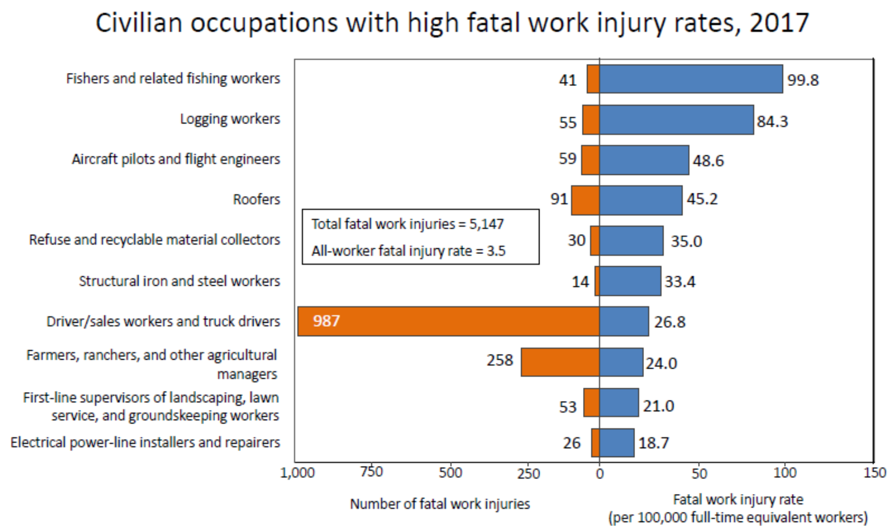

Figure 1: Fatal occupational injuries as reported in 2017, logging has the second highest rate per 100,000 full-time equivalent workers. Bureau of Labor Statistics CFOI, 2018.

Logging on steep slopes of the western United States is one of the most dangerous occupations in the United States. Hazards associated with this work include, but are not limited to; workers struck by dislodged and falling logs, repetitive movements over unstable terrain leading to chronic joint damage, work in almost any weather condition, and long shifts.

Tethered logging systems are ground-based systems that use a winch, either externally, or internally powered to provide stability and traction to the equipment operating on the slope. These tethered systems offer the opportunity to move workers from hazardous operations on the ground to the protection of a cab, and to increase safety of subsequent operations through bunching of timber.

Latest reporting from industry in Oregon, using tethered logging systems, shows over 97 cutter equivalent years have been completed by tethered systems. Conventional hand cutting could have seen 2-4 deaths and numerous injuries over this period of time. Tethered system injuries during this time frame were zero and no time loss injuries were reported. This significant reduction in injuries and death are conservative as timber falling statistics are not fully reported at state and federal levels. In addition, Oregon data only covers hours on steep slopes. However, mechanized cutting also occurs on other slopes likely substituting for additional cutter hours.

We found that OVERALL worker safety is improved and environmental impacts appear minimal compared to conventional harvest techniques.

1. Tethered operations reduce worker exposure to falling hazards, dislodged logs and rocks.
2. Tethered operations reduce worker hazards from falls, sprains and strains, and chronic use resulting from working on steep terrain.
3. Tethered systems are ideal for harvesting storm damaged stands with trees hung up and twisted together. Hand falling in these conditions is highly risky.
4. Worker productivity is increased and machine operation is preferable to manual logging for new workers.
5. Tethered assist improves machine traction on steep slopes, allowing more area to be managed from the safety of a machine cab.
6. Impact to western Oregon clay soils has been minimal from measurements on compaction (soil penetrometer), soil moisture, and erosion.
7. Operators are exposed to less stress, shock, and physical demands than traditional logging occupations.
8. Our team has suggested an approach that the state of Oregon can proceed from tethered machines operating under a research variance to state approved regulation.
9. One concern is that as industry adopts the new technology, there are going to be areas the systems are not going to be able to access. This will leave difficult terrain for the remaining hand fallers to work, potentially leading to greater risk for people in this line of work.

Translation of Findings

Thirty-four presentations have been made at regional, national, and international meetings, and two additional presentations are scheduled. Invitations to present findings have been extended by all major logging organizations in the Pacific Northwest. Several workshops have been held. Project findings will be instrumental in formulating logging regulations in Oregon and members of the research team are assisting the Forest Activities Advisory Committee of OROSHA in this effort.

Research Outcomes/Impact

Research outcomes are being documented in ten publications (four peer-reviewed manuscripts have been published, one is in press, one is in review, and four are in preparation). The research team has been sought for presentations in other states of the Pacific Northwest to share their insights on the new tethered technologies.

Section 2 – Scientific Report

Background

Logging comprises a significant component in rural economies throughout the United States, especially in the western states including California, Idaho, Montana and Washington. In Oregon, the logging portion of the forestry sector generates about 8,000 jobs and produces approximately $701 million in goods, and much of this employment and income is retained within rural areas of the state, which often have fewer employment options (Adams et al. 2012).

Logging is dangerous work looking to transition to new methods to improve worker safety and meet reduced workforce availability/willingness to engage in this line of work (Image 1). Workers compensation rates sometimes equal or exceed employees' wages. It is very costly to employers to hire timber fallers and choker setters. However, after the workers compensation is paid the employee doesn't see much more direct compensation compared to other jobs that are much less dangerous and physically demanding. The lack of interest by young people to enter the logging workforce has been also recognized as a major difficulty encountered by the US forest sector.

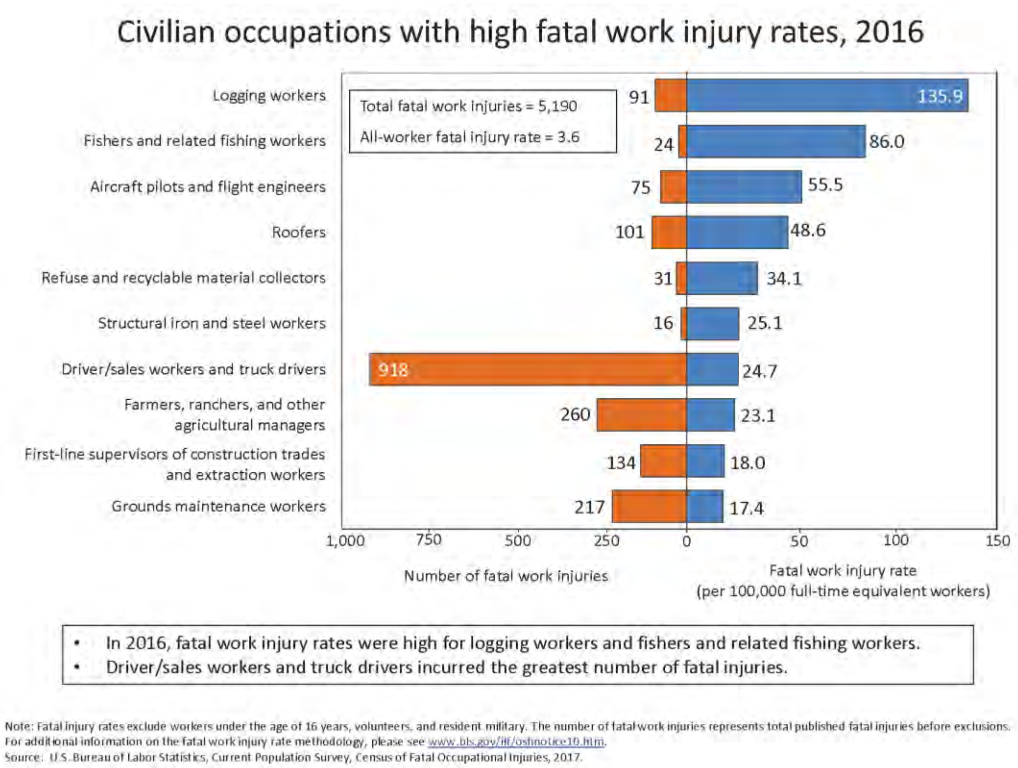

Figure 2: Fatal injury rate of American workers by hazardous occupations for 2016, logging had the highest fatality rate per 100,000 full-time equivalent workers.

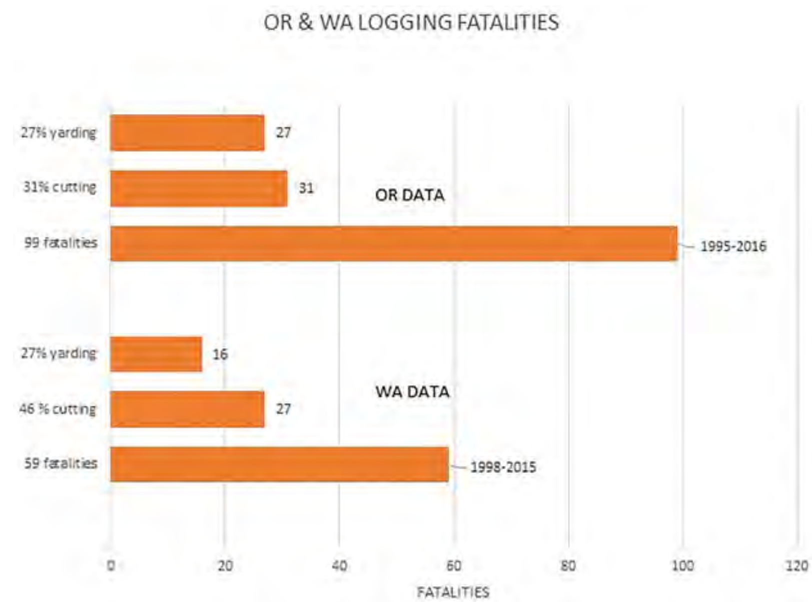

Figure 3: Oregon and Washington logging fatalities. From Garland et al. 2019.

Mechanization is one method that has been successful in reducing logging-related accidents. In West Virginia, between 1995 and 2000, felling injury claims were reduced from 19.4 per 100 workers to 5.2 per 100 workers (Bell, 2002). Struck-by injuries also showed a significant reduction after the introduction of mechanized felling into the West Virginia logging industry (Bell, 2002). Thus, the goal for this project is to encourage the development of mechanization using self-leveling feller-buncher, grapple yarding, and cable-assisted forest vehicles in the Pacific Northwest logging industry to replace or reduce the hazardous tasks currently being performed on our steep forest lands. Mechanization of timber cutting not only protects the faller, but permits timber to be pre-bunched (Image 2) in a manner that makes setting chokers and yarding much easier and safer for the rigging crew. Logs are placed to lead by a tethered feller-buncher over pre-determined yarding corridors. This technique reduces the complexity in choking logs, increases productivity, and provides overall safer working conditions.

This project looked at transitioning logging industry workers from being directly exposed to hazards associated with logging, to reducing worker exposure through the use of mechanized felling and yarding equipment on steep slopes. Reported injuries and deaths are down in Oregon and Washington using tethered systems compared with traditional hand felling. One issue of concern is that as the industry adopts the new technology of tethered logging systems, there are going to be areas that the current systems are not going to be able to access. This will leave even more difficult and complex terrain for the remaining hand fallers to work, potentially leading to greater risk for people in this line of work.

Image 1: Rigging crew in timber that has been manually felled.

Image 2: Timber laid out in pre-bunched piles from tethered feller-buncher on steep slopes reduces worker fatigue, exposure to unseen hazards, and speeds the yarding process. When asked what the difference is between setting chokers in pre-bunched vs. hand fallen timber, one crew

member said with a chuckle, "It's kind of like stealing from the boss," when working in pre-bunched timber.

Specific Aims

To accomplish the goals of this project, four aims were developed.

AIM 1. Demonstrate safe operation of new logging systems

AIM 2. Assess the practical and physiological response of logging workers

AIM 3. Develop guidelines and design criteria for new logging systems

AIM 4. Develop and deliver outreach programs to introduce safe mechanization to loggers

Specific Aims Accomplishment

To accomplish the specific aims, tasks were developed for each aim.

AIM 1. Demonstrate safe operation of new logging systems

Task 1. Locate and survey skyline or machine corridors for Self-leveling feller-buncher + conventional yarding (FBCY), Self-leveling feller buncher + grapple yarding (FBGY) and Manual timber falling and choker setting + cable logging (conventional logging system) – three ground slope conditions (30-40%, 40-50%, and 50-60%) and two soil conditions (wet and dry). Determine theoretical maximum payload capacity using a skyline payload analysis program.

Task 2. Place a remote camera to assist operator visibility for FBGY sites.

Task 3. Identify, mark, and survey machine corridors and anchor locations for Cable-assisted harvesting + cable-assisted forwarder (CHCF) sites.

Task 4. Place internal and external cameras within the equipment to perform detailed time studies and monitor operator behavior and response (Aim 2), as well as machine operability (Aim 3).

Task 5. Test 18 replicates of FBCY, FBGY, CHCF and conventional logging systems under suite of monitoring and instrumentation systems to facilitate physiological and operative response of workers (Aim 2), develop and test design guidelines for logging operation (Aim 3) and provide the substance to develop and deliver education and training components (Aim 4).

AIM 2. Assess the practical and physiological response of logging workers

Task 1. Enlist a limited number of operators, at least 5 will be needed across age and experience ranges.

Task 2. Perform detailed interviews prior to the study to provide background data for cooperating operators.

Task 3. Monitor operator actions and reactions while operating on typical and steep slopes. Items to be measured will include operator's heart rate, camera recording of eye movements, and body movements, whole-body vibration at low frequencies, and periodic interviews immediately after a hazardous situation on a slope. Measurement of respiration and galvanic skin response may also be possible to detect a physiological change to work conditions.

Task 4. Responses to findings can be compared with a larger survey of machine operators who currently operate on steep slopes using the conventional logging system to compare the hazards, responses to risk, and operating practices along with a characterization of operators.

Task 5. Perform observational studies using a behavioral observation scale of key operator behaviors. Workloads will be monitored and will include heart rate measures of manual felling and choker setting.

Task 6. Perform detailed time studies to link characteristics of the task and the outcome for the three systems to measure the differences in work exposure to hazards and unsafe actions on the part of the work force.

Task 7. Compare hazard exposures from changes to system by documenting exposure likelihood using behavioral observation scales for job tasks. Compare operations in typical and steep slopes with workload measures, physical measures, and operating circumstances from time study observations for cooperating operators.

AIM 3. Develop guidelines and design criteria for new logging systems

Task 1. Evaluate the limits of self-leveling cabs within the framework of the state forest practices and OSHA regulations use on steep terrain.

Task 2. Identify the impact of soil moisture, strength and type on mobility of non-cable assisted felling machines mobility on steep slopes.

Task 3. Determine the change in risk for setting chokers on bunched stems by analysis of feller-bunchers under static and dynamic loading on steep terrain and evaluating the cable tensions in the yarding system during operation.

Task 4. Measure the exposure to new hazards for workers in managing the smaller bunches of logs while attaching them to the overhead cable system by evaluating cable tensions during the "break-out" or yarding phase of lifting the log payload off the ground.

Task 5. Associate detailed time studies with performance of equipment and tractive response (e.g. slip of equipment vs. worker action) for FBCY, FBGY and CHCF systems to evaluate unsafe operator actions.

Task 6. Collect dimensions of the falling machine to determine weight and center of gravity for various positions of the boom and amount of cable on the drum for internal winch systems using data collected from soil pressure cells.

Task 7. Establish guidelines for required operative constraints for anchors and equipment for the FBCY, FBGY and CHCF systems. For all systems, slope debris, and soil constraints will be presented in the form of easy-to-use design charts. For the FBCY and FBGY systems, anchoring limits will be presented based on cable selection and anchor type. For the CHCF system, required cable strength will be presented based on payload and site conditions.

AIM 4. Develop and deliver outreach programs to introduce safe mechanization to loggers

Task 1. Develop logging training manuals for self-leveling feller-bunchers, grapple yarding, and cable-assisted forest vehicles in English and Spanish.

Task 2. Present and disseminate results to various state agencies that document the changes in the work practices for the FBCY, FBGY, and CHCF systems when compared with the conventional yarding system.

Task 3. Use the results from Aims 1 through 3 to develop the inputs for regulations to promote safe logging practices on steep slopes.

Task 4. Disseminate results through peer-reviewed journals and conference proceedings to advance the understanding of mechanized steep slope logging operations.

Methodology

Interviews

At the beginning of the study, operators, logging contractors, and landowners were interviewed under conditions of informed consent and anonymity. Operators were assessed using the Nordic Questionnaire for health conditions, age, weight, height, experience and working conditions. Logging contractors were asked circumstances of their operation, safety statistics, working conditions for operators, plans for tethered logging systems, equipment configurations and capital costs, and personal attributes of age, experience, and work/firm history. Landowners were queried on area/volume suitable for tethered logging, safety statistics, scope of tethered and conventional logging, personal characteristics, and expectations for future tethered logging.
At the end of the study, operators, contractors, and landowners were re-interviewed for the same criteria as well as general assessments of their experiences with tethered logging. Operators were asked to identify any critical incidents from their experience during the study. All data were kept confidential for the subjects.

Operator Measures

Our project has measurements on individual operators using non-tethered and tethered operations, using different machines, and at differing times in the operators' experience. We are measuring operators' vital conditions for:

- heart rate;
- galvanic skin response;
- temperature; and
- whole-body vibration.

Eye-tracking glasses are worn by the operators and a camera shows the inside of the cab and operating views. Operators have been interviewed for fatigue and measured their typical sleep period. Demographic data of age, experience, height, weight, prior injuries and complaints, and wage/hours basis are available. Our research on grapple yarding technologies is now underway. We are hopeful that our research will help inform development of safety guidance and regulations, experience and training needs of operators, machine designs, and planning and management of steep slope operations. For details, see Garland et al. (2019).

Operators of 11 tethered logging systems participated in our study. This included signing them up for the study, explaining informed consent. Once an operator agreed to participate in the study, they were outfitted with vision tracking video recording glasses, a Go-Pro camera was placed in the cab, accelerometers were placed on the head, shoulder, and rigid part of the seat, and the operator was outfitted with an Empatica E4 wristband. The vision tracking glasses allowed the research team to examine what the operator was focusing on through the shift. The Go-Pro video was synced with the vision tracking glasses to see what the terrain, timber, weather, and other conditions were experienced. Using the time from the videos, accelerometer data peaks were analyzed to see if large shocks were related to operating conditions (steepness, drop offs, high stumps). The Empatica E4 wristband is a medical grade biometric tracking system. Data from the Empatica unit were analyzed with the above data to see if there were certain conditions that increased the level of stress experienced by the operator. Additionally we were able to outfit a faller with the accelerometers and Empatica for several hours and the vision tracking glasses and Go-Pro while cutting a tree. A choker setter was outfitted with the Empatica and accelerometers for a shift. The data for the tethered operators was compared to the hand faller and choker setter.

Time studies

Cable-assisted (or tethered) mechanized harvesting has recently been introduced to the Pacific Northwest of the United States, and is rapidly being adopted by the forest industry. However, potential environmental impacts, productivity and cost of the new harvesting systems have not been well-assessed. Our study aimed to examine the effects of cable assistance on soil compaction, system productivity and cost through a field-based experiment. A harvester-forwarder system was used to thin a harvest unit on dry soils in western Oregon with and without cable-assistance. We conducted a detailed time study during operations and collected soil measurements before and after machine passes. Machine productivity ranged from 28.75 m3 to 92.36 m3 per scheduled machine hour, with resulting unit costs for untethered and tethered systems ranging from $13.19/m3 to $17.78/m3. Our results showed reduced soil impacts in both extent and degree of soil compaction when cable assistance was employed. The reduced extent of soil impacts is attributed to a reduction in track wander owing to the operative tensions of the tether cable, and the smaller increase in soil density appears to be attributed to combined effects of initially denser soil conditions and reduced shear displacement as a result of cable-assistance.

We also conducted a comparative case study in southern Oregon to investigate the economic and environmental impacts of cable-assisted, mechanized timber felling (FBCY system) in steep terrain by comparing mechanical felling with conventional manual felling followed by cable-logging. We performed detailed time studies on manual felling, mechanical felling, cable-logging after manual felling, and cable-logging after mechanical felling. Environmental impacts of these systems were measured through pre-felling, post-felling, and post-extraction samples of soil bulk density, penetration resistance, water infiltration rates, and sediment yield. The significance of this research is the development of data that can provide insights into potential economic and environmental impacts of cable-assisted timber harvesting relative to the conventional harvesting method in steep terrain.

Pressure testing

The stability of tethered equipment was found to be a function of equipment dimensions, equipment configuration, weight, ground pressures, eccentricity, cab level, hillslope inclination and tether tension. To confirm these assumptions and provide the basis for a physics-based model to assess tether tension required for safe operation, a series of field tests were performed to understand the interaction of equipment on steep ground, measured through ground pressures. Several pieces of equipment, with and without a tether, were evaluated in a variety of possible configurations to assess how the center of gravity of machinery changes, and how ground pressures change commensurately. The distribution of ground pressures defines how the base of the machine engages the strength of the underlying soil. Under eccentric configurations, only part of the track is engaged, and the machine may be in an unstable configuration (e.g. prone to sliding). Use of a tether in tension reduces eccentricity and increases track engagement, increasing (1) resistance to sliding from the underlying soil, and (2) resistance to sliding from cable tension. The configuration of ground pressure cells is shown in Figure 4. The distribution of ground pressures for tethered and untethered equipment is shown in Figure 5. The ground pressures change notably with the location of the boom, as well as with the leveling of the cab. This reflects changing eccentricity of the machine with configuration. Notably, when 10 tons of tether tension are considered, the pressure distribution shifts, engaging the track length more evenly, and effectively allowing for a more stable configuration. Further, uphill orientation of the cab and boom results in more even track engagement and a more stable state. These findings were the basis for physics-based models for equipment stability (Sessions et al. 2017, and Belart et al. 2019).

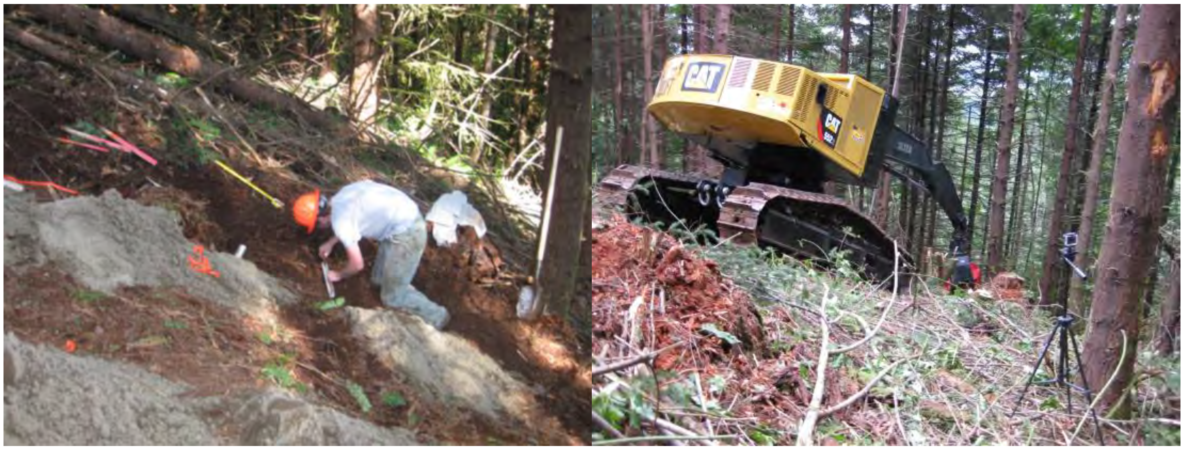

Image 3: Researcher installing pressure cells to help determine the change in ground pressure between tethered and untethered feller-buncher. Feller-buncher, untethered, going through ground pressure testing on steep slopes.

Image 4: Researcher Ben Leshchinsky overseeing data collection during a ground pressure test.

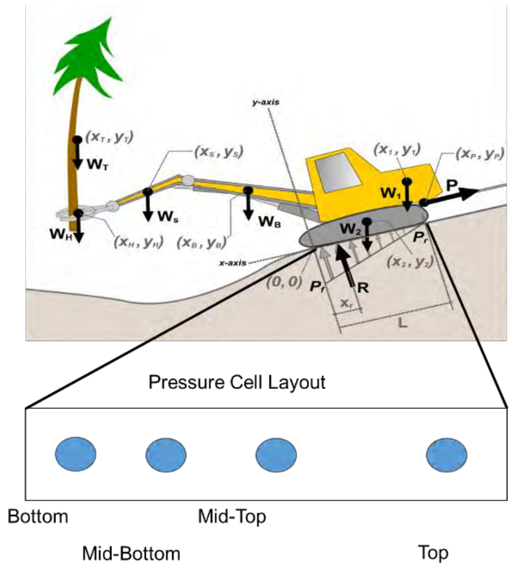

Figure 4. Free body diagram of a tethered feller-buncher with a directional felling head on a rigid suspension tracked undercarriage with boom downhill. P_f is the pressure at the leading edge of track. For downhill travel P_f is at the lower end of the track; for uphill travel P_f is at the upper end of the track. Nomenclature is defined below.

Variable	Definition	Units	Value (Downhill)	Value (Uphill)
P	Cable (Tether) Tension	kgf	Varies	Varies
R	Resultant	kgf	Dependent	Dependent
W_T	Weight of Tree	kgf	Varies	Varies
W_H	Weight of Cutting Head	kgf	2610	2610
W_S	Weight of Stick	kgf	2270	2270
W_B	Weight of Boom	kgf	3630	3630
W_1	Weight of Cab/Engine	kgf	12700	12700
W_2	Weight of Undercarriage	kgf	14520	14520
X_P, y_P	Coordinates of Hitch Point	m	(3.81,0.76)	(3.81,0.76)
x_r	Distance to Pressure Resultant	m	Dependent	Dependent
x_T, y_T	Coordinates of Tree CG	m	(-7.37,10.16)	(9.75,10.16)
X_H, y_H	Coordinates of Cutting Head CG	m	(-7.37,0.91)	(9.75,0.91)
X_S, y_S	Coordinates of Stick CG	m	(-6.10,3.05)	(7.01,3.05)
X_B, y_B	Coordinates of Boom CG	m	(-2.03,3.05)	(5.79,3.05)
X_1, y_1	Coordinates of Cab/Engine CG	m	(L,1.83)	(0L,1.83)
X_2, y_2	Coordinates of Undercarriage CG	m	(0.5L,0.84)	(0.5L,0.84)
P_f	Pressure at Front of Tracks	kPa	Dependent	Dependent
P_r	Pressure at Rear of Tracks	kPa	Dependent	Dependent
S	Slip	-	0.15	0.15
ϕ	Soil Internal Angle of Friction	°	15, 30	15, 30
c	Soil Cohesion	kPa	7, 14	7, 14
K	Soil Deformation Modulus	cm	1.27	1.27
HG	Grouser Height	cm	5.10	5.10
L	Sprocket to Sprocket Length	m	4.27	4.27
LE	Effective Track Length	m	Varies	Varies
TW	Track Width	m	0.61	0.61
μ	Apparent Traction Coefficient	-	Dependent	Dependent
MR	Motion Resistance Coefficient	kgf/kgf-Normal	0.025	0.025

Table 1. Definitions and base equipment, soil, operating conditions for examples.

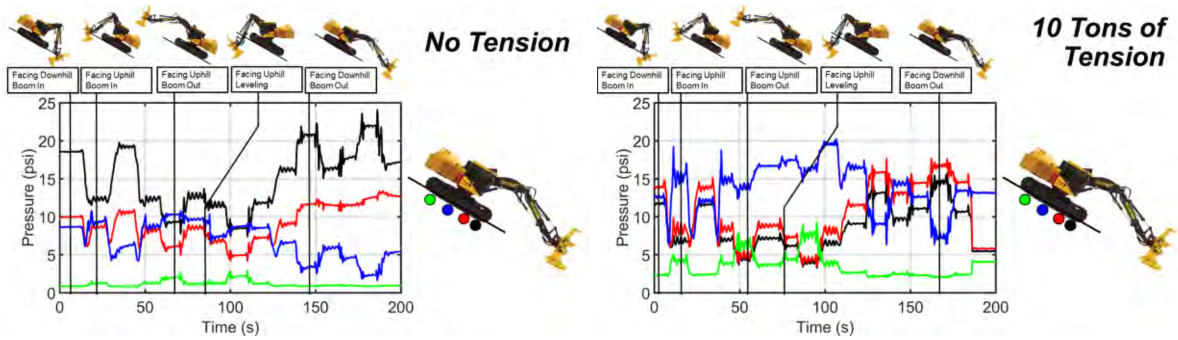

Figure 5. Pressure profiles for tethered (and untethered when P=0 kgf) feller-bunchers for various slopes and tree weights.

Results

AIM 1. Demonstrate safe operation of new logging systems

Task 1. Locate and survey skyline or machine corridors for Self-leveling feller-buncher + conventional yarding (FBCY), Self-leveling feller buncher + grapple yarding (FBGY) and Manual timber falling and choker setting + cable logging (conventional logging system) – three ground slope conditions (30-40%, 40-50%, and 50-60%) and two soil conditions (wet and dry). Determine theoretical maximum payload capacity using a skyline payload analysis program.

Task 1 was undertaken in two study areas, one in the OSU Research Forest, Corvallis, Oregon and the other on industrial forest land in southwest Oregon near Roseburg, Oregon.

On the study site at the OSU Research Forest, machine testing was performed on slopes ranging from 28% to 52% for feller-bunchers with and without a tether. Stability analyses were developed from these tests (Sessions et al. 2017, Belart et al. 2019) for a variety of soil conditions. Ground pressures were examined from testing.

On the southwest Oregon site, we were able to use empirical data, rather than theoretical data, to compare conventional manual felling and cable yarding and tethered feller-buncher felling and cable yarding (FBCY) in the same stand, with the same cable yarder and crew. FBCY was substituted for FBGY because the industrial owner did not have a grapple carriage available at the time of the experiment.

Task 2. Place a remote camera to assist operator visibility for FBGY sites

Not implemented. Advances in carriage technology made this approach inefficient. Cameras are now available on the skyline carriage itself.

Task 3. Identify, mark, and survey machine corridors and anchor locations for Cable-assisted harvesting + cable-assisted forwarder (CHCF) sites

Machine corridors for cable-assisted harvester and forwarder sites were identified, marked, and surveyed on the OSU College Research site by project personnel. Testing was performed on a corridor ranging from 10% to 60% for a tethered and untethered wheeled harvester and forwarder. Pressure cells were used to monitor soil-machine interaction, but many of the pressure cells were lost in testing. Anchoring consisted of conventional stump anchors, which showed little response to the low tether loading.

On the southwest Oregon site, with conventional and tethered feller-buncher felling, corridors were identified by company foresters and logging personnel.

Task 4. Place internal and external cameras within the equipment to perform detailed time studies and monitor operator behavior and response (Aim 2), as well as machine operability (Aim 3).

Machines were instrumented with GoPro cameras and in some cases vision tracking glasses that operators wore. This video was analyzed along with accelerometer data. When an accelerometer showed an operator was exposed to a heavy G load, the video for that time frame was reviewed to see if there were any obvious causes for the elevated shock load, and if there are recommendations that can be made to operators to minimize their exposure to high levels of shock.

Task 5. Test 18 replicates of FBCY, FBGY, CHCF and conventional logging systems under suite of monitoring and instrumentation systems to facilitate physiological and operative response of workers (Aim 2), develop and test design guidelines for logging operation (Aim 3) and provide the substance to develop and deliver education and training components (Aim 4).

We monitored a timber faller and rigging slinger for physical conditions of the work. No cooperators had a FBGY system in place that we were able to assess.

AIM 2. Assess the practical and physiological response of logging workers

Task 1. Enlist a limited number of operators, at least five will be needed across age and experience ranges.

Operators of 11 tethered logging systems participated in our study. This included signing them up for the study and explaining informed consent. Once an operator agreed to participate in the study, they were outfitted with vision tracking video recording glasses, a Go-Pro camera was placed in the cab, accelerometers were placed on the head, shoulder, and rigid part of the seat, and the operator was outfitted with an Empatica E4 wristband.

Task 2. Perform detailed interviews prior to the study to provide background data for cooperating operators.

At the beginning of the study, operators, logging contractors, and landowners were interviewed under conditions of informed consent and anonymity. Operators were assessed using the Nordic Questionnaire for health conditions, age, weight, height, experience, and working conditions. Logging contractors were asked circumstances of their operation, safety statistics, working conditions for operators, plans for tethered logging systems, equipment configurations and capital costs, and personal attributes of age, experience, and work/firm history. Landowners were queried on area/volume suitable for tethered logging, safety statistics, scope of tethered and conventional logging, personal characteristics, and expectations for future tethered logging.

At the end of the study, operators, contractors, and landowners were re-interviewed for the same criteria as well as general assessments of their experiences with tethered logging. Operators were asked to identify any critical incidents from their experience during the study. All data were kept confidential for the subjects.

Task 3. Monitor operator actions and reactions while operating on typical and steep slopes. Items to be measured will include operator's heart rate, camera recording of eye movements, and body movements, whole-body vibration at low frequencies, and periodic interviews immediately after a hazardous situation on a slope. Measurement of galvanic skin response may also be possible to detect a physiological change to work conditions.

Image 5: Cooperating operator outfitted with biometric monitoring devices. PI John Garland talking with cooperators about project logistics and participant availability.

Operators were outfitted with a suite of monitoring equipment. This included vision tracking eye-glasses and associated laptop computer to record, accelerometers, and an Empatica (*The E4 wristband is a wearable research device that offers real-time physiological data acquisition and software for in-depth analysis and visualization)*. Additionally, GoPro cameras were placed in the cab to be able to observe the operator movement within the cab. The vision tracking glasses allowed the IRB members of the research team to review what the operator was looking at and assessing while running the machine. We could see that some operators used visual cues from the machine, such as how far a hydraulic piston had moved to let them know when a tree would be cut from the stump because they couldn't always see the saw as it was cutting. Accelerometers were used to analyze exposure to shock from operating machines, then looking at GoPro and glasses videos at times of higher levels of shock to see what activities lead to this shock load. The Empatica system recorded measures blood volume pulse (BVP), from which heart rate variability can be derived, 3-axis accelerometer captures motion-based activity, EDA sensor (GSR Sensor) measures the constantly fluctuating changes in certain electrical properties of the skin, the infrared thermopile reads peripheral skin temperature, and the internal real-time clock provides 5ppm high accuracy time reference.

Task 4. Responses to findings can be compared with a larger survey of machine operators who currently operate on steep slopes using the conventional logging system to compare the hazards, responses to risk, and operating practices along with a characterization of operators.

During the course of the study, operators, contractors, and landowners were engaged in research as they became available and willing to participate. At the continuation of the study, additional tethered logging operators started operations in Oregon but were not able to be included in the study. These total operators form a pool of experience that can be interviewed in future research but our research was not able to interview the operators not included and engaged in the research. Additional funding should be sought to conduct a survey (telephone) of operators engaged in tethered logging in Oregon for full perspective of operator experiences and issues. Interviews are continuing.

Task 5. Perform observational studies using a behavioral observation scale of key operator behaviors. Workloads will be monitored and will include heart rate measures of manual felling and choker setting.

Task analyses of the jobs in the study have documented the subtasks, knowledge, skills, abilities and risks for the following jobs:

- Mechanized felling operator steep slopes
- Shovel operator yarding logs tethered
- Harvester operator using tethered wheeled harvester on steep slopes
- Forwarder operator tethered
- Conventional felling
- Conventional yarding

Behavioral observation scale assessments were made for the operations in the study to identify time in the task and exposure to hazards of the work. See example in Appendix 1.

In addition, the Empatica system was used to collect heart rate of manual fellers and choker setters. Both positions had significantly elevated heart rate compared to machine operators, as well as, much more fluctuation in heart rate as they went about different tasks within the scope of their work.

Task 6. Perform detailed time studies to link characteristics of the task and the outcome for the three systems to measure the differences in work exposure to hazards and unsafe actions on the part of the work force.

No cooperators had a FBGY system in place that we were able to assess.

Task 7. Compare hazard exposures from changes to system by documenting exposure likelihood using behavioral observation scales for job tasks. Compare operations in typical and steep slopes with workload measures, physical measures, and operating circumstances from time study observations for cooperating operators.

What our research can show for traditional and new technologies is the difference in the hazards and worker exposure as well as the reduction in workers exposed to the hazards. The hazards of the work were identified by the task analysis. Table 2 shows a partial comparison of the hazard exposure for the tree felling with traditional hand felling and using a felling machine for selected tasks. A review and comparison shows the new technology is projected to virtually remove most of the dangerous hazards found in traditional hand felling on steep slopes, such as slips and falls; struck by overhead hazards; and struck by objects while cross cutting. However, new technologies using large, heavy equipment on steep slopes have deadly hazards for machine rollover and chainshot hazards. The frequency is so low for these hazards that the new technologies are much safer. Similar differences can be seen comparing traditional cable yarding with use of grapple yarding of tree piles bunched on steep slopes. Thus, new technologies reduce the hazards workers face on the job.

Manual Cutting	Mechanized Cutting
Hazards of walking in the wood	Tipovers/Rollovers
Slips	
Trips	
Falls	
Heat/Cold	
Knees/Back	
Chainsaw hazards	Maintenance hazards
Kickback	
Cuts	
Noise	
Eye/face injuries	
White fingers	
Widowmakers	Whole body vibration
Snags	Neck/shoulder
Falling & rolling	Cumulative
Logs/trees	
Tension	
Wood	
Fatigue induced injuries	Overhead/frontal hazards
	Chainshot hazards

Table 2. Hazard comparison for manual and mechanized cutting. From Garland et al. (2019).

Reduction in workers exposed to hazards

The productivity of the new technologies of steep slope logging also reduces the number of workers exposed to the hazardous tasks in felling and yarding machines.

The saving of 97 cutter years in Oregon substantially reduces the number of cutters exposed to hazards in the most dangerous job in logging. The combined effects of reducing the type of hazards faced by operators and the reduction in workers exposed to hazards are compelling reasons for tethered logging operations.

AIM 3. Develop guidelines and design criteria for new logging systems

Task 1. Evaluate the limits of self-leveling cabs within the framework of the state forest practices and OSHA regulations use on steep terrain.

State agencies have not yet set limits for equipment operations. Stability and tension analyses have been completed for a range of conditions and documented in Sessions et al, 2017, and Belart et al., 2019.

Task 2. Identify the impact of soil moisture, strength and type on mobility of non-cable assisted felling machines mobility on steep slopes.

Through development of theoretical models that can incorporate soil shear strength, machine configuration, tether tension (or no tether present) and slope inclination, we are able to effectively determine the stability of equipment at a variety of slope inclinations and soil conditions. During field trials, we unexpectedly observed a sliding of an untethered machine on wet clay at a 35% slope, which is within "safe" allowable operating limits for equipment in Oregon. We forensically analyzed the equipment stability using our model and shear strength measurements made in the field, finding that our model predicted failure at a 38% slope without tether tension. With a moderate tether tension, the machine would have been stable up to a 60% slope.

These analyses were extended to a variety of soil conditions, slope angles and equipment dimensions. We found that machine orientation and tether tension can significantly influence the stability of these machines on steep slopes. Further, certain soils may actually be stronger with modest moisture (i.e. sands), while others are significantly weaker with moisture (i.e. clays), as shown in Figure 6 (Belart et al. 2019).

Currently, we are completing a methodology for the sliding stability of wheeled, tethered equipment and expect to submit a manuscript for peer reveiw in early 2020.

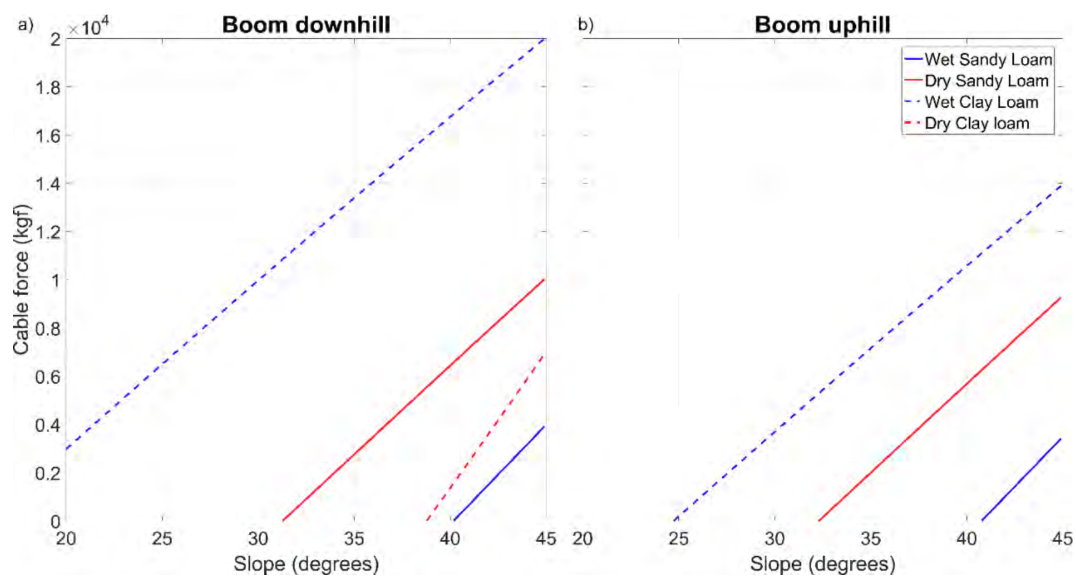

Figure 6. Cable tension at different ground slopes for different soils in dry and saturated conditions

Task 3. Determine the change in risk for setting chokers on bunched stems by analysis of feller-bunchers under static and dynamic loading on steep terrain and evaluating the cable tensions in the yarding system during operation.

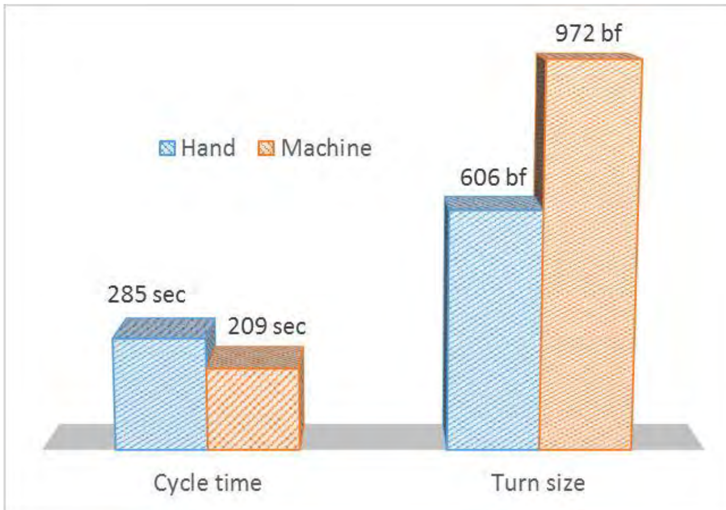

Figure 7: Time study data showing increase in productivity of tethered machine versus hand felling. Both used the same rigging crew and yarder, 27% faster, 60% more volume -> 120% higher productivity.

Our case study showed that tethered feller-buncher productivity in cutting was twice the productivity of manual felling, although it was more expensive per tree cut due to higher cost of the machine than a timber faller. However, pre-bunching of cut trees by the feller buncher allowed an increase of 60% per carriage load. Taking advantage of this larger turn size, crews spend less time to yard the same amount of wood and are exposed to fewer hazards as the trees have been bunched simplifying choker setting. In addition to larger turn sizes, turn times were reduced 27% in the tethered and pre-bunched system further reducing the amount of time workers are exposed to yarding hazards for the same volume of wood.

Task 4. Measure the exposure to new hazards for workers in managing the smaller bunches of logs while attaching them to the overhead cable system by evaluating cable tensions during the "break-out" or yarding phase of lifting the log payload off the ground.

The Behavioral Observation Scale differences between conventional yarding and yarding of bunched piles shows differences in the type of hazards and the number of workers exposed during yarding. The hazards of walking on terrain with scattered logs are greater than walking to piled logs and the hazards of moving logs to the corridor are greater than yarding logs in piles under the skyline. Furthermore, the yarding crew can be reduced by 1-3 people when piles are yarded. Plus, the overall productivity gains will reduce the number of workers per volume yarded.

The Behavioral Observation Scale assessments for machine operations identify new hazards related to tethered operations involving maintenance on steep slopes, machine tipovers/rollovers being struck by trees, or hazards from "chainshot" events. While these new hazards are low probability events, they can be catastrophic.

The other increase in hazards is to the timber fallers who will be cutting trees on terrain unsuitable for mechanized cutting. These timber fallers will be cutting the remaining worst of the worst terrain. In addition, there can be additional hazards from the mixture of hand falling and mechanized falling that needs to be addressed in planning combined operations.

Task 5. Associate detailed time studies with performance of equipment and tractive response (e.g. slip of equipment vs. worker action) for FBCY, FBGY and CHCF systems to evaluate unsafe operator actions.

A harvester-forwarder (CHCF) system was used to thin a harvest unit on dry soils in western Oregon with and without cable-assistance. We conducted a detailed time study during operations and collected soil measurements before and after machine passes. Machine productivity ranged from 28.75 m3 to 92.36 m3 per scheduled machine hour, with resulting unit costs for untethered and tethered systems ranging from $13.19/m3 to $17.78/m3. Our results showed reduced soil impacts in both extent and degree of soil compaction when cable assistance was employed. The reduced extent of soil impacts is attributed to a reduction in track wander owing to the operative tensions of the tether cable, and the smaller increase in soil density appears to be attributed to combined effects of initially denser soil conditions and reduced shear displacement as a result of cable-assistance (Green et al. 2019).

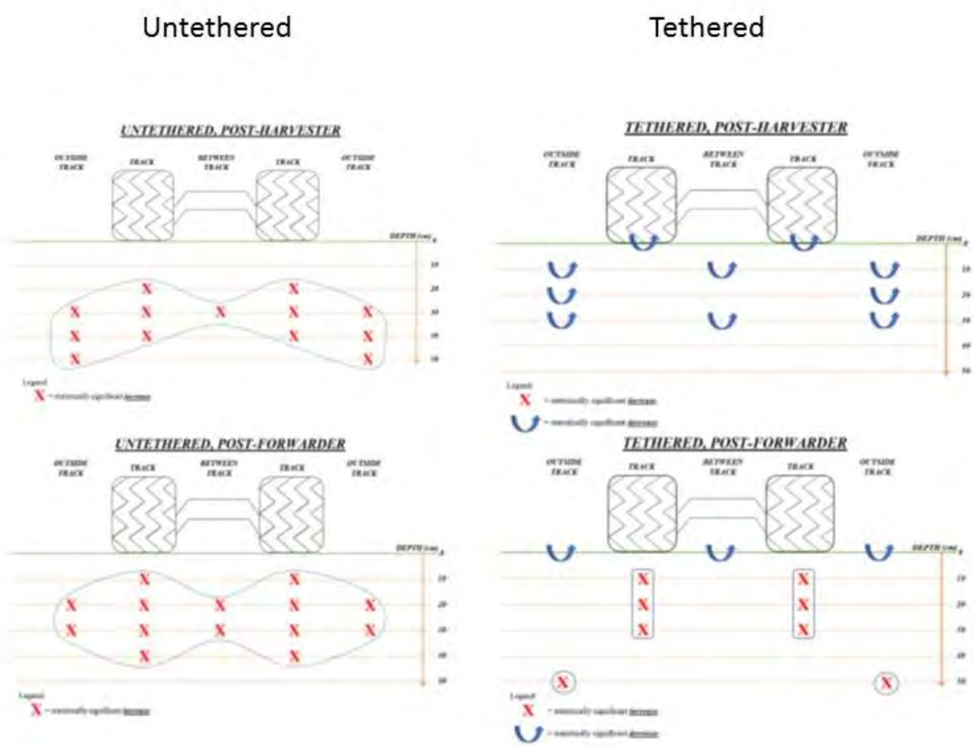

Figure 8: Bubble Disturbance Images showing statistically significant increases/decreases in soil density because of untethered harvesting (a) and forwarding (c), and tethered harvesting (b) and forwarding (d).

No cooperator was able to be scheduled with the grapple yarder system (FBGY) so a conventional cable yarder using chokers (FBCY) was substituted. The FBCY system that was studied had a stump-to-truck cost reduction of over 30% compared to conventional manual cutting and cable yarding in southwest Oregon. It was found that delay free cycle times to fell trees were 27 seconds for feller-buncher and 59 seconds for hand falling per tree on average. The feller-buncher spent approximately 30% of its time swinging logs to pre-bunched stacks for yarding. Yarding of the feller-buncher area had an average delay-free cycle time of 3.5 minutes per turn with an average turn size of 970 board feet per turn. Hand felling had an average cycle time of 4.8 minutes per turn with an average turn size of 610 board feet per turn. The tethered feller-buncher system was 27% faster with 60% more volume leading to an overall higher production rate of 120%.

Image 6: Graduate student, Preston Green, conducting time study work on yarding efficiency in hand felled timber to be compared with yarding efficiency of tethered assist, felled and pre-bunch timber.

Task 6. Collect dimensions of the falling machine to determine weight and center of gravity for various positions of the boom and amount of cable on the drum for internal winch systems using data collected from soil pressure cells.

The center of gravity for a variety of equipment was determined implicitly through machine specifications and measured dimensions (Sessions et al. 2017, Belart et al. 2019). Soil pressure cells were used to corroborate estimates based on moment equilibrium analyses and site topography (work ongoing). The response of tether tension was used to assess changes in ground pressures owing to tether tension.

Task 7. Establish guidelines for required operative constraints for anchors and equipment for the FBCY, FBGY and CHCF systems. For all systems, slope debris, and soil constraints will be presented in the form of easy-to-use design charts. For the FBCY and FBGY systems, anchoring limits will be presented based on cable selection and anchor type. For the CHCF system, required cable strength will be presented based on payload and site conditions.

Equipment operative constraints are presented in the form of easy-to-use design charts in Sessions et al. (2017) and Belart et al. (2019). This accounts for a range of soil conditions. Upon improved understanding of typical anchoring systems for tethered systems, we elected to rely on typical machine anchoring specifications developed and published by the team (Mancuso et al. 2019). This work presents design charts for machine anchors for a wide range of soil conditions.

AIM 4. Develop and deliver outreach programs to introduce safe mechanization to loggers

Task 1. Develop logging training manuals for self-leveling feller-bunchers, grapple yarding, and cable-assisted forest vehicles in English and Spanish.

This task is continuing, drawing from results in peer-reviewed publications.

Task 2. Present and disseminate results to various state agencies that document the changes in the work practices for the FBCY, FBGY, and CHCF systems when compared with the conventional yarding system.

This task is in progress and depends on the schedule of state safety code committees (Forest Activities Advisory Committee). Public land management agencies and private landowners are interested in tethered logging systems to accomplish harvests and land management goals. The Research Team has provided presentations to agencies in Oregon, Washington, California, Utah, and Montana. Through presentations at various meetings, private landowners have been made aware of tethered logging practices issues and concerns. Safety issues have been addressed at these meetings as well as to Oregon and Washington Logging Safety Conferences.

Image 7: Members of Oregon State steep slope logging research group present recent findings on tethered logging systems to Bureau of Land Management (BLM) work group.

Task 3. Use the results from Aims 1 through 3 to develop the inputs for regulations to promote safe logging practices on steep slopes.

In Washington State, tethered logging systems are not covered by specific codes and the slope steepness is not addressed. In Oregon, slope limits were already in the safety codes and a variance procedure (with requirements) was used by OROSHA to allow steep slope operations and gather information for regulations. Oregon's Forest Activities Advisory Committee (FACC) provides guidance to OROSHA on logging regulations including new technologies like tethered logging. The OSU Research Team has been attending FACC meetings and providing input into the regulatory process. Dr. John Garland, PE is the Subcommittee chair of FACC for steep slope logging and is working to develop regulations based in part on the study findings. The FACC meets quarterly and will likely develop draft regulations in the next two meetings (Dec. 8th and March 12th, 2020). Idaho incorporated Oregon variance requirements in part as the regulatory guidance for logging operations in Idaho.

Task 4. Disseminate results through peer-reviewed journals and conference proceedings to advance the understanding of mechanized steep slope logging operations.

Project results are being documented in ten journal articles: four published, one in press, one in review and four in preparation. Thirty-four presentations have been given to local, regional, national, and international audiences for a wide range of stakeholders and two more presentations are planned.

Discussion

Emerging Equipment

New equipment is coming into the logging industry for use on steep slopes. The images below show the base machine and feller-buncher for a two part tethered system. The base machine has a winch which provides a set amount of tension through a cable to the tethered machine down the hill. Radio communication between the two machines lets out, or reels in, cable to provide constant cable assist. The operator in the tethered machine can increase or decrease the desired tension based on the working conditions they face through the radio communication between machines.

Image 8: Base machine of a tethered logging system. Radio communications between the tethered machine and base machine control cable spooling to provide desired cable assist.

Image 9: Tethered machine cutting a tree on steep ground.

Raised grousers as seen in the image below, allow the tethered machine track to get better traction on steep slopes than a traditional machine track. This helps maintain machine stability in conjunction with the cable assist.

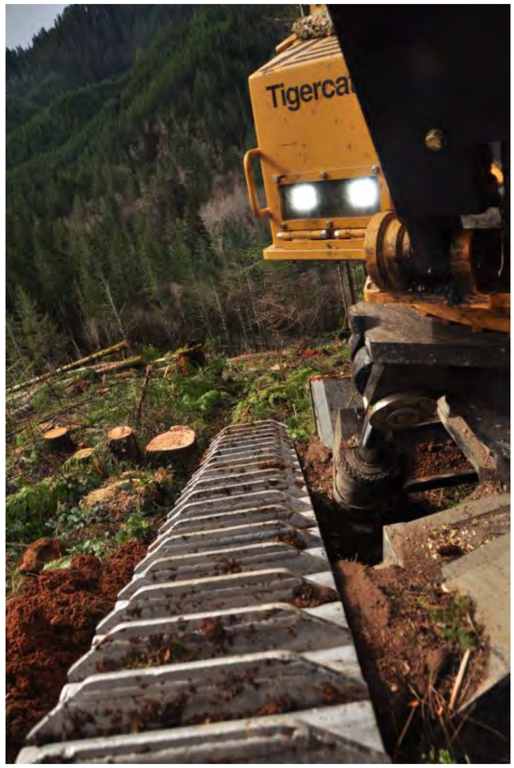

Image 10: Grousers on a tethered machine have additional height added to assist with traction, stability and safety.

The grapple carriage in the image below can be operated remotely from the yarder, eliminating the need to place rigging crew members near active log yarding, which is the second most dangerous logging activity behind hand felling. The yarder operator, through the use of high resolution cameras mounted to the carriage and screens mounted in the yarder cab, can position and activate the tongs to grab a turn of logs to be yarded to the landing. Other grapple carriage systems without a camera system use a spotter in the yarding area to position the carriage and activate the tongs. This individual can be several hundred(s) of feet away, in a safer location than is afforded traditional choker setters. There is reduced requirement for a remote carriage operator to need to be continuously climbing over and around slash and downed logs as they do not need to directly touch logs to choke and yard. The remote carriage operator can slowly move along the yarding corridor as the yarding progresses.

Image 11: A grapple carriage eliminates the need for choker setters to interact directly with logs on steep terrain. Some can be operated remotely by the yarder engineer through the use of high quality cameras.

Stability of Tethered Equipment

A model of equipment stability and traction was developed (Sessions et al. 2017, Belart et al. 2019). Analyses showed that the use of deeper grousers, higher cable tensions, wider tracks, and uphill boom orientation all increase gradeability, stability, and safety during operation. Inversely, effective track length (hence, increased soil pressures) and stability are decreased from grappling of heavier trees, operation on weaker soils, fully extended boom operation in the downhill direction and increasing slope. Equipment track geometry can have an effect on sliding stability, grouser height being the one with the greater effect of the two analyzed scenarios. Tether tension decreases by a greater amount at less pronounced slopes, and the effect decreases as slope increases.

Soil properties generally govern equipment stability when compared with equipment geometry. Stability is directly dependent on soil moisture; higher moistures in clayey soils may reduce stability, whereas the opposite may be true in sandier soils. Consideration of the influence of these properties is important, especially when considering safe operation, appropriate use of cable assistance, and decreased soil disturbance.

The influence of soil shear strength, namely cohesion and angle of friction, directly affects equipment stability. Stability has a linearly positive relation with angle of friction and a positive nonlinear relation with cohesion.

A short case study in the field illustrates that under wet conditions, untethered equipment may fail on relatively gentle slopes. However, this adverse scenario may be avoided through the use of cable assistance.

Future work could improve on this approach by taking into account the influence of equipment when asymmetrically oriented on a slope (e.g., adversely placed on a cross-slope), account for cable not being in line the equipment direction, leveling cab equipment, account for uneven terrain and hummocks, and better assess dynamic conditions during movement. However, this framework provides a logical approach toward assessing the sliding stability of tethered machinery on steep slopes, a condition that is critical for safe operation of “cable-assisted” equipment.

Challenges to Implementation - Regulations

A common rule for ground-based equipment operating on slopes has been 35%. To address the issues limiting operations on steep slopes we examined soil impacts, equipment stability, and reduced worker exposure.

The stability of the entire tether system depends upon the stability of the roadside tether winch machine at the upper end of the harvest unit. Or, when the tether winch machine is at the lower end of the unit, for anchoring of a sheave at the upper end of a harvest unit. In areas with weak anchor stumps, a continuous bridle using frictionless blocks can be used to spread the tether load evenly to anchor stumps even as the tethered machine varies the angle it is pulling on the stumps (Lyons et al. 2019a). We developed a method of trilateration to locate the elements of a three-stump anchor and used a particle swarm algorithm to solve for the tension in the bridle and the location of the bridle block. It was found that the bridle tension in the three-stump anchor system with continuous bridle is more strongly controlled by the location of the two outside stumps, and it is relatively insensitive to the location of the middle stump. The effect on tether tension when using trees to redirect the machine tether was also examined (Lyons et al. 2019b).

Labor Availability

Logging operations are typically described as difficult, dangerous, dirty, and declining. Tethered logging systems offer improvements to the work difficulty, safety performance, and work in weather and terrain. The effect on the number of workers is likely in the opposite direction as tethered logging would likely reduce the number of workers needed.

We looked at cost and productivity in tethered operations to better understand the contribution of the operator. Analysis indicated that the system’s increased productivity could allow higher operator wages thus attracting more operators.

Environmental Impacts

Regulators are wary of adopting this new technology due to concerns about soil disturbance, and sediment delivery to streams. To address this issue we began looking at soil compaction with wheel-based systems, and have an ongoing study looking at soil compaction and issues around seedling planting in tracks and corridors, changes in infiltration rates, soil moisture through time, and erosion through time. Initial results indicate no measurable soil accumulation in erosion fences, no significant change to soil structure from bulk density, penetrometer, and infiltrometer data collection. There appears to be a slight increase in volumetric soil moisture under tethered machine tracks. The two studies to date have been located in western Oregon, with both sites having silty clay sand soils. Requests for studies by part of the OSU research team have been requested in other regions, Olympic Peninsula of Washington State, Northern Idaho's Nez Perce/Clearwater National Forest, and Colorado.

Conclusions

OVERALL worker safety is improved and environmental impacts appear minimal or less compared to conventional harvest techniques. Specific conclusions are:

1. Tethered operations reduce worker exposure to falling hazards, dislodged logs and rocks.

2. Tethered operations reduce worker hazards from falls, sprains and strains, and chronic use resulting from working on steep terrain.

3. Tethered systems are ideal for harvesting storm damaged stands with trees hung up and twisted together. Hand falling in these conditions is highly risky with fallers placing themselves under and between unstable trees and branches that could come down unexpectedly. The use of tethered systems puts the operator in the safety of a machine cab designed to withstand impact from falling timber. Additionally, the machine can manipulate fallen material to allow for better access to trees to be cut.

Image 12: A feller-buncher operating in storm-damaged stand. Note horizontal tree in background under the boom.

4. Worker productivity is increased.

5. Tethered assist improves machine traction on steep slopes, allowing more area to be managed from the safety of a machine cab.

6. Impact to western Oregon clay soils has been minimal from measurements on compaction (soil penetrometer), soil moisture, and erosion.

7. Operators are exposed to less stress, shock, and physical demands than traditional logging positions using tethered logging systems. Pre-bunched timber can be yarded by a grapple carriage or if using traditional cable chokers crew are exposed to much fewer obstacle and easier access to attach the logs to the choker cables.

8. Our team has suggested an approach that the state of Oregon can proceed in moving from tethered machines operating under a research variance to a state approved regulation.

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Sessions, J., B. Leshchinsky, W. Chung, K. Boston, and J. Wimer. 2017. Theoretical Stability and Traction of Steep Slope Tethered Feller-Bunchers. Forest Science 63(2):192-200.

U.S. Bureau of Labor Statistics, 2018. Current Population Survey, Census of Fatal Occupational Injuries.

Appendix 1: Data Collection and Task Analysis Examples

BEHAVORIAL OBSERVATION MEASURES: STEEP SLOPE OPERATORS

ACTIVITY			TIME MEASURES				
	RARELY 0-30%	OCCASIONALLY 30-45%	FREQUENTLY 45-65%	USUALLY 65-85%	ALMOST ALWAYS 85-95%	ALWAYS 95%+	NOT APPLICA
TRAVELING HAZARDS	○	○	○	○	○	○	○
OVERHEAD HAZARDS	○	○	○	○	○	○	○
FRONTAL HAZARDS	○	○	○	○	○	○	○
MAINTENANCE HAZARDS	○	○	○	○	○	○	○
STABILITY INCIDENT, ROCKING,SHARP MOVEMENTS	○	○	○	○	○	○	○
CHAINSHOT HAZARDS	○	○	○	○	○	○	○
HEAT/COLD	○	○	○	○	○	○	○
NOISE (DOSIMETER)	○	○	○	○	○	○	○
LINE FAILURE	○	○	○	○	○	○	○
HANDLES MACHINE SMOOTHLY, MIN EXCESS MOVEMENTS	○	○	○	○	○	○	○
MAINTAINS SAFE DISTANCES	○	○	○	○	○	○	○
USES PLAN FOR FELLING STRIP	○	○	○	○	○	○	○
START UP INSPECTIONS	○	○	○	○	○	○	○
OTHER	○	○	○	○	○	○	○
OTHER	○	○	○	○	○	○	○
OTHER	○	○	○	○	○	○	○

OBSERVER	1 What happened when…(event description)?
DATE	2 What caused the event?
WEATHER	3 What did you do when the event occurred?
MACHINE	4 How serious or dangerous was the event?
OPERATOR CODED ID	5 How often does such an event occur?
LOCATION	6 Would you consider the event a "near miss" or a typically occurring event?

TASK ANALYSIS EXAMPLE

Task/Subtask: Forwarder Operation - Loading

KNOWLEDGE	SKILLS	ABILITIES	RISKS	MOTIVATIONS
*Limits of crane & machine	*Operate smoothly within limits	*Vision, esp. depth perception	Vehicle overturning on slope	Motiv: Information-
*Species indentif.	*Quick operation when needed	*Hand-eye-foot coordination	*Frontal object penetration	*pieces per load
*Sorting criteria	*Builds safe loads up to machine limits	*Judgement	*Maintenance hazards, if maint occurs	*time per load
*Positioning among piles	*Handles unusual stems, e.g. oversize, crooks, etc.	*Spatial orientation	*Neck-shoulder damage	*loads per time
*Pick indexing		*Coordination		*weight per load
*Maintenance demands during loading				Quality checks on load
				De-Motiv: Poor workplace (piles) by Harvester operator
				*Time alone

Appendix 2: Project Members

Principal Investigators

John Sessions, PhD, PE, University Distinguished Professor

Woodam Chung, PhD, Stewart Professor of Forest Engineering

Ben Leshchinsky, PhD, PE, Associate Professor, Richardson Chair in Forestry

Tamara Cushing, PhD, Assistant Professor and Extension Specialist

John Garland, PhD, PE, Garland and Associates

Laurel Kincl, PhD, Associate Professor and Certified Safety Professional

Jeff Wimer, BS, Strachan Scholar, Senior Instructor II, Manager of Student Logging Program

Kevin Boston, PhD, PE, Lecturer, Humboldt State University (2016-2017)

Affiliated Investigators

Francisca Belart, PhD, Assistant Professor and Extension Specialist

Kevin Lyons, PhD, RPF, Lematta Associate Professor of Forest Engineering

Brett Morrissette, MF, Senior Faculty Research Assistant (2018-2019)

Robert Crawford, BS, Faculty Research Assistant (2016-2017)

Preston Green, MS, MBA, Graduate Student

Appendix 3: Peer-reviewed Publications (10)

1. Chung, W., B. Morrissette, P. Green, B. Leshchinsky, F. Belart, J. Sessions, J. Wimer and J. Garland. 2019. Effects of pre-bunching logs with a tethered feller-buncher on the productivity and costs of cable logging. In Preparation.

2. Chung, W. B. Morrissette, B. Leshchinsky, K. Bladon, J. Hatten, F. Belart, J. Sessions, J. Wimer and J. Garland. 2019. Impacts of tethered logging on soil disturbance: a case study in southwest Oregon. In Preparation.

3. Garland, J., F. Belart, R. Crawford, W. Chung, T. Cushing, S. Fitzgerald, P. Green, L. Kincl, B. Leshchinsky, B. Morrissette, J. Sessions and J. Wimer. Safety aspects of operators in steep slope logging. In Preparation.

4. Leshchinsky, B., F. Belart, K. Lyons, and J. Sessions. A mobility model for tethered wheeled skidders and forwarders. In Preparation.

5. Lyons, K., J. Sessions and J. Wimer. 2019b. The effect on tether tension when using trees to redirect live machine tethers. In Review, Biosystems Engineering.

6. Green, P., W. Chung, B. Leshchinsky, F. Belart, J. Sessions, S. Fitzgerald, J. Wimer, T. Cushing, and J. Garland. 2019. Insight into the Productivity, Cost and Soil Impacts of Cable-assisted Harvester-forwarder Thinning in Western Oregon. In Press. Forest Science.

7. Lyons, K., J. Sessions and J. Wimer. 2019a. Design of continuous bridle multiple-stump anchors. International J. of Forest Engr. doi:10.1080/14942119.2020.1685833. https://www.tandfonline.com/eprint/QEUCNYEEP69BTTHPRFKB/full?target=10.1080/14942119.2020.1685833. Online November 3, 2019.

8. Garland, J., F. Belart, R. Crawford, W. Chung, T. Cushing, S. Fitzgerald, P. Green, L. Kincl, B. Leshchinsky, B. Morrissette, J. Sessions and J. Wimer. 2019. Safety in steep slope logging operations, Journal of Agromedicine 24(2):138-145, doi: 10.1080/1059924X.2019.1581115. Online March 12, 2019 https://doi.org/10.1080/1059924X.2019.1581115.

9. Belart, F., B. Leshchinsky, J. Sessions, W. Chung, P. Green, J. Wimer, and B. Morrissette. 2019. Sliding Stability of Cable-Assisted Tracked Equipment on Steep Slopes. Forest Science 65(3):304-311. Online Dec 20, 2018. https://academic.oup.com/forestscience/advance-article/doi/10.1093/forsci/fxy064/5256532#

10. Sessions, J., B. Leshchinsky, W. Chung, K. Boston, and J. Wimer. 2017. Theoretical Stability and Traction of Steep Slope Tethered Feller-Bunchers. Forest Science 63(2):192-200.

Appendix 4: Presentations (36)

1. Chung, W., B. Leshchinsky, B. Morrissette, P. Green, K. Bladon, J. Hatten, F. Belart, J. Sessions, and J. Wimer. 2019. Soil Impacts of Tethered Logging Systems: Theory, Field Experiments and GIS Tool for Assessment. To be presented at the USDA Forest Service Northern Region Soil, Water, and Fish Annual Meeting, December 3-5, 2019, Missoula, MT.

2. Chung, W., B. Morrissette, P. Green, B. Leshchinsky, K. Bladon, J. Hatten, F. Belart, J. Sessions, and J. Wimer. 2019. Tethered Logging Systems: Cost, Productivity and Environmental Impacts. To be presented at the USDA Forest Service Northern Region Timber Management Team Annual Meeting, December 4, 2019, Missoula, MT.

3. Chung, W., B. Morrissette, P. Green, B. Leshchinsky, K. Bladon, J. Hatten, and J. Sessions. Productivity and Environmental Impacts of Cable-assisted Logging – A case study in southern Oregon, USA, Joint Meeting of FORMEC and COFE, October 6-9, 2019, Sopron, Hungary.

4. Morrissette, B.A. (presenter), W. Chung, K. Bladon, B. Leshchinsky, J. Hatten, J. Sessions. 2019. Comparison of erosion potential between manual and cable-assisted mechanized felling on steep slopes – A case study in southern Oregon, USA. XXV IUFRO Congress, September 29-October 5, 2019, Curitiba, Brazil.

5. Garland, J. (presenter). Safety in Steep Slope Logging. 2019 Western Agriculture Safety and Health– Cultivating Collaborations conference, Seattle, WA, August 8, 2019

6. Chung, W., F. Belart, P. Green, B. Morrissette (presenters). 2019. Soil impacts of tethered logging in Oregon. BLM Aquatic Habitat Management Working Group Annual Spring Meeting, April 17, 2019, Dallas, OR.

7. Chung, W. (presenter), B. Leshchinsky, B. Morrissette, P. Green, F. Belart, K. Bladon, J. Hatten, J. Sessions, K. Lyons, J. Garland, and J. Wimer. 2019. Soil impacts of tethered logging in Oregon. Confederated Tribes of Warm Springs Forest Management Interdisciplinary Team Meeting, Corvallis, OR, April 8, 2019.

8. Green, P. (presenter), W. Chung, F. Belart, S. Fitzgerald, B. Leshchinsky, B. Morrissette, J. Sessions, J. Wimer, and J. Garland., 2019. Soil Impacts of a Cable-assisted Harvester-forwarder Thinning in Western Oregon. The Northwest Forest Soils Council 2019 Winter Meeting, March 21-22, 2019, Lincoln City, OR.

9. Garland, J. (presenter). Steep Slope Logging Research Recommendations. Forest Activities Advisory Committee. OR OSHA. Salem OR. March 14, 2019.

10. Belart, F. Winch-assist harvester anchoring review. Cable Anchoring Workshop: failure mechanisms, safe design and new technologies. March 6, 2019. Springfield, OR.

11. Garland, J. (presenter). Winch-assisted Tethered Logging for Steep Slopes. Northwest Safety Logging Summit - For Safety Professionals. PNASH Conference. Eugene, OR. February 19, 2019.

12. Chung, W. and P. Green (presenters). 2019. Soil impacts of tethered logging in Oregon. Webinar for the Dixie National Forest soil scientists and timber sale administrators, February 12, 2019, Corvallis, OR.

13. Garland, J. (presenter). Steep Slope Logging Research. Washington Contract Loggers Association Safety Meeting. Grand Mound, WA. January 19, 2019.

14. Chung, W. (presenter), B. Garrelts, B. Morrissette, P. Green, B. Leshchinsky, F. Belart, K. Bladon, J. Hatten, J. Sessions, J. Garland. 2019. Tethered Logging in Southwest Oregon: A Research Perspective. Western Regional Council on Forest Engineering Conference, Eugene, OR, January 17, 2019.

15. Green, P. (presenter), W. Chung, F. Belart, S. Fitzgerald, B. Leshchinsky, B. Morrissette, J. Sessions, J. Wimer, and J. Garland., 2019. Tethered Cut-to-length in western Oregon: Productivity, cost and environmental impacts of steep slope harvesting in western Oregon. Western Regional Council on Forest Engineering Conference, Eugene, OR, January 17, 2019.

16. Belart, F. Winch-assist harvester anchoring review. Cable Anchoring Workshop: failure mechanisms, safe design and new technologies. November 19th, 2018. Eugene, OR.

17. Belart F. (presenter), B. Leshchinsky, J. Sessions, W. Chung, P. Green, J. Wimer, B. Morrissette and J. Garland. Tether assist equipment stability and soil impacts in steep slope logging. Council on Forest Engineering. Williamsburg, VA. July 15-18, 2018.

18. Chung, W. (presenter), B. Morrissette, P. Green, B. Leshchinsky, F. Belart, K. Bladon, J. Hatten, and J. Sessions. 2018. Cable-Assisted Steep Slope Harvesting – Research on Soil Impacts. Council on Forest Engineering. Williamsburg, VA. July 15-18, 2018.

19. Chung, W. (presenter), B. Leshchinsky, F. Belart, J. Garland, P. Green, B. Morrissette, J. Sessions, and J. Wimer. 2018. Ongoing Research on Cable-Assisted Steep Slope Harvesting Systems in North America. Invited Seminar at Korea National Institute of Forest Science, Seoul, South Korea, June 20, 2018.

20. Chung, W. (presenter). P. Green, B. Leshchinsky, J. Sessions, J. Garland, J. Wimer, and S. Fitzgerald. 2018. Effects of Cable-Assistance on Reducing Soil Disturbance during Mechanized Timber Harvesting. The 6th International Forest Engineering Conference, Rotorua, New Zealand, April 16-19, 2018.

21. Green, P. (presenter), F. Belart, R. Crawford, W. Chung, S. Fitzgerald, B. Leshchinsky, B. Morrissette, J. Sessions, J. Wimer, and J. Garland. 2018. Steep Slope Research at Oregon

State University. FPInnovations Steep Slope Initiative Meeting, Vancouver, BC, Canada. January 16, 2018.

22. Garland, J. (presenter). Operators in Steep Slope Logging and Safety Measurement: An OSU Study in Protecting the Logging Workforce. Pacific Logging Congress In Woods Seminar. Corvallis, OR. September 13, 2018.

23. Garland, J. (presenter). F. Belart, W. Chung, T. Cushing, L. Kincl, B. Leshchinsky, B. Morrissette, J. Sessions, and Jeff Wimer. 2018. Steep Slope Tethered Logging. 18th Update Seminar on Wood Harvesting and Forest Transportation Systems, April 9, 2018. Ribeirão Preto, Brazil

24. Green, P. (presenter), W. Chung, B. Leshchinsky, J. Sessions, S. Fitzgerald, J. Wimer. 2017. Soil disturbance of cable-assisted operations in the NW USA. The 2017 Pacific Logging Congress, Paradise Valley, AZ, November 7, 2017.

25. Garland, J. (presenter). Steep Slope Logging. Oregon Department of Forestry Sales Planning and Layout. NW OR Region. Tillamook, OR. Nov 6, 2017.

26. Garland, J. (presenter), F. Belart, R. Crawford, W. Chung, T. Cushing, L. Kincl, B. Leshchinsky, J. Sessions, J. Wimer. 2017. Operators In Steep Slope Logging And Safety Measurement. 50th Anniversary of the International Symposium on Forestry Mechanization: "Innovating the competitive edge: From research to impact in the forest value chain" Brasov, Romania, 25-29 September 2017.

27. Green, P. (presenter), W. Chung, B. Leshchinsky, J. Sessions, S. Fitzgerald, J. Wimer. 2017. Soil Disturbance of a Cable-Assisted CTL Harvester Forwarder Thinning in Northwest US. 50th Anniversary of the International Symposium on Forestry Mechanization: "Innovating the competitive edge: From research to impact in the forest value chain" Brasov, Romania, 25-29 September 2017.

28. Green, P. (presenter), W. Chung, R. Crawford, J. Garland, B. Leshchinsky, J. Sessions, J. Wimer. 2017. Productivity and cost of cable-assisted felling and extraction in the Pacific Northwest, USA. IUFRO 125th Anniversary Congress, September 18-22, 2017, Freiburg, Germany.

29. Garland, J. (presenter). 2017. Ergonomics Research Meeting, IUFRO 125th year Celebration. September 21, 2017. Freiburg, Germany.

30. Green, P. (presenter), F. Belart, R. Crawford, W. Chung, T. Cushing, J. Garland, L. Kincl, B. Leshchinsky, J. Sessions, and J. Wimer, 2017. Steep Slope Logging Research at OSU – Eye movement tracking to grapple yarding, collaboration for a safer work environment. Council on Forest Engineering Annual Meeting, Bangor, ME. July 30 – August 2, 2017.

31. Garland, J. (presenter). 2017. NIOSH Meeting of Grantees, Steep Slope Logging Research. June 20, 2017. Denver, CO.

32. Garland, J. (presenter). 2017. Operators in steep slope logging and safety measurement: An OSU Study in protecting the logging workforce - Development of innovative logging techniques for a safe working environment. Steep Slope Logging Conference. Kelso Longview, WA. TimberWest Magazine. April 19, 2017.

33. Garland, J. (presenter). 2017. Operators in Steep Slope Logging and Safety Measurement. WR COFE. Eugene, OR. January 19, 2017.

34. Sessions, J (presenter)., J. Garland (presenter), F. Belart, R. Crawford, W. Chung, T. Cushing, L. Kincl, B. Leshchinsky, and J. Wimer. 2018. Protecting the Logging Workforce: Development of Innovative Logging Techniques for a Safer Working Environment. Pacific Logging Congress. November 9, 2016. San Diego, CA.

35. Garland, J. (presenter). 2016. Safety Perspective. (Steep Slope Logging Panel). Demo 2016 and COFE 2016 joint meeting. Vancouver, BC. September 20, 2016

36. Boston, K. (presenter), W. Chung, T. Cushing, J. Garland , L. Kincl, B. Leshchinsky, J. Sessions, and J. Wimer. 2016. Protecting the Logging Workforce: Development of Innovative Logging Techniques for a Safer Working Environment. Western Regional Council on Forest Engineering. January 14, 2016. Eugene, OR.

Appendix 5: Theses (1)

Green, P. 2019. Insight into the Productivity, Cost and Soil Impacts of a Cable-assisted Harvester-forwarder Thinning in Western Oregon. M.S. thesis. Oregon State University, Corvallis. 48 pp.