AN ABSTRACT OF THE THESIS OF

Preston Q. Green for the degree of Master of Science in Sustainable Forest Management presented on February 18, 2019

Title: Insight into the Productivity, Cost and Soil Impacts of a Cable-assisted Harvester-forwarder Thinning in Western Oregon

Abstract approved:

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Woodam Chung

Timber harvesting in the Pacific Northwest (PNW) region of the United States of America (USA) has a long history of explosive growth, environmental litigation and regulation, economic downturn, and workforce dynamics that have created a current environment where cable-assisted harvesting is quickly gaining popularity among private and public land managers alike. While logging continues to be one of the deadliest occupations in the United States, an increasing primary concern for many privately- and federally-owned lands in the western United States is soil disturbance. In addition, the large long-term capital investment required of these systems places additional pressures on prospective adopters. The economic and environmental impact from cable-assisted harvesting machines is largely undocumented from a scientific perspective, and lack of information can in some cases be grounds for exclusion of cable-assistance as a possible harvesting system.

Cable-assistance could provide a host of benefits to the timber industry, such as a reduction in logging accidents and the ability of an aging workforce to continue working.

However, with such a significant capital investment required and undocumented environmental (soil) impact, adopters of cable-assisted systems are left to face these decisions with an inadequate supply of information.

The purpose of this research, through a case study approach, is to quantify the productivity and cost (P&C) and soil impacts of a harvester and forwarder operating with and without the use of cable-assistance on dry clay soils in western Oregon. Detailed time study data was collected in order to generate regression models for both machines under each system, while bulk density and penetration resistance data was collected before harvesting, after harvesting, and after forwarding across the machine corridor and down to a soil depth of 50 cm.

Untethered and tethered harvesting showed estimated productivity values of 115.45 and 79.01 m^3 per productive machine hour (PMH), respectively, while forwarding productivity was estimated at 35.94 and 42.54 m^3/PMH for untethered and tethered, respectively. Depending on the coupling of the harvest operation, machine productivity ranged from 28.75 m^3/SMH to 92.36 m^3/SMH, with resulting unit costs for untethered and tethered systems ranging from \$13.19/m^3 to \$17.78/m^3. Differences in harvester productivity were possibly attributable to different operators and the narrower operating window when operating using cable-assistance.

Soil compaction results showed a smaller geographically impacted area, smaller increases in soil density, and in some cases a *decrease* in soil density using cable-assistance. The reduced coverage effect, primarily through the reduction of track wander, creates a tradeoff between coverage area and coverage intensity. The smaller increases, and decreases, in soil density is a product of reduced shear displacement of soil. This shear reduction is due to a better weight distribution provided by cable-assistance. As a result, this soil can likely be subjected to more passes before the onset of densification occurs if using cable-assistance.

Insight into the Productivity, Cost and Soil Impacts of a Cable-assisted Harvester-forwarder Thinning in Western Oregon

by
Preston Q. Green

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Thank you.

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INTRODUCTION

Background

Soil Compaction in Forest Harvesting

Soil compaction in timber harvesting operations has long been a concern not only in the PNW region of the USA, but across the globe. Soil compaction is primarily driven by soil physical properties and machine properties. Soil physical properties include but are not limited to moisture content, particle size distribution, and soil type, with terrain slope also thought to play a significant role. Machine properties such as contact pressure, number of passes, and operator experience are likewise important. Soil compaction as a result of harvesting can lead to increased erosion, decreased root and plant growth, and decreased water infiltration and permeability, among many other negative consequences.

Cut-to-Length (CTL) Harvesting

Across the PNW region of the USA, CTL harvesting systems have become increasingly popular over the last few decades. CTL harvesting involves two purpose-built forest machines:

1. Harvester – robust, all-terrain vehicle having a fully enclosed cab for a machine operator and a large boom with a cutting implement used to harvest trees. The enclosed cab provides safety benefits from overhead hazards and other objects a hand faller encounters while falling trees. The harvester separates the tree from the stump, processes the tree to remove limbs and tops, and cuts the tree into desired log lengths.

2. Forwarder – a machine with a similar cab and boom, but the boom has a set of grapples used for picking up and loading logs into a trailer-like bunk transported with the machine. After loading, the forwarder transports these processed logs from the forest floor to the roadside where logs are loaded onto trucks and hauled off-site for further processing and/or shipment.

The safety gains, efficient handling of small-diameter trees (less machine handling per tree), and production of high-quality products makes CTL harvesting systems a viable alternative to other more costly or infeasible harvesting systems (Kellogg et al., 1992). From a human resources perspective, these mechanized systems also have a lower workers compensation insurance rate (Bettinger et al., 1993).

Harvesting Landscape in the Pacific Northwest

In addition to evolving harvesting systems, the physical harvesting environment is changing as well. In the PNW, the landscape for timber production is characterized by steep slopes, large amounts of rainfall that create slippery and unstable surfaces, brush and fallen debris that inhibits walking, and uneven terrain. These factors make falling trees by hand extremely dangerous and deadly. In the early 1990's, the average tree size harvested in western Oregon was projected to decrease from 21 to 17 inches diameter at breast height (dbh) over the following 5.5 decades, with western Oregon holding approximately 55% of commercial timberland in slope classes between 16% and 55% (Bettinger et al., 1993). The feasibility of increasing the use of mechanized harvesting operations will depend on environmental impacts, adequate forest inventories, production costs, and markets (Bettinger and Kellogg, 1993). The cable yarders and older logging machinery used in the region have become too costly on a per-volume basis to harvest smaller-diameter wood. Modern CTL harvesting machines are being purpose-built to effectively handle smaller-diameter wood.

Logging in the Pacific Northwest United States

Logging is one of the most dangerous job in the United States and in 2016 logging workers had the second highest fatal injury work rate among civilian occupations (United States Bureau of Labor Statistics). As a result of high accident and fatality rates, insurance and workers compensation rates for logging jobs is considerably high. The logging workforce is aging, and these workers are searching for jobs less physically demanding. The forest industry faces a continued battle of keeping workers, particularly as the construction industry offers higher wages and a wider selection of occupations (United States Bureau of Labor Statistics). Hand fallers are at especially high risk of injury and death due to overhead hazards when falling trees. Safer harvesting through the use of machines is the primary driver for replacing hand felling with machine felling.

Cable-assisted Harvesting

A new variation of using CTL and other harvesting systems is the implementation of cable-assistance. This harvesting system adaptation uses cable, winching, and anchoring technology to assist machines on steep or unstable terrain. Cable-assisted, or tethered harvesting, involves the use of an anchor uphill of the harvesting or extracting machine, such as a tree or stationary piece of purpose-built/outfitted equipment (bulldozer, excavator, etc.). This anchor is connected to the harvesting/extraction machine via wire rope(s). Two main tethered systems exist in the PNW, with a main difference between the systems being the action of the wire rope providing assistance. A static system uses a winch placed on the active harvesting/extraction machine. In this way, wire rope is paid out from the working machine and is stationary relative to the ground once out of the machine and in tension. A static system commonly uses a tree or piece of stationary equipment as the uphill anchor. A dynamic system uses an uphill winch placed at the anchor of the system. This system feeds out wire rope from the anchor machine, and the wire rope is in motion relative to the ground whenever the harvesting/extraction machine is in motion. This research uses a static system.

Current Challenges for Cable-assisted Harvesting Implementation

Soil compaction is a common concern among natural resource professionals and the general public and has the potential to shut down harvesting operations if found to exceed allowable limits. However, the effects on soil compaction as a result of cable-assisted harvesting is largely undocumented in scientific literature. In addition, the productivity and cost of these systems is similarly missing in scientific literature. Large capital investments are often required to operate these systems, and productivity, as a way to measure return on investment, payoff period, etc., can provide prospective adopters of these systems with more complete information to make decisions. With an aging workforce and high initial financial requirement for cable-assisted systems, productivity can be a very useful tool for logging workers looking to the future. Current timber harvesting systems might greatly benefit from cable-assistance, particularly in the realms of safety, production and cost, and environmental impacts.

Research Questions

This research aims to address the previously mentioned challenges for cable-assisted harvesting through a case study of the compaction as well as productivity and cost of a thinning operation on dry clay soils in western Oregon. Specifically, we address:

1. By using cable-assistance, is there a less negative impact on soil compaction as compared to traditional, unassisted systems? That is, does the use of cable-assistance result in soils that are less compacted than if conventional, unassisted systems were used?

2. How does the productivity and cost of cable-assisted harvesting compare to that of unassisted harvesting in the same scenario as question 1. above?

Hypotheses

As the goal of this research was to quantify the compaction and productivity and cost of the systems studied, the hypothesis for each aspect of this research was:

H_o: The presence of cable-assistance reduces maximum track pressures, thereby reducing the observed level of compaction.

H_o: The presence of cable-assistance has little effect on unit cost of harvested wood.

Research Objectives

The objectives of this research are to quantify the levels of compaction and the productivity and cost of cable-assisted harvesting, but also to assist in filling the information gaps surrounding these same areas. This project investigated these areas of research using the following as the basis for research.

1. Quantify the compaction impacts of a harvester and forwarder operating with and without the use of cable-assistance on dry clay soils in a thinning operation in western Oregon.

2. Develop productivity and cost models for the same harvester and forwarder in the same operating environment as previously discussed.

LITERATURE REVIEW

The effects of machinery on forest soils have been an ongoing concern for more than 40 years in North America (McNabb et al. 2001), as timber harvesting and skidding have the potential to cause detrimental soil and site disturbances (Kozlowski 1999; Najafi and Solgi 2010; Solgi et al. 2015). Logging practices in previous decades in the Pacific Northwest have increased both regulation and best management practices surrounding soil disturbance, owing to the increasing importance of soil disturbance in context of environmental and regeneration concerns. From the increase in harvesting mechanization observed during previous decades, some machinery has grown bigger, heavier, and increasingly more specialized to accommodate the growing needs of worldwide lumber markets. Subsequently, the axle weight of some tractors, harvesters, and trailers and the consequent impact on soil have increased over time (Van den Akker et al. 2003; Godwin et al. 2008). A major environmental concern is soil compaction, the degree to which depends on a variety of factors, including ground pressures, soil type, moisture, and mineralogy.

Cable-assistance, an innovative mechanized harvesting system that uses tension in a wire rope anchored upslope to assist with traction and gradeability of equipment on steep slopes (Sessions et al. 2017), is a system gaining popularity worldwide for its numerous benefits. Cable-assistance was born out of a desire to increase timber faller and choker setter safety on steep slopes, as well as the potential for increased felling and yarding productivity in New Zealand, Europe, Canada, and the Pacific Northwest of the United States (Sessions et al. 2017). Safety improvements for workers are due to reducing the type of hazards faced by workers and the time workers are exposed to hazards. Though there is a limited body of scientific literature focusing on the compaction effects of forest machinery while using cable-assistance, existing literature surrounding un-assisted forest machinery provides a reasonable starting point for hypothesizing what the compaction effects while using cable-assistance might be.

Cambi et al. (2015) summarized factors affecting vehicle-induced compaction of forest soils and their effects, and suggests that causes of compaction can be categorized into soil and machine/human factors. Notable soil factors include initial low bulk density (Hillel 1998; Powers et al. 2005), sufficient moisture content (McDonald and Seixas 1997; Raper 2005; Han et al. 2009; Ampoorter et al. 2012), particle size distributions yielding large void space (McNabb et al. 2001; Berli et al. 2004; Magagnotti et al. 2012), and slope (Agherkakli et al. 2010), all of which are thought to favor soil compaction. Machine/human-based factors include number of trips (Wallbrink et al. 2002), harvesting direction (Jourgholami et al. 2014), vehicle weight (Jansson and Wästerlund 1999), tire/track characteristics (Jansson and Johansson 1998; Sheridan 2003), and wheel inflation pressure (Alakukku et al. 2003; Sakai et al. 2008). Compaction is more likely at early passes, but the effects are diminished after 10-15 trips (Cambi et al. 2015). Uphill versus downhill harvesting, higher vehicle weight, less-experienced operators, and higher contact and wheel inflation pressure are all conditions in which increased soil compaction is more likely to occur.

Negative impacts of forest compaction include decreased soil porosity (Lenhard 1986; Seixas and McDonald 1997; Ampoorter et al. 2007), decreased water infiltration and permeability (Currie 1984; Arthur et al. 2013), increased runoff (Startsev and McNabb 2000; Croke et al. 2001; Christopher and Visser 2007), decreased air permeability and oxygen supply (Frey et al. 2009), decreased root growth (Qi et al. 1994; Whalley et al. 1995; Gaertig et al. 2002), and decreased tree growth (Ares et al. 2005; Blouin et al. 2005; Demir et al. 2010).

However, there are several cases where logging-induced topsoil mixing and displacement are positive in terms of regeneration; for example, it may be beneficial in forests where the organic horizons are so thick as to prevent seedling roots from reaching the mineral soil to access water and nutrients (Perala and Alm 1990; Prévost 1997; Löf et al. 2012). In addition, Gomez et al. (2002) found a notable extended period of plant-available water in a compacted clay loam soil. Based on work developed by Sessions et al. (2017), cable-assistance demonstrates theoretical efficacy in improving stability and gradeability and potentially reducing soil disturbance. Visser and Stampfer (2015) state that it can be assumed that a tethered assist system will reduce soil disturbance through reduced slippage of the tracks compared with that for untethered vehicles.

Likewise, tethered Cut-To-Length (CTL) harvesting, a form of mechanized harvesting, could provide both the theoretical stability and gradeability benefits in addition to the potential for reduced soil impacts under controlled use of mechanized harvesting equipment. First made popular in Scandinavia, CTL harvesting uses a combination of a harvester to fell and process the tree into logs, followed by a forwarder that accumulates log piles and bring them to roadside (Visser and Stampfer 2015). CTL harvesting accounted for roughly 30% of the world’s mechanically harvested wood as of

1998 (Tiernan et al. 2004) and has since risen to 40% (Ponsse n.d.). Mechanization can also bring about a reduction in struck-by injuries and numbers of injury claims rates, as evidenced by Bell (2002) in West Virginia. In comparison, cable yarding, a mainstay of steep terrain harvesting operations, remains both expensive (Raymond 2012) as well as hazardous relative to ground-based harvesting operations (Klun and Medved 2007).

The purpose of our study is to compare the compaction effects, productivity and cost of an untethered and tethered wheeled harvester and forwarder using flexible tracks in a thinning stand for a set of site conditions in western Oregon. Specifically, we analyzed the depth and spread of changes in soil physical properties (i.e., dry bulk density and penetration resistance) across a machine corridor with and without cable-assistance taking into account slope, machine passes, and original soil condition.

MATERIALS AND METHODS

Study Area

The harvest was completed on Oregon State University's McDonald Dunn Research Forest in a 57.4-ha harvest unit named "Quick Draw" (Figure 1). Coordinates for Quick Draw are N 44° 38' 14.83" W 123° 19' 51.66".

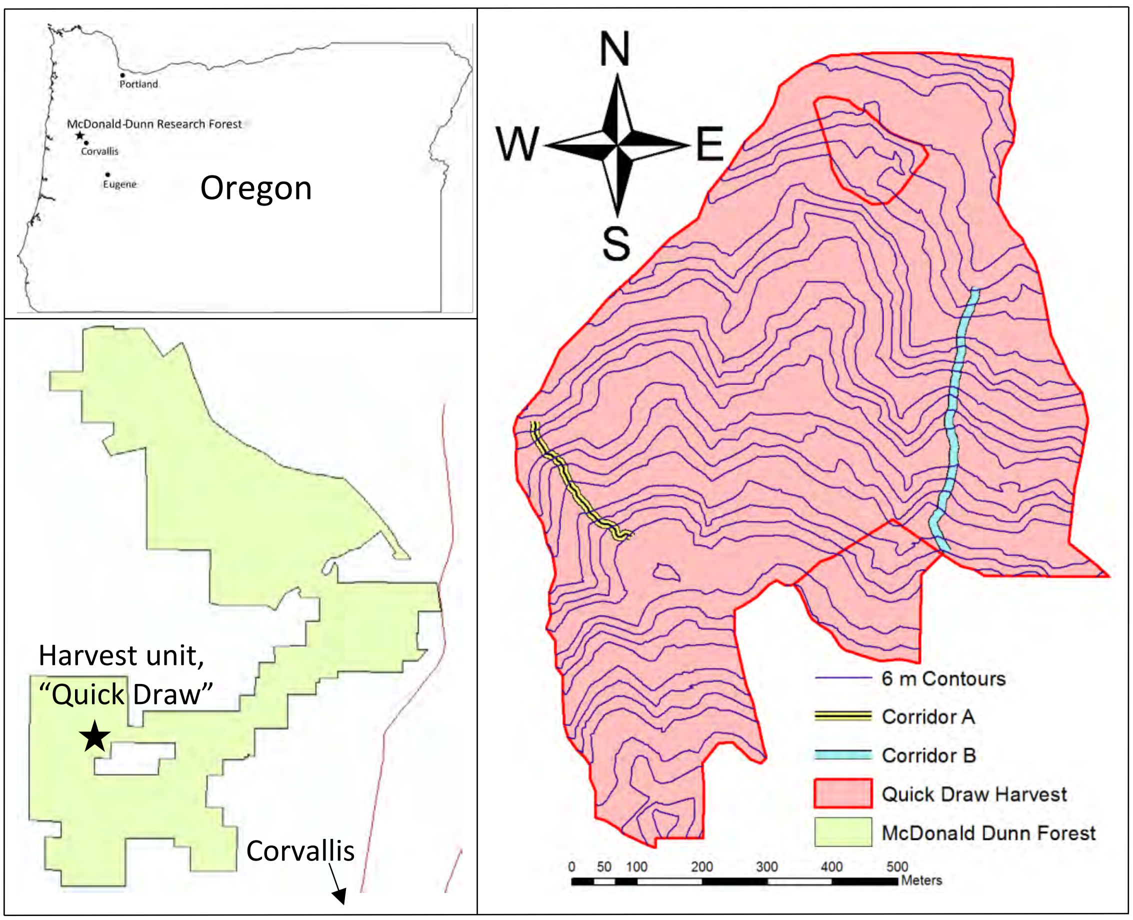


Figure 1 A study thinning unit ("Quick Draw") located in Oregon State University's McDonald-Dunn Research Forest in western Oregon.

A majority of the harvest unit contain *Price* soils, which are well-drained, moderately deep soils with high clay content (27-50%) that exhibit medium to rapid runoff and moderately slow permeability (Fillmore, 2009). *Price* soils are a fine textured gravelly and cobbly material weathered from dominantly basaltic colluvium.

The study stand is comprised mainly of Douglas-fir (*P. menziesii*), grand fir (*A. grandis*), and bigleaf maple (*A. macrophyllum*). Pre-harvest volume levels were 441.6, 60.2, and 13.6 m^3/ha for Douglas-fir, grand fir, and bigleaf maple, respectively. Harvest prescriptions were 120 and 20.4 m^3/ha of removal for Douglas-fir and grand fir, respectively. No specific harvest levels were given for bigleaf maple. Average tree diameter at breast height (dbh) for residual and harvested Douglas-fir trees was 49.5 and 35.1 cm, respectively; and 48.3 and 33.5 cm for grand fir, respectively. Trees for removal were painted prior to the start of harvesting by the landowner. The stand is estimated to be 60 years old and has not previously been commercial-thinned. Post-forwarder depths of slash were recorded for both corridors and not found to be statistically significantly different between the two (p-value = 0.0783).

Harvest System and Machine Operators

A CTL harvesting system was implemented to thin the studied stand with a 240 kW Ponsse[1] Bear harvester and 205 kW Elephant King forwarder. The Bear weighs 23,800 kg and the Elephant King 22,900 kg. The Elephant King has a load capacity of 20,000 kg. Both are 8-wheeled machines and operated with flexible tracks attached during the entire time of observation. Tracks had paddles approximately 10.5 cm high with alternating

[1] Mention of trade names is for information only and does not constitute an endorsement.

grousers 3.5 cm high. Tires on the machine had an approximate width of 75 cm and diameter of 149 cm. All operators were highly experienced with years of experience. The same operator was used for all forwarding operations, but two different operators were used for tethered and untethered harvesting operations as personal circumstances prevented the original operator from completing all harvesting work. Each harvester operator harvested their entire corridor; there was no mixing of operators on the same corridor. Skid trails were designated prior to harvesting.

Corridor Selection

Two ridgetop corridors were selected for study; Corridor A (244 m) for untethered operations and Corridor B (442 m) for tethered operations (Figure 1). Percent slope measured at each sample location ranged from 8-50% with an average of 27% for the untethered corridor, and 7-49% with an average of 30% for the tethered corridor. Percent slope was not found to be significantly different between the two corridors (p-value = 0.3558). Corridors were selected *a priori* using GIS and verified in the field for operational feasibility. Both corridors were selected to ensure a wide variety of timber (i.e., multiple sorts) within boom reach of both machines. These ridgetop corridors also provided varying terrain and sufficient length for tethered operations as compared to the rest of the harvest unit.

Data Collection

Sampling Protocol

Soil samples were taken at fixed sample locations before harvesting, after harvesting, and after forwarding in an attempt to capture the impacts of machine passes on soil. In order to maintain sample location during and after harvest, each sample location was marked via spray paint on residual trees. Each corridor had evenly spaced sample locations (32 sample locations at 7.62 m for the untethered corridor, 29 sample locations at 15.24 m for the tethered corridor).

At each sample location, samples were taken between the wheel tracks, in the machine wheel track, and outside of the machine tracks (termed 'sub-locations' hereafter) (Figure 2). As it was not possible to determine exact machine travel location prior to harvesting, only one pre-harvest sample was taken at each sample location and assumed to be representative of nearby soil. The right track and outside track (as seen if looking up from the bottom of the corridor) was chosen as the sample side from a coin toss. Samples outside the wheel track were collected within a meter of the track but outside the apparent influence of machine activity.

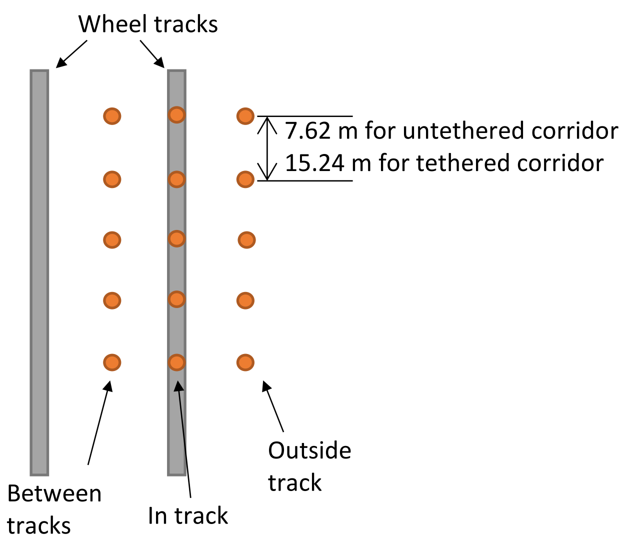


Figure 2 Untethered and tethered corridor sampling schematic.

Productivity and Cost

Detailed time study data were collected along both studied corridors via video cameras and manual stopwatch methods. Two camera operators sat in the machine cab with the machine operator to record independent variables, such as machine movement and tree diameter (dbh). Video data was processed in a computer lab, manually collecting time elements and independent variables.

Similar to the work conducted by Nurminen et al. (2006), we defined one harvester cycle as the cutting of a single tree, and one forwarder cycle (turn) as the forwarding of one load (starting with an empty bunk at the top of the corridor and returning to the top of the corridor and emptying that load). Turn distance was defined as the maximum length the forwarder traveled down the corridor when completing each cycle (turn). Volume estimations were collected via dbh and average piece count per tree for harvesting, and via counting and measuring sitting volume in roadside decks for forwarding. The following cycle time elements were observed during the time study:

- Harvester
  - Move – any period when the wheels are moving and the primary purpose is for movement between trees.
  - Cut preparation – includes brushing (removal of undergrowth and unmerchandisable or hazardous trees from around tree to be felled) and positioning of head around standing tree to be felled. Starts when boom starts moving and ends when felling head is secured to tree and chainsaw starts to move.
  - Fell and process – starts when cutting for felling starts, ends when the tree is fully limbed and bucked. These were combined because it was common for the operator to manipulate the stem of the tree during felling and slide the

head up the bole of the tree, effectively starting to limb before the tree came to rest on the ground.
    - Bunch – sorting felled and processed trees into decks; starts when felling and processing is finished and ends when tracks start moving or other task begins (cut preparation, for example).
    - Delay – delays were classified according to the following, and used for both harvester and forwarder observations:
        - Administrative – talking with harvesting supervisor, other operators, other professional representatives, etc.
        - Mechanical – machine maintenance/breakdown, harvesting head maintenance/breakdown, etc.
        - Operational – tether maintenance/movement/setup, maintenance of/waiting at landing, etc.
        - Personal – lunch break, personal time, activities not related to work, etc.
    - Other – any other productive time, e.g., clearing of obstacles while moving, piling of slash, ejection of tops, and locating the next tree for picking up or felling.
- Forwarder
    - Travel empty – starts when wheels start moving, ends when wheels stop moving and first loading cycle begins. Measured from landing to first deck or bunch of logs.
    - Intermediate travel – starts when machine starts to move after the first or subsequent loading of logs, ends when machine stops for subsequent loading of logs at next deck/pile.
    - Loading – starts when machine is stopped and grapple starts to move, ends when grapple comes to rest and machine starts moving.
    - Travel loaded – starts with machine movement after loading the last bunch of logs for that turn, ends when machine arrives at roadside deck and stops moving for unloading.
    - Unloading – starts when machine stops track movement and starts grapple movement, ends when machine ends grapple movement and starts track movement.

Independent variables collected for each machine were:

- Harvester
    - dbh (cm) – gathered from onboard computer in harvester
    - Distance between stops (m) – ocular estimation based on observed track rotations
    - Number of pieces processed per tree – counted via video data
    - Number of passes
- Forwarder

- Outhaul distance (m) – distance from roadside deck to first log pile for loading, gathered from a GPS placed in machine cab.
- Sawlog, pulp volume total (SVT, PVT m^3) – measured via counting log sorts during loading
- Number of pieces, stops, and swings per turn – counted via video data
- Number of passes

Operational costs were determined via the COST model developed by Ackerman et al. (2014), and Table 1 shows initial cost inputs for determining machine hourly rates. The utilization rate[2] of 80% (taken from the COST model) was reduced to 75% as the setup and takedown of cable-assistance was assumed an operational delay. The tethered operations also included an estimated $100,000 investment per machine for a winch system.

Table 1 Cost parameters used in machine rate calculations.

	Untethered		Tethered	
Cost Inputs	Harvester	Forwarder	Harvester	Forwarder
Machine Fixed Cost Inputs				
Base Machine Price	$720,000	$730,000	$720,000	$730,000
Attachment Price	$0	$0	$100,000	$100,000
Salvage Value[3], Base Machine	20%	20%	20%	20%
Salvage Value, Attachment				
Expected Economic Life (PMH), Base	4,865	4,865	4,865	4,865
Expected Economic Life (PMH), Attachment	4,865	4,865	4,865	4,865
Interest Rate	15%	15%	15%	15%
Machine Variable Cost Inputs				
Fuel Cost (cost/liter)	$0.87	$0.87	$0.87	$0.87
Fuel Consumption (liter/PMH)	26	21	26	21

[2] Machine utilization (MU) is the Scheduled Machine Hours (SMH) that the machine is used to actually do the work that it was designed for [MU (%) = Productive Machine Hours (PMH) / Scheduled Machine Hours (SMH)].

[3] Salvage value expressed as a percent of purchase price.

Oil and Lubrication Cost[4]	12.6%	7.9%	15.0%	11.7%
Maintenance and Repair[5], Base	100%	100%	100%	100%
Maintenance and Repair, Attachment	100%	100%	100%	100%
Operator Costs				
Average Net Wage (cost/hour)	$24.00	$24.00	$24.00	$24.00
Variable Social Charges[6]	45%	45%	45%	45%
Fixed Social Charges[7]	$15,600	$15,600	$15,600	$15,600
Productivity and Operations (general input)				
Scheduled Machine Hours (SMH) per year	2,080	2,080	2,080	2,080
Machine Utilization Rate (%)	80%	80%	75%	75%

Soil Compaction

Bulk density samples were taken at each sample location and sub-locations (i.e., between tracks, in track, outside track) to capture 1) the influence of machine passes on bulk density at the soil surface, and 2) how the spatial impact of these machines behaves (termed 'zone of influence' hereafter). A 164-cm^3 cylindrical soil core was used to collect samples and driven into the ground until level, then carefully extracted. The sample was placed in a plastic collection bag for laboratory evaluation of moisture content and dry bulk density shortly after collection. In addition to bulk density samples, five bulk soil samples were collected for each corridor at sample locations 1, 8, 15, 23, and 30. Of these 10 bulk soil samples collected, soil grain size distribution analyses showed samples were of the silty clay (4), clay (3), sandy clay loam (2), and loam (1) textural classes. Corridor A only had one medium-textured sample (A23) while the remaining samples were all fine-textured across both corridors.

[4] Oil and lubrication cost expressed as a percent of fuel cost/PMH.
[5] Maintenance and Repair expressed as percentage of the replacement value of the machine/attachment.
[6] Variable Social Charges are pensions, levies, etc., expressed as a percentage of wage.
[7] Fixed Social Charges are PPE, training, operator transportation, etc., expressed as cost per year.

Penetration resistance measurements were taken at each sample location and sub-location from 10 to 50 centimeters in depth at 10 cm intervals to observe horizontal and vertical zone of influence (compaction) with depth as a result of machine traffic. A 60° static cone penetrometer with needle pressure gauge and dual-rod design (to eliminate soil friction factor) with 1.5 cm^2 maximum area from Humboldt Manufacturing was used.

All data was collected during the last half of August 2017 over four field days, in which time no precipitation was measured in the geographic region. A weather station just north of Corvallis recorded 0.48 cm of rain 3 days prior to our first day of data collection, but no rain prior to that for 57 days. We assumed little to no change in soil moisture content during or between operations.

Data Analysis

Productivity and Cost

Equations for delay-free cycle time (DFCT) were generated for each machine using multiple linear regression techniques and independent variables collected. The same independent variable values within the observed range were used in the equations generated in order to make more direct comparisons across corridors. The untethered corridor did not include the additional cost of the cable-assistance system, though the same machines were used for both corridors and operators are committed to at a minimum the purchase price of cable-assistance, regardless of their implementation in active harvesting operations. That is, if an operator chooses to purchase a cable-assisted harvesting system, the owning and operating cost of that system will reflect the purchase of cable-assistance regardless of whether or not the actual tether is used during active operations.

Soil Compaction

For each corridor, pre-harvest data was separately compared to post-harvest and post-forwarding data to determine significant changes within the untethered and tethered corridors. This analysis was done with a two-sample t-test assuming unequal variance, a hypothesized difference between means of zero, and an alpha of 0.05. Since the original ranges of penetration resistance were different across each corridor, penetration resistance was analyzed for percent change from original condition in order to make comparisons between the untethered and tethered corridors. To further elucidate the impact of machine passes and other potential influencing factors on compaction, we conducted a multiple linear regression analysis using original soil condition, machine passes, and slope as independent variables with percent change in penetration resistance as the dependent variable. This analysis was conducted using penetration resistance data aggregated from 10-50 cm at each sub-location post-forwarding, as it was assumed to include impact from harvesting as well.

RESULTS

Productivity and Cost

Our time study data showed that the average delay-free cycle times (DFCT) of the harvester were 0.98 and 1.33 minutes for untethered and tethered operations, respectively (Table 2). This difference was primarily driven by the difference in average distance between stops (DBS) of 7.15 m untethered and 4.11 m tethered, as determined through ocular observation of track rotations. Because the two corridors were located in the same harvest unit, similar average values for dbh and pieces per tree were observed for both corridors. In the case of forwarding, tethered forwarding similarly showed a longer DFCT of 40 minutes compared to 30.6 minutes untethered, but an average turn distance of 302.5 m tethered compared to 172.5 m untethered (Table 2). Sawlog and pulp wood volumes were similar between the two corridors, but the tethered corridor had slightly higher sawlog and lower pulp volumes than the untethered corridor. Sawlog volume was carried in every turn for both corridors, while pulp volume was carried in three turns on the untethered corridor and one turn on the tethered corridor. No outliers were observed during data collection.

Table 2 Summary statistics (mean ± standard error) for each corridor and machine from detailed time study raw data (DFCT = delay-free cycle time, DBS = distance between stops, SVT = sawlog volume per turn, PVT = pulp volume per turn) and significance when compared to its untethered/tethered counterpart (* < 0.05, ** < 0.01, *** < 0.001).

	Untethered Harvester	Tethered Harvester	Untethered Forwarder	Tethered Forwarder
N	110	168	8	8
DFCT (min)	0.98 ± 0.5**	1.33 ± 1.1**	30.60 ± 8.2	40.01 ± 11.0

dbh (cm)	29.7 ± 10.0	29.4 ± 8.7		
DBS (m)	7.15 ± 9.7**	4.11 ± 6.7**		
Pieces/Tree	3.35 ± 1.0	3.38 ± 1.0		
Turn dist. (m)			172.5 ± 54.8*	302.5 ± 104.9*
SVT (m^3)			14.7 ± 11.4	18.7 ± 8.7
PVT (m^3)			4.8 ± 7.4	2.0 ± 5.6

In order to make more direct comparisons across corridors, a multiple linear regression analysis was completed using the observed data to generate equations for estimating DFCT (Table 3). The untethered and tethered harvester analysis both showed dbh and DBS to be significant (p-values < 0.001), while untethered forwarding showed all three variables to be significant (p-values < 0.05), and tethered forwarding showed no significant variables (p-values > 0.17). F significance similarly showed the tethered forwarder model a poor explanation of the observed data, with a value of 0.127, whereas the other three models all showed significance < 0.05 (Table 3).

Table 3 Multiple linear regression analysis summary results and significance (* < 0.05, ** < 0.01, *** < 0.001).

		Coefficients	p-value	R Square	F	Significance F
Untethered Harvester	Intercept	-0.112	0.400	50.1%	35.531	< 0.001
	dbh (cm)***	0.023	< 0.001			
	DBS (m)***	0.022	< 0.001			
	# Pieces	0.076	0.105			
Tethered Harvester	Intercept	-0.200	0.527	23.0%	16.298	< 0.001
	dbh (cm)***	0.039	< 0.001			
	DBS (m)***	0.056	< 0.001			
	# Pieces	0.037	0.654			
Untethered	Intercept	-7.500	0.287	92.2%	15.846	0.011
	Dist. (m)*	0.092	0.012			
	SVT (m^3)*	0.946	0.011			

	PVT (m^3)**	1.742	0.006			
Tethered Forwarder	Intercept	-17.356	0.713	72.6%	3.537	0.127
	Dist. (m)	0.108	0.178			
	SVT (m^3)	1.136	0.413			
	PVT (m^3)	1.786	0.215			

When compared at the same values of dbh, DBS, and number of pieces per tree (29.5 cm, 5.31 m, and 3.37, respectively), untethered harvesting showed a lower predicted DFCT of 0.94 minutes compared to 1.37 minutes tethered, likely owing to the higher weight given to DBS in the tethered model. Weighted average volume per piece was estimated at 0.537 m^3/log, taken from samples of the forwarded volume once at roadside.

When comparing forwarding productivity regression using the same independent variables to both corridors (turn distance of 200 meters [arbitrarily chosen to avoid extrapolation] and average sawlog and pulp volumes of 16.73 and 3.37 m^3/turn, respectively), tethered forwarding showed a lower predicted DFCT of 29.2 minutes compared to 32.6 minutes for the untethered forwarder.

Untethered and tethered harvesting showed estimated productivity values of 115.45 and 79.01 m^3 per productive machine hour (PMH), respectively, while forwarding productivity was estimated at 35.94 and 42.54 m^3/PMH for untethered and tethered, respectively.

As different operating conditions can heavily influence machine productivity, we present two analyses in order to observe a range of productivities based on a coupled or decoupled system. Some harvesting scenarios require close coordination of work with little lead-time between the harvester and forwarder, while others allow for full independence between the machines. As such, system productivity can change depending on the presence and intensity of bottlenecks in the operation.

When considering the uncoupled system first, harvester productivity was estimated at 92.36 and 59.26 m^3/SMH untethered and tethered, respectively. Forwarder productivity was estimated at 28.75 and 31.91 m^3/SMH untethered and tethered, respectively. Total unit cost was \$13.19/m^3 and \$15.08/m^3 untethered and tethered, respectively (Table 4a).

When assuming a coupled system (machines do not work independently of each other), the forwarder becomes the bottleneck in both tethered and untethered operations. As a result, the productivity of the untethered system was 28.75 m^3/SMH, compared to 31.91 m^3/SMH for the tethered system (Table 4b). Total unit cost was \$17.40/m^3 for the untethered corridor and \$17.78/m^3 for the tethered corridor (Table 4b), with harvesting accounting for 43.9% and 47.0% of total unit cost for untethered and tethered, respectively.

Table 4a Uncoupled system costs and productivity summary.

		Untethered		Tethered	
		Harvester	Forwarder	Harvester	Forwarder
Productivity (m^3/SMH)		92.36	28.75	59.26	31.91
Machine Fixed Costs	\$/SMH	\$133.55	\$116.93	\$144.77	\$128.95
Machine Variable Costs	\$/SMH	\$140.70	\$121.29	\$147.72	\$129.65
Operator Costs	\$/SMH	\$42.30	\$42.30	\$42.30	\$42.30
Total	\$/SMH	\$316.55	\$280.52	\$334.79	\$300.89
	\$/m^3	\$3.43	\$9.76	\$5.65	\$9.43

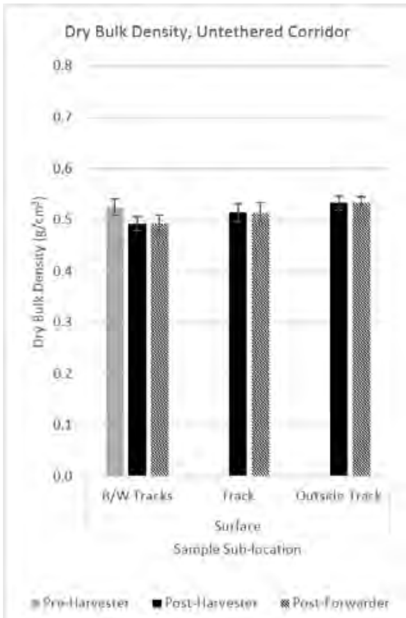
System Total	\$/SMH	\$597.07	\$635.68
	\$/m³	\$13.19	\$15.08

Table 4b Coupled system costs and productivity summary.

		Untethered		Tethered	
		Harvester	Forwarder	Harvester	Forwarder
Productivity (m^3/SMH)		28.75	28.75	31.91	31.91
Machine Fixed Costs	\$/SMH	\$133.55	\$116.93	\$144.77	\$128.95
Machine Variable Costs	\$/SMH	\$43.80	\$121.29	\$79.53	\$129.65
Operator Costs	\$/SMH	\$42.30	\$42.30	\$42.30	\$42.30
Total	\$/SMH	\$219.65	\$280.52	\$266.61	\$300.89
	\$/m^3	\$7.64	\$9.76	\$8.35	\$9.43
System Total	\$/SMH	\$500.17		\$567.50	
	\$/m^3	\$17.40		\$17.78	

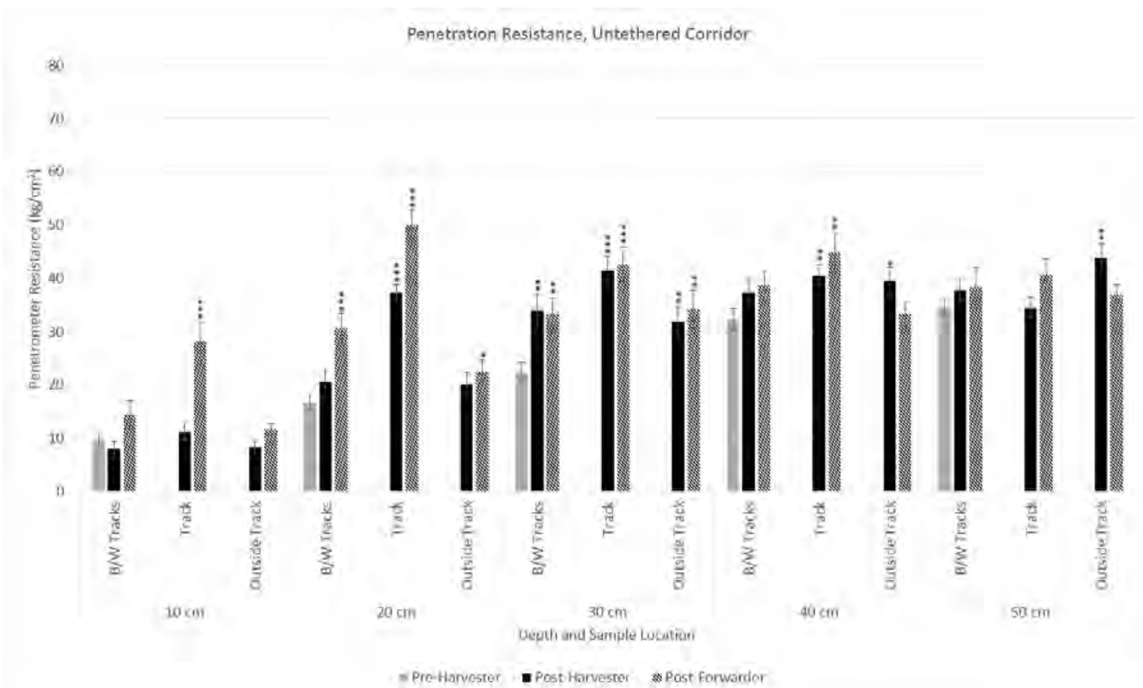
Soil Compaction

Figure 3 shows post-harvester and post-forwarder data compared against pre-harvest data across both corridors at all depths and sample sub-locations. Figure 4 illustrates significant increases and decreases in penetration resistance and dry bulk density samples as a result of harvesting and forwarding for both the untethered and tethered corridors. Though sampling was only conducted via one side of the machine travel corridor, results are mirrored in Figure 4 for illustrative purposes.



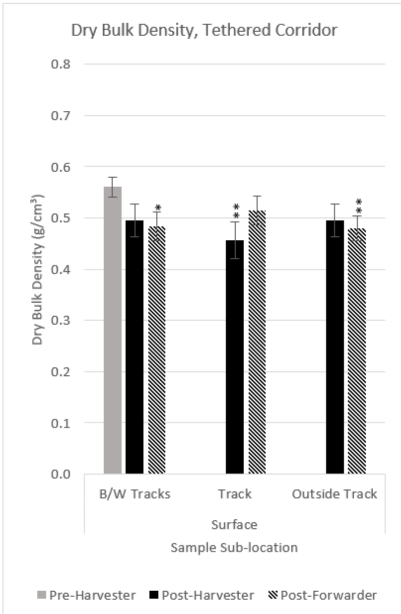
Dry Bulk Density, Untethered Corridor
Dry Bulk Density (g/cm³)
B/W Tracks
Track
Outside Track
Surface
Sample Sub-location
Pre-Harvester
Post-Harvester
Post-Forwarder

(a)

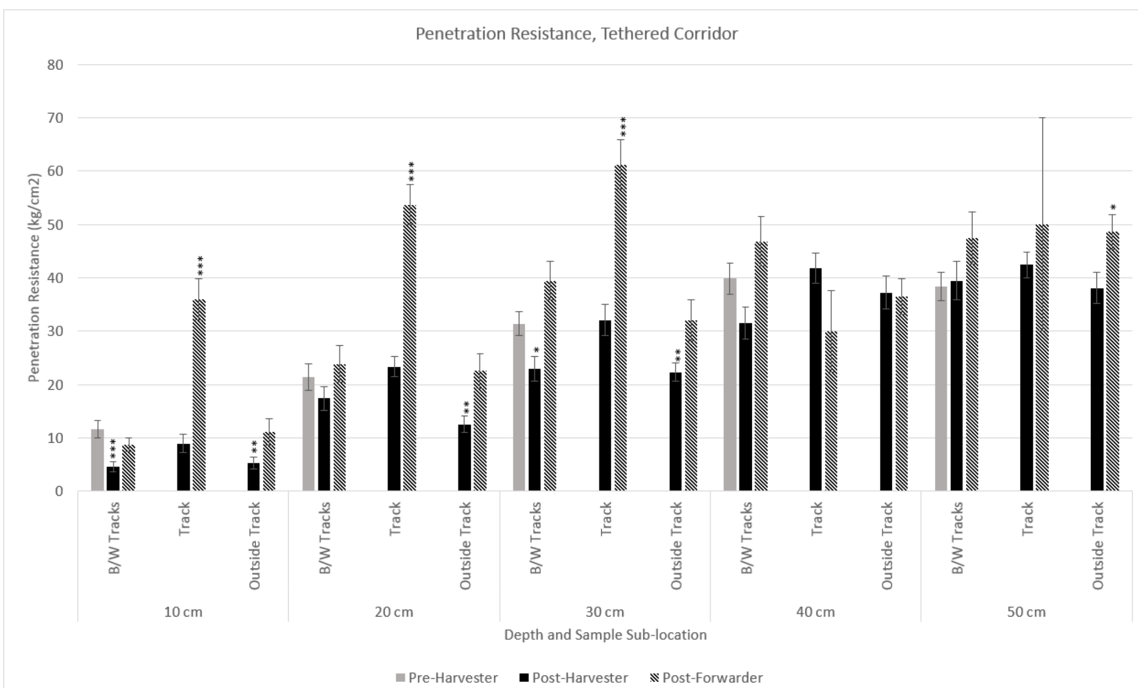


Penetration Resistance, Untethered Corridor
Penetrometer Resistance (kg/cm²)
10 cm
20 cm
30 cm
40 cm
50 cm
Depth and Sample Location
Pre-Harvester
Post-Harvester
Post-Forwarder

(b)

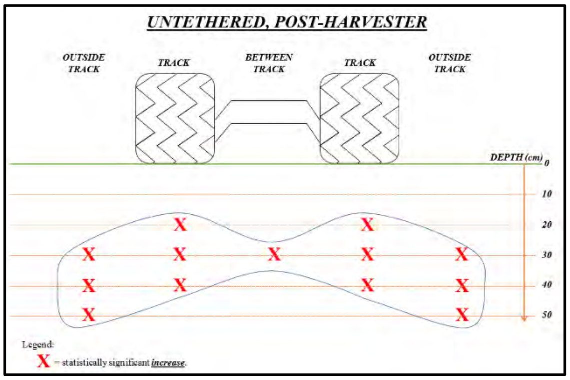


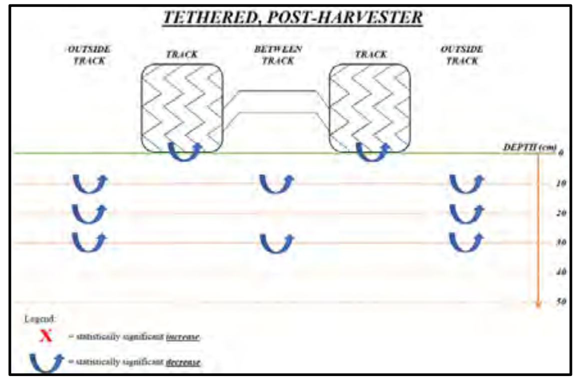
(c)



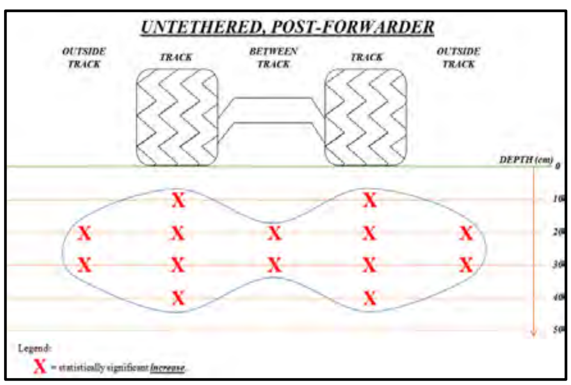
(d)

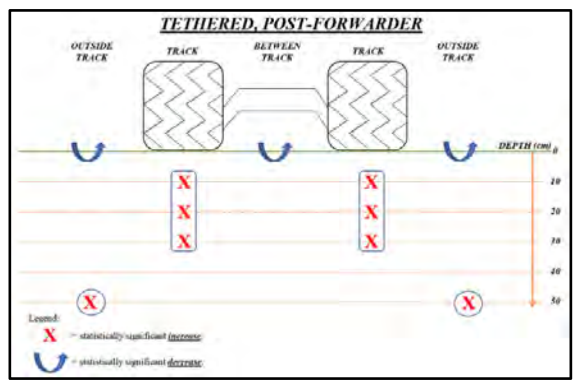
Figure 3 (a, b, c, d) Average dry bulk density (a and c) and penetration resistance (b and d), untethered and tethered corridors with error bars and significance (* < 0.05, ** < 0.01, *** < 0.001).





(a) (b)





(c) (d)

Figure 4 (a, b, c, d) Bubble Disturbance Images showing statistically significant increases/decreases in soil density as a result of untethered harvesting (a) and forwarding (c), and tethered harvesting (b) and forwarding (d).

Both the untethered harvester and forwarder showed statistically significant increases in penetration resistance when compared to pre-harvest samples in a majority of sample sub-locations (Figures 3b, 4a and 4c). Untethered post-harvester between tracks showed the least significant increases at just 30 cm (from 22.2 to 34 kg/cm^2 penetration resistance [p-value = 0.0025]), while track measurements showed increases from 20-40 cm (from 16.7 to 37.3 [p-value < 0.0001], 22.2 to 41.5 [p-value < 0.0001], and 32.4 to 40.6 [p-value = 0.0055] kg/cm^2 penetration resistance, respectively) and outside tracks revealed significant increases from 30-50 cm (from 22.2 to 31.9 [p-value = 0.0089], 32.4 to 39.5 [p-value = 0.0319], and 34.6 to 43.9 [p-value = 0.0038] kg/cm^2 penetration resistance, respectively) (Figures 3b and 4a). While the majority of untethered harvesting sub-locations had a significant increase in penetration resistance, a slight decrease, though not significant, was observed at 10 cm between tracks and outside tracks, and at 50 cm in track (p-values > 0.33) (Figures 3b and 4a).

Untethered forwarding showed a similarly large horizontal and vertical spread of significant influence. Between tracks measurements showed a significant increase at 20 and 30 cm (from 16.7 to 30.7 [p-value < 0.001], and 22.2 to 33.2 [p-value = 0.0047] kg/cm^2 penetration resistance, respectively), while track measurements showed increases at 10, 20, 30 and 40 cm (from 9.8 to 28.2 [p-value < 0.001], 16.7 to 49.8 [p-value < 0.001], 22.2 to 42.7 [p-value < 0.001], and 32.4 to 44.8 [p-value = 0.0070] kg/cm^2 penetration resistance, respectively). Outside track measurements had significant increases at 20 and 30 cm (from 16.7 to 22.4 [p-value = 0.0436] and 22.2 to 34.2 [p-value = 0.0053] kg/cm^2 penetration resistance, respectively) (Figure 3b, 4c). Increases, although not significant, were observed at all other sample sub-locations post-forwarder.

No significant increases or decreases in dry bulk density were seen as a result of untethered harvesting or forwarding (p-values > 0.10), though both increases (untethered post-harvester and post-forwarder outside tracks) and decreases (post-harvester and -forwarder tracks and between tracks) were observed (Figure 3a). No reductions in penetration resistance were seen in any sub-locations as a result of untethered forwarding (Figure 3b, 4c).

Tethered post-harvester showed significant *decreases* in penetration resistance from 10-30 cm outside tracks (from 11.7 to 5.3 [p-value = 0.0019], 21.4 to 12.5 [p-value = 0.0040], and 31.4 to 22.3 [p-value = 0.0020] kg/cm^2, respectively) and from 10 and 30 cm between tracks (from 11.7 to 4.6 [p-value = 0.0004], and 31.4 to 22.9 [p-value = 0.0106] kg/cm^2, respectively) (Figure 3d, 4b). Surface dry bulk density for tethered post-harvester track measurements also showed a significant decrease from 0.56 to 0.45 g/cm^3 [p-value = 0.0095] (Figure 3c, 4b). Increases, though not significant at alpha = 0.05, were observed in track measurements from 20-50 cm and between track measurements at 50 cm (p-values > 0.2) (Figure 3d).

Tethered post-forwarder showed an increase in penetration resistance in track measurements from 10-30 cm (from 11.7 to 36.0 [p-value < 0.001], from 21.4 to 53.7 [p-value < 0.001], and 31.4 to 61.3 [p-value < 0.001] kg/cm^2, respectively) and outside track measurements at 50 cm (from 38.4 to 48.6 [p-value = 0.0206] kg/cm^2) (Figure 3d, 4d). Insignificant increases were observed at 10 cm outside tracks; 20, 30 cm between and outside tracks; 40, 50 cm between tracks; and 50 cm track (Figure 3d). Insignificant decreases were observed in 10 cm between tracks and 40 cm tracks and outside tracks (Figure 3d). In addition, significant decreases in dry bulk density were observed between and outside tracks (from 0.56 to 0.48 [p-value = 0.0173] and 0.48 [p-value = 0.0054] g/cm^3, respectively) (Figure 3c, 4d) after tethered forwarding. Track dry bulk density also decreased from 0.56 to 0.51 g/cm^3 (p-value = 0.1343) (Figure 3c). All bulk density averages were below the root-growth limiting bulk density values of clay and loam soils of 1.4 and 1.55 g/cm^3 (Coder 2000).

The multiple linear regression analysis performed to examine the influence of external factors on percent change in penetration resistance indicated that original condition of the soil was significant in all sample sub-locations for both untethered and tethered post-forwarding (p-values < 0.0088). Slope was not significant at any locations (p-values > 0.05), while number of passes was only significant for the tethered corridor post-forwarder outside track measurements (p-value = 0.0375) (Table 5).

Table 5 Results of multiple linear regression models developed to predict percent change in penetration resistance at all sub-locations in each corridor shown in terms of p-value of each independent variable and Model R Squared.

	Post-Forwarder Untethered			Post-Forwarder Tethered		
	BT	T	OT	BT	T	OT
Original Condition	0.0012	< 0.001	0.0002	0.0191	0.0282	0.0002
Slope	0.0503	0.0858	0.0969	0.4006	0.8646	0.2672
Passes	0.4372	0.1321	0.9322	0.5794	0.5670	0.0594
R Squared	44%	64%	44%	31%	34%	43%

DISCUSSION

Productivity and Cost

A different average distance between stops (DBS) was observed between the untethered and tethered harvester (Table 2), possibly playing a large role in productivity differences. This difference in DBS could be a product of operator skill gap, or because of a limitation in operating window while tethering the harvester. That is, the harvester might be more limited in machine orientation while tethering in order to maintain machine alignment with tether, or to reduce sidehill exposure on steeper slopes. A smaller operating window at each stop could result in the shorter DBS observed while tethered, and a subsequently lower productivity. It is unclear how to articulate differences in harvester productivity to either different operators or the use of cable-assistance.

Our observed harvester productivity appears to be higher than those reported in previous studies. Jiroušek et al. (2007) observed productivity ranging from 13.5 to 60.5 m^3/PMH in Ireland, and Hiesl and Benjamin (2013) summarized harvester productivity ranging from 4.9 to 26.7 m^3/PMH. However, most of these past studies occurred in the 1980's and 1990's with less advanced technology, and thus it is difficult to make direct comparisons with the previous studies. In addition, the large average piece size likely played a large role in our observed productivity.

Our delay-free cycle time model for tethered forwarding was not statistically significant. Eriksson and Lindroos (2014) noted forwarding productivity in thinning as especially difficult to model, with only about one-third of observed variation being explained through their models using up to 12 explanatory variables. They noted mean stem size (m^3, derived from the total harvested volume on a site divided by the corresponding sum of harvested trees) as the single variable that explained most of the variation, similar to our study that used average piece size and count as a proxy to determine load size.

An important consideration in the use of cable-assistance is the different types of operational downtime that may occur depending on the presence of a tether. Not using cable-assistance has the potential to result in more unanticipated downtime due to machine trafficability and traction issues, as was observed in our research. The untethered harvester on Corridor A was briefly stuck when trying to return to the top of the corridor, and ultimately needed to tether to return to the corridor. The operator spent less than 10 minutes using just the machine to return to the corridor before using cable-assistance to successfully return. When tethering, operational downtime comes in the form of connecting and disconnecting the tether, a delay that can be accounted and planned for in operational planning. We observed a mean ± standard error of 2.5 ± 1.0 minutes for hooking and unhooking the tether from 18 observations (2 from the harvester, 16 from the forwarder). This is also why we used a utilization rate for tethered operations that was 5% lower than for untethered operations, also contributing to the observed cost difference.

The higher forwarder productivity when tethered could be a product of the increased trafficability when tethered, as well as the larger average turn size (20.7 tethered compared to 19.5 m^3/turn untethered) (Table 2). The improved weight distribution could also allow for higher turn volumes as total tractive force is improved in tethered operations.

Soil Compaction

The presence of a tether changes the interaction of equipment with underlying soil, but this complex relationship is governed by initial soil density, soil type, moisture, machine type and machine coverage/footprint. From the results of this study, we propose both horizontal and vertical potential benefits of using cable-assistance in ground-based harvesting: reduced track coverage resulting from limited track wander (defined as the tendency for the equipment wheels (or tracks) to vary in alignment with multiple passes) and reduced shear displacement due to decreased slip and peak pressures. Each are governed by different underlying mechanisms, and these benefits can be further broken down into their horizontal and vertical components, relative to the ground surface.

Horizontal benefits of the tether can be summarized as a reduction in track footprint, as tethered operations could control repetitive machine passes over the same terrain with limited wander. This reduction in track wander is shown through a comparison of Figures 4a, 4b, and 4c, 4d. During and after untethered harvesting and forwarding, it was visually observed that the footprint of machine travel was not in exactly the same place with each subsequent pass, indicating some amount of passes were not over the same exact path. This could explain the zone of influence observed in our untethered operations due to a widening of the actual travel path of the harvesting and forwarding trail. This same magnitude of wander was not observed following tethered harvesting and forwarding. Without the use of cable-assistance, a machine might contact a larger surface area, with fewer passes over any one location. With the use of cable-assistance, a machine might be in contact with a smaller area, albeit more often. Since most soil compaction likely happens with initial passes (Gent et al. 1984; Brais and Camire 1998), untethered operations, though they might result in fewer passes per area, might still exhibit significant impact on these trafficked areas.

The potential vertical benefits of a tether are primarily driven by a reduction in shear loading and peak pressures. Sessions et al. (2017) highlighted that the tether more evenly distributes weight of a machine across its tracks as it travels, resulting in decreased slip and peak pressures. These benefits directly translate to a reduction in the shear load on a soil, and all of these phenomena are likely responsible for the differences in penetration (vertical) resistance we observed between the untethered and tethered corridors (Figures 3 and 4). In our study the use of cable-assistance commonly resulted in a more diminished percent increase in penetration resistance after harvesting and forwarding (Table 6), which may be partly attributed to higher pre-harvest penetration resistance on the tethered corridor. Previous research has highlighted the influence of initial soil density when testing for compaction in forest harvesting (Jamshidi et al. 2008; Hillel 1998; Powers et al. 2005). Our untethered corridor had a statistically significant lower average pre-harvest penetration resistance when values from each corridor were aggregated and compared across corridors (22.8 and 28.1 kg/cm^2 for untethered and tethered corridors, respectively; p-value 0.0026). However, comparisons across the untethered and tethered corridors at similar levels of original penetration resistance still show that the tethered corridor had a lower increase in penetration resistance (Figure 5, Figure 6), particularly post-harvester. At lower levels of original penetration resistance, the effect of a tether is more pronounced as initially less-dense soils show larger gains in increased penetration resistance. Rowe (1962) found that initially less-dense materials are more prone to contract while denser materials tend to dilate, similar to what was observed here, particularly after tethered harvesting between and outside wheel tracks (Table 6, Figure 3d, Figure 4b). These lower levels of penetration resistance could likely be a result of lower peak pressures due to better weight distribution along the tracks because of the tether.

Table 6 Rank, location, and percent change in penetration resistance for each sub-location when aggregated from 10-50 cm.

Post-Harvester			Post-Forwarder		
Rank	Location	Change %	Rank	Location	Change %
1	Untethered Track	51%	1	Untethered Track	106%
2	Untethered Outside Track	30%	2	Tethered Track	89%
3	Untethered Between Tracks	22%	3	Untethered Between Tracks	41%
4	Tethered Track	7%	4	Untethered Outside Track	27%
5	Tethered Between Tracks	-15%	5	Tethered Between Tracks	18%
6	Tethered Outside Track	-17%	6	Tethered Outside Track	11%

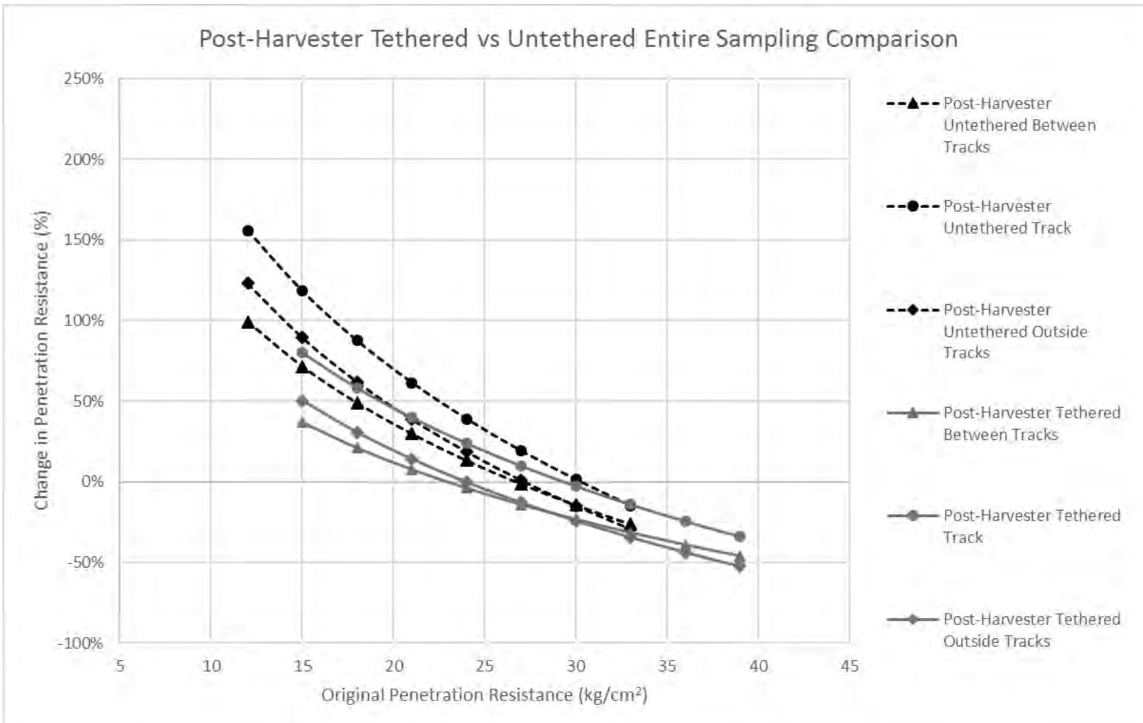


Figure 5 Post-harvester percent increase in penetration resistance based on original penetration resistance.

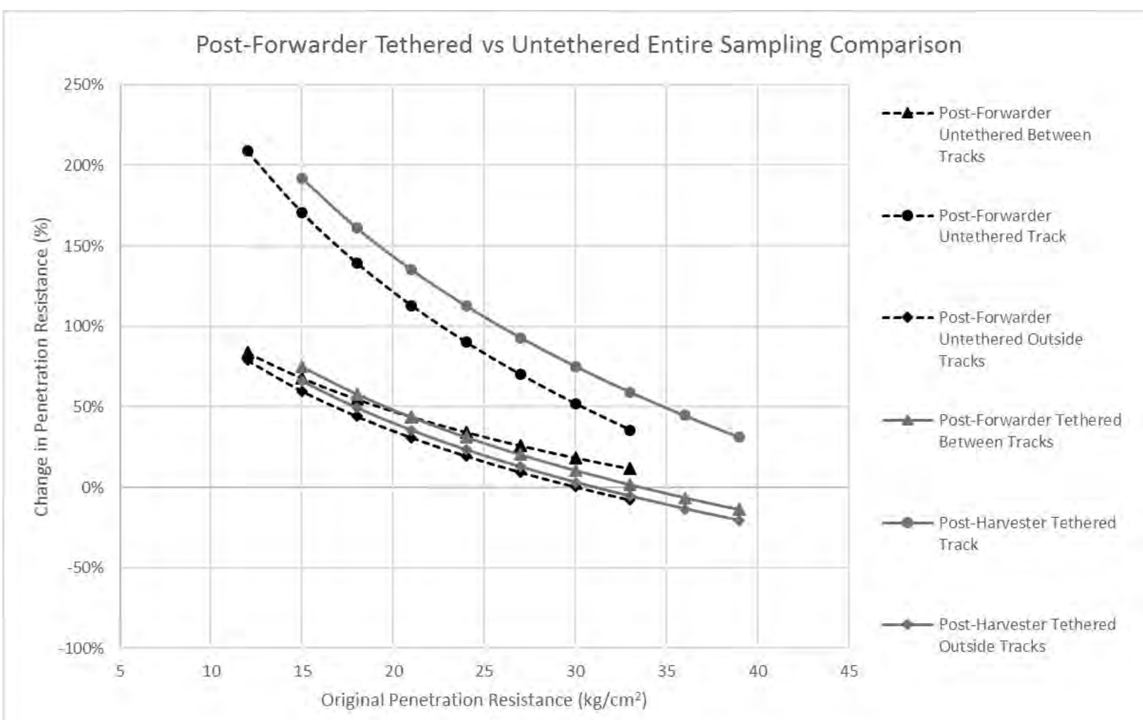


Figure 6 Post-forwarder percent increase in penetration resistance based on original penetration resistance.

The change in penetration resistance with depth is also notably different between the tethered and untethered regime. For the untethered case, there is an observed increase in penetration resistance both post-harvester and especially post-forwarder with depth (Figure 3b), particularly in the top 20-40 cm underneath the track footprint. While the surface material may cyclically displace and mildly densify or loosen, the slightly denser underlying material is confined and subject to densification from the repeated passes of equipment and the corresponding vertical pressures. This trend is supported by increases in penetration resistance inside and outside of the track footprint in comparison to the undisturbed case, particularly at depths of 10-40 cm, where the soil is confined and stress concentrations from the equipment are relatively high. This phenomenon is presented visually in Figure 4a and 4c, where bulbs of statistically significant increased penetration resistance are observed directly within a soil depth where pressure increases from the equipment are still expected to be large. For example, using a Boussinesq pressure distribution, the vertical stress increase is still upwards of 70% of the ground pressure at 40 cm in depth for a 75-cm wide tire (Terzaghi et al. 1996).

The tethered case demonstrated different behavior, tending to exhibit loosening post-harvester and concentrated densification post-forwarder. As stated previously, the initial penetration resistance of the tethered corridor (Corridor B), was notably higher than its untethered counterpart, thus, loosening was observed near and around the tracks at the upper reaches of soil after harvesting (Figure 4b). Subsequently, as slight displacement of soil occurred during machine travel (tethered harvester), already dense material loosened, particularly at the top 0-40 cm (Figure 3d, 4b). Jansson and Johansson (1998) observed a similar decrease in bulk density in the upper 10 cm of soil for a tracked vehicle operating on silt loam soils. This initially loosened, unconfined material provides a buffer that requires more energy (i.e. equipment passes) to become densified once more. Here again, the benefit of reduced shear loading (Sessions et al. 2017) may play an important role. As the tether reduces shear stresses in the soil required for traction, the soil can withstand more energy (passes) before being fully displaced and subsequently densified again. When the forwarder completed its passes, the largest increase in penetration resistance of all regimes was observed, especially in the top 20-30 cm (Figure 3d). While the tethered harvester, a lighter machine compared to a loaded forwarder, may have loosened and displaced the already dense soil surrounding the tracks, the forwarder densified the underlying soil confined underneath and around the track footprint after numerous passes (Figure 4d). With a tether to maintain alignment and reduce wander, the heavier, loaded forwarder tended to densify the in-place soil with its numerous passes. It is possible, but conjecture, that more densification, albeit concentrated, would have been observed in the untethered case would track wander have been reduced. For the tethered, post-forwarder case, loosening still occurred at the surface between and outside of the wheel tracks as the material is unconfined and subsequently displaced with equipment travel (Figure 4d), a product of the initially higher soil density.

Prior research has also highlighted the importance of machine passes and ground slope when considering compaction as stated in the introduction section. The untethered corridor experienced two passes from the harvester, while half of the tethered corridor experienced two passes and the other half had four passes due to operational requirements. Both corridors had 16 forwarder passes, though not on all sample locations as each turn traveled a different distance down each corridor. In both corridors, initial forwarder passes traveled the entirety of the corridor, but following passes covered less of the corridor as wood was extracted from the corridor from the bottom-up. Regression results showed passes were not significant in either corridor (p-values > 0.05) (Table 5).

We found no statistical relationship between slope and percent increase in penetration resistance, though the untethered corridor p-values were much lower than those of the tethered corridor (Table 5). Similarly, Zamora-Cristales et al. (2014) found no apparent pattern when using regression analysis to test for a relationship between slope and observed soil strength up to 450 mm in depth on steep slopes after a thinning using a harvester-forwarder in western Oregon and a similar penetrometer method of data collection. It is also unclear, and not accounted for in this research, how the changing footprint of the machine as it moves over undulating terrain common in steep-slope harvesting environments affects the measurements taken.

In summary, it is likely that the presence of a tether may assist in minimizing soil disturbance primarily through an ability to maintain consistent travel paths whilst maintaining soil integrity. Increased track wander may decrease the magnitude of observed densification; however, it may affect a larger area more negatively. Changes in soil bulk density are a function of ground pressures and initial porosity – in these comparisons, there was a notable increase in density in the untethered corridor, likely as the undisturbed soil was not particularly dense. Conversely, there was loosening and dilation observed in the tethered corridor where soil was more dense, potentially as a result of lower peak pressures and decreased slip provided by the tether. If wander and shear load are diminished, it is possible that initial loosening will provide an initial buffer of soil at the surface that must once again be densified with added passes. That is, although loosening may still initially occur, a reduction in slip, reducing displacement, may increase the number of passes required before the onset of densification. As such, through reducing displacement of the overlying soil with subsequent passes, the densification of the underlying material will take more passes to occur due to the existing buffer of topsoil.

CONCLUSIONS

Our research compared the site impacts, productivity and cost of a CTL harvesting system with and without the use of cable-assistance. We observed reduced harvester productivity and increased forwarder productivity as a result of tethering. As a combined system, the tethered harvester and forwarder showed a slightly higher unit production cost than the untethered system mainly due to increased machine rates and decreased harvester productivity. The differences in harvester productivity in the untethered and tethered corridors could not be attributed to a single specific root cause, as different operators as well as cable-assistance were variables in this research. Though this research is just one case study comparing an untethered and tethered harvester and forwarder, this study showed a lessened spatial distribution of machine influence on compaction because of tethered operations and original soil conditions. Our research suggests the use of cable assistance can reduce track coverage and reduce shear displacement, and thus likely lessen potential soil impact caused by forestry machines. Future research should be directed towards similar comparisons using different moisture contents, soil types, in-corridor slash loads, and machines. Long-term compaction and erosion impacts are also important.

As operations progress onto steeper and steeper slopes as a result of the stabilizing forces provided by a tether (effectively extending the range of operable conditions), more attention must be paid to ground conditions such as soil type/texture, moisture content, and initial bulk density, as these are still the mediums by which machine trafficability and safety are governed. As machines become a less limiting factor on steep terrain, operator training and ability, machine maintenance and design, and regulations should likewise be examined to shore up deficits that might not have previously existed.

BIBLIOGRAPHY

Ackerman, P., H. Belbo, L. Eliasson, A. de Jong, A. Lazdins, and J. Lyons. 2014. The COST model for Calculations of Forest Operations Costs. *International Journal of Forest Engineering.* 25(1): 75-81.

Agherkakli, B., A. Najafi, and S.H Sadeghi. 2010. Ground based operation effects on soil disturbance by steel tracked skidder in a steep slope of forest. *Journal of forest science*. 56(6): 278-284.

Alakukku, L., P. Weisskopf, W.C.T Chamen, F.G.J. Tijink, J.P. van der Linden, S. Pires, C. Sommer, and G. Spoor. 2003. Prevention strategies for field traffic-induced subsoil compaction: a review: Part 1. Machine/soil interactions. *Soil and Tillage Research*. 73(1-2):145-160.

Ampoorter, E., A.D. Schrijver, L. van Nevel, M. Hermy, and K. Verheyen. 2012. Impact of mechanized harvesting on compaction of sandy and clayey forest soils: results of a meta-analysis. *Annals of Forest Science.* 69(5):533-542.

Ampoorter, E., R. Goris, W.M. Cornelis, and K. Verheyen. 2007. Impact of mechanized logging on compaction status of sandy forest soils. *Forest Ecology and Management* 241(1-3):162-174.

Ares, A., T.A. Terry, R.E. Miller, H.W. Anderson, and B.L. Flaming. 2005. Ground-based forest harvesting effects on soil physical properties and Douglas-fir growth. *Soil Science Society of America Journal*, 69(6):1822-1832.

Arthur, E., P. Schjønning, P. Moldrup, M. Tuller, and L.W. de Jonge. 2013. Density and permeability of a loess soil: Long-term organic matter effect and the response to compressive stress. *Geoderma*. 193:236-245.

Bell, J.L., 2002. Changes in logging injury rates associated with use of feller-bunchers in West Virginia. *Journal of Safety Research*. 33(4):463-471.

Berli, M., B. Kulli, W. Attinger, M. Keller, J. Leuenberger, H. Flühler, S.M. Springman, and R. Schulin. 2004. Compaction of agricultural and forest subsoils by tracked heavy construction machinery. *Soil and Tillage Research*. 75(1):37-52.

Bettinger, P., and L.D. Kellogg. 1993. Residual stand damage from cut-to-length thinning of second-growth timber in the Cascade Range of western Oregon. *Forest Products Journal.* 43(11, 12).

Bettinger, P., J. Sessions, and L.D. Kellogg. 1993. Potential timber availability for mechanized harvesting in Oregon. *West. J. Appl. For.* 8(1):1-5.

Blouin, V.M., M.G. Schmidt, C.E. Bulmer, and M. Krzic. 2005. Mechanical disturbance impacts on soil properties and lodgepole pine growth in British Columbia's central interior. *Canadian Journal of Soil Science*. 85(5):681-691.

Brais, S., and C. Camire. 1998. Soil compaction induced by careful logging in the claybelt region of northwestern Quebec (Canada). *Canadian Journal of Soil Science*. 78(1):197-206.

Cambi, M., G. Certini, F. Neri, and Marchi, E., 2015. The impact of heavy traffic on forest soils: a review. *Forest Ecology and Management*. 338:124-138.

Christopher, E.A., and R. Visser. 2007. Methodology for evaluating post harvest erosion risk for the protection of water quality. *New Zealand Journal of Forestry*. 52(2):20.

Coder, K.D. 2007. *Soil compaction & trees: Causes, symptoms & effects.* University of Georgia School of Forest Resources, Athens, GA. 99 p.

Croke, J., P. Hairsine, and P. Fogarty. 2001. Soil recovery from track construction and harvesting changes in surface infiltration, erosion and delivery rates with time. *Forest Ecology and Management*. 143(1-3):3-12.

Currie, J.A.. 1984. Gas diffusion through soil crumbs: the effects of compaction and wetting. *Journal of Soil Science*. 35(1):1-10.

Demir, M., E. Makineci, A. Comez, and E. Yilmaz. 2010. Impacts of repeated timber skidding on the chemical properties of topsoil, herbaceous cover and forest floor in an eastern beech (*Fagus orientalis Lipsky*) stand. *Journal of Environmental Biology*. 31(4):477.

Eriksson, M., and O. Lindroos. 2014. Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. *International Journal of Forest Engineering*. 25(3):179-200.

Fillmore, M. 2009. *Soil Survey of Benton County*. United States Department of Agriculture. 1465 p.

Frey, B., J. Kremer, A. Rüdt, S. Sciacca, D. Matthies, and P. Lüscher. 2009. Compaction of forest soils with heavy logging machinery affects soil bacterial community structure. *European Journal of Soil Biology*. 45(4):312-320.

Gaertig, T., H. Schack-Kirchner, E.E. Hildebrand, and K.V. Wilpert. 2002. The impact of soil aeration on oak decline in southwestern Germany. *Forest Ecology and Management*. 159(1-2):15-25.

Gent, J.A., R. Ballard, A.E Hassan, and D.K. Cassel. 1984. Impact of Harvesting and Site Preparation on Physical Properties of Piedmont Forest Soils 1. *Soil Science Society of America Journal*. 48(1):173-177.

Godwin, R., G. Spoor, B. Finney, M. Hann, and B. Davies. 2008. The current status of soil and water management in England. *Warwickshire, UK: Royal Agricultural Society of England*. 7 p.

Gomez, A., R.F. Powers, M.J. Singer, and W.R. Horwath. 2002. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. *Soil Science Society of America Journal*. 66(4):1334-1343.

Han, S.K., H.S. Han, D.S. Page-Dumroese, and L.R. Johnson. 2009. Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest. *Canadian Journal of Forest Research*. 39(5):976-989.

Hiesl, P., and J. Benjamin. 2013. Applicability of international harvesting equipment productivity studies in Maine, USA: A literature review. *Forests*. 4(4):898-921.

Hillel, D. 1998. *Environmental soil physics: Fundamentals, applications, and environmental considerations*. Elsevier, San Diego, California, United States of America. 771 p.

Jamshidi, R., D. Jaeger, N. Raafatnia, and M. Tabari. 2008. Influence of two ground-based skidding systems on soil compaction under different slope and gradient conditions. *International Journal of Forest Engineering*. 19(1):9-16.

Jansson, K.J., and J. Johansson. 1998. Soil changes after traffic with a tracked and a wheeled forest machine: a case study on a silt loam in Sweden. *Forestry: An International Journal of Forest Research*. 71(1):57-66.

Jansson, K.J., and I. Wästerlund. 1999. Effect of traffic by lightweight forest machinery on the growth of young Picea abies trees. *Scandinavian Journal of Forest Research*. 14(6):581-588.

Jiroušek, R., R. Klvač, and A. Skoupý. 2007. Productivity and costs of the mechanized cut-to-length wood harvesting system in clear-felling operations. *Journal of forest science*. 53(10):476-482.

Jourgholami, M., S. Soltanpour, M. Etehadi Abari, and E.K. Zenner, E.K., 2014. Influence of slope on physical soil disturbance due to farm tractor forwarding in a Hyrcanian forest of northern Iran. *iForest-Biogeosciences and Forestry*. 7(5):342.

Kellogg, L.D., P. Bettinger, S. Robe, and A. Steffert. 1992. Mechanized harvesting: a compendium of research. Forest Research Laboratory, College of Forestry, Oregon State University, Corvallis, OR. 401 p.

Klun, J., and M. Medved. 2007. Fatal accidents in forestry in some European countries. *Croatian Journal of Forest Engineering*. 28(1):55-62.

Kozlowski, T.T. 1999. Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research.* 14(6):596-619.

Lenhard, R.J. 1986. Changes in Void Distribution and Volume During Compaction of a Forest Soil 1. *Soil Science Society of America Journal*. 50(2):462-464.

Löf, M., D.C. Dey, R.M. Navarro, and D.F. Jacobs. 2012. Mechanical site preparation for forest restoration. *New Forests*. 43(5-6):825-848.

Magagnotti, N., R. Spinelli, O. Güldner, and J. Erler. 2012. Site impact after motor-manual and mechanised thinning in Mediterranean pine plantations. *Biosystems Engineering*. 113(2):140-147.

McDonald, T.P., and F. Seixas. 1997. Effect of slash on forwarder soil compaction. *International Journal of Forest Engineering*. 8(2):15-26.

McNabb, D.H., A.D. Startsev, and H. Nguyen. 2001. Soil wetness and traffic level effects on bulk density and air-filled porosity of compacted boreal forest soils. *Soil Science Society of America Journal*. 65(4):1238-1247.

Najafi, A., and A. Solgi. 2010. Assessing site disturbance using two ground survey methods in a mountain forest. *Croatian Journal of Forest Engineering*. 31(1):47-55.

Nurminen, T., H. Korpunen, and J. Uusitalo. 2006. Time consumption analysis of the mechanized cut-to-length harvesting system. *Silva Fennica*. 40(2):335-363.

Perala, D.A., and A.A. Alm. 1990. Reproductive ecology of birch: a review. *Forest Ecology and Management*. 32(1):1-38.

Ponsse, *Cut-to-Length Method*, Ponsse, accessed September 21 2018, <https://www.ponsse.com/ponsse/business-sector/cut-to-length-method>

Powers, R.F., D.A. Scott, F.G. Sanchez, R.A. Voldseth, D.S. Page-Dumroese, J.D. Elioff, and D.M. Stone. 2005. The North American long-term soil productivity experiment: findings from the first decade of research. *Forest Ecology and Management*. 220(1-3):31-50.

Prévost, M. 1997. Effects of scarification on seedbed coverage and natural regeneration after a group seed-tree cutting in a black spruce (Picea mariana) stand. *Forest Ecology and Management*. 94(1-3):219-231.

Qi, J., J.D. Marshall, and K.G. Mattson. 1994. High soil carbon dioxide concentrations inhibit root respiration of Douglas fir. *New Phytologist*. 128(3):435-442.

Raper, R.L. 2005. Agricultural traffic impacts on soil. *Journal of Terramechanics*. 42(3-4):259-280.

Raymond, K. 2012. Innovation to increase profitability of steep terrain harvesting in New Zealand. *New Zealand Journal of Forestry*. 57(2):19-23.

Rowe, P.W. 1962. The stress-dilatancy relation for static equilibrium of an assembly of particles in contact. *Proc. R. Soc. Lond. A*. 269(1339):500-527.

Sakai, H., T. Nordfjell, K. Suadicani, B. Talbot, and E. Bøllehuus. 2008. Soil compaction on forest soils from different kinds of tires and tracks and possibility of accurate estimate. *Croatian Journal of Forest Engineering*. 29(1):15-27.

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.

Seixas, F. and T. McDonald. 1997. Soil compaction effects of forwarding and its relationship with 6-and 8-wheel drive machines. *Forest Products Journal.* 47(11/12):46-52.

Sheridan, G.J. 2003. A comparison of rubber-tyred and steel-tracked skidders on forest soil physical properties. *Soil Research*. 41(6):1063-1075.

Solgi, A., R. Naghdi, and M. Nikooy. 2015. Effects of Skidderon Soil Compaction, Forest Floor Removal and Rut Formation. *Madera y Bosques*. 21(2):147-155.

Startsev, A.D. and D.H. McNabb. 2000. Effects of skidding on forest soil infiltration in west-central Alberta. *Canadian Journal of Soil Science*. 80(4):617-624.

Terzaghi, K., R.B. Peck, and G. Mesri. 1996. *Soil mechanics in engineering practice*. John Wiley & Sons, New York, New York, United States of America. 549 p.

Tiernan, D., G. Zeleke, P.M.O Owende, C.L. Kanali, J. Lyons, and S.M. Ward. 2004. Effect of working conditions on forwarder productivity in cut-to-length timber harvesting on sensitive forest sites in Ireland. *Biosystems Engineering*. 87(2):167-177.

United States Department of Labor Statistics. 2018. *Census of Fatal Occupational Injuries Charts, 2017.* Online.

United States Department of Labor Statistics. 2017. *May 2016 State Occupational Employment and Wage Estimates Oregon.* Online.

Van den Akker, J.J.H., J. Arvidsson, and R. Horn. 2003. Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. *Soil and Tillage Research*. 73(1/2):1-8.

Visser, R. and K. Stampfer. 2015. Expanding ground-based harvesting onto steep terrain: A review. *Croatian Journal of Forest Engineering*. 36(2):321-331.

Wallbrink, P.J., B.P. Roddy, and J.M. Olley. 2002. A tracer budget quantifying soil redistribution on hillslopes after forest harvesting. *Catena*. 47(3):179-201.

Whalley, W.R., E. Dumitru, and A.R. Dexter. 1995. Biological effects of soil compaction. *Soil and Tillage Research*. 35(1-2):53-68.

Zamora-Cristales, R., P.W. Adams, and J. Sessions. 2014. Ground-Based Thinning on Steep Slopes in Western Oregon: Soil Exposure and Strength Effects. *Forest Science*. 60(5):1014-1020.