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

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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. This study aims 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 to 92.36 m^3 per scheduled machine hour, with resulting unit costs for untethered and tethered systems ranging from \$13.19 to \$18.13/m^3. 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.

Keywords: steep terrain, soil impacts, tethered assist system, machine rates, harvesting

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). Regulation and management have both taken an increasingly stronger role in active forestry as the importance of soil disturbance has grown over time. 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 weights 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.

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), which in turn can reduce stand productivity (Labelle and Jaeger 2011).

However, there are several cases where logging-induced topsoil mixing and displacement seems to have been beneficial 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.

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(2002) found a notable extended period of plant-available water in a compacted clay loam soil.

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).

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 suggested 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), extent of sensitive area (Soman et al. 2019) and slope (Agherkakli et al. 2010), all of which are thought to enhance soil compaction from machine traffic. 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 occurs more likely at several initial passes, with compaction approaching the maximum extent 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.

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 would 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 at the stump and a forwarder that accumulates log piles and brings them to the 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 2019). 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 was to compare compaction effects, productivity and cost of untethered and tethered wheeled harvesters and forwarders 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.

Methodology

Study Area

The harvest was completed on Oregon State University's McDonald Research Forest in a 57.4 hectare harvest unit named "Quick Draw" (Figure 1). Coordinates for Quick Draw were 44°38'14.83" N, 123°19'51.66" W. The majority of the harvest unit contained *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 was comprised mainly of Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), and bigleaf maple (*Acer macrophyllum*). Pre-harvest volume rates were 442, 60, and 14 m^3/ha for Douglas-fir, grand fir, and bigleaf maple, respectively. Harvest prescriptions were 120 and 20 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. Inventory information following an external inventory cruise was also provided by the landowner. The stand was estimated to be 60 years old and has not previously been commercial-thinned.

Harvest System and Machine Operators

A CTL harvesting system was implemented to thin the study stand with a 260 kW Ponsse[1] Bear harvester and 210 kW Elephant King forwarder. The Bear weighed 23,800 kg and the

Management and Policy Implications

Machines using cable-assistance can densify initially loose soil or loosen initially dense soil depending on soil type, texture, moisture content, and machine configuration. As these changes progress throughout a harvesting operation, and with cable-assistance limiting wander, there is likely to exist a tradeoff between machine coverage and concentration of impact. Cable-assistance might decrease machine coverage but increase the magnitude of disturbance, though this is heavily dictated by operational traffic and initial soil conditions and type. Due to reduced shear displacement, cable-assistance can increase the number of passes required before the onset of densification, prolonging a machine's ability to operate on sensitive terrain. Although the stabilizing forces provided by the cable enables ground-based machines to operate on steep slopes, effectively extending the range of operable conditions, more attention must be paid to ground conditions such as soil type and texture, moisture content, and initial bulk density, as these are still the mediums by which machine trafficability, safety and environmental impacts are governed. As machine operability becomes less of a limiting factor on steep terrain, operator training, machine maintenance and design, and regulations should likewise be examined to ensure safe and appropriate use of this new technology.

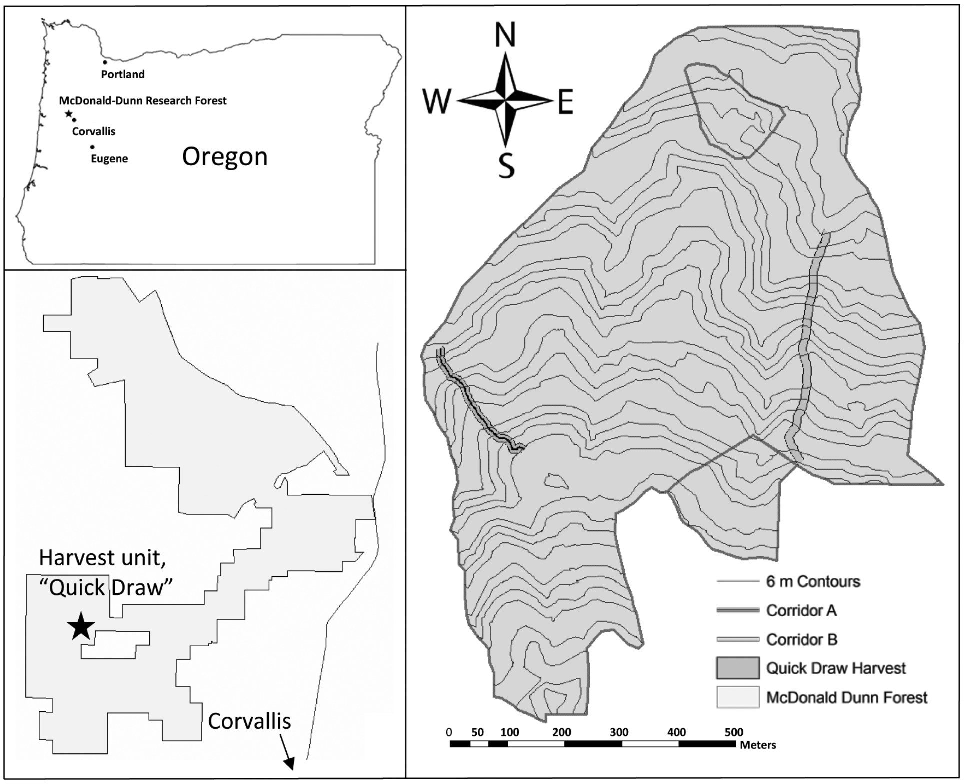

Figure 1. A study thinning unit ("Quick Draw") located in Oregon State University's McDonald-Dunn Research Forest in western Oregon.

Elephant King 22,900 kg. The Elephant King had a load capacity of 20,000 kg (Ponsse 2019). Both were 8-wheeled machines and operated with flexible tracks weighing 2000 pounds each attached during the entire time of observation. In-field measurements showed tracks have paddles approximately 10.5 cm high with alternating grousers 3.5 cm high. Tires on the machine had an approximate width of 75 cm and diameter of 149 cm. This operation only required a crew size of two people—one harvester and one forwarder operator. 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. Operators worked for a private company and were well-experienced—the two harvester operators had 25 and 27 years of experience, respectively, and the forwarder operator had nine years of experience. Each harvester operator harvested their entire corridor; however, there was no mixing of operators on the same corridor.

Corridor Selection

Two ridgetop corridors were selected for study: Corridor A (244 m in length) for untethered operations and Corridor B (442 m in length) for tethered operations (Figure 1). Percent slope measured with a clinometer 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.

Data Collection

Productivity and Cost

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

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 as the forwarding of one load. Volume estimations were collected via the onboard harvester computer and sitting roadside decks after forwarding. While harvesting, diameter measurements were recorded for each time cycle. Of the roadside decks, 97 logs were sampled for diameter at both ends and length in order to estimate average piece size (i.e., log volume) per sort. Total piece count was also recorded during and after 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 un-merchandisable or hazardous trees from around the tree to be felled) and positioning of head around

the 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). Sorting by species and grade is completed here for the rest of the operation.
  - 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 machine passes across each sample location.
- 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 machine passes across each sample location.

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. We assumed the fuel consumption remained constant regardless of tethering. The utilization rate of 80% (taken from the COST model) was used for untethered machines, although it was reduced to 70% for tethered machines based on our observed delays associated with the setup and takedown of cable-assistance. The tethered operations also included an estimated $100,000 investment per machine for a winch system.

Soil Compaction

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

Table 1. Cost parameters used in machine rate calculations.

Cost Inputs	Untethered		Tethered	
	Harvester	Forwarder	Harvester	Forwarder
Base Machine Price ($)	720,000	630,000	720,000	630,000
Attachment Price ($)	0	0	100,000	100,000
Expected Economic Life (years)[1]	2.92	2.92	3.12	3.12
Salvage Value (%)	20	20	20	20
Utilization Rate (%)	80	80	70	70
Repair and Maintenance (%)[2]	100	100	100	100
Interest, Insurance and Taxes (%)	15	15	15	15
Fuel Consumption (l/PMH)	26	21	26	21
Fuel Cost ($/liter)	0.87	0.87	0.87	0.87
Lube and Oil (%)	12.6	7.9	15.0	11.7
Labor ($/hr)	24.00	24.00	24.00	24.00
Variable Social Charges (%)[3]	45	45	45	45
Fixed Social Charge ($/year)[4]	15,600	15,600	15,600	15,600
Overhead Cost (%)	10	10	10	10
SMH per Year	2080	2080	2080	2080

[1] Expected Economic Life is a pre-emptive calculation from the COST model.
[2] Percent of annual depreciation.
[3] Variable Social Charges are pensions, levies, etc., expressed as a percentage of wage.
[4] Fixed Social Charges are personal protective equipment, training, operator transportation, etc., expressed as cost per year.

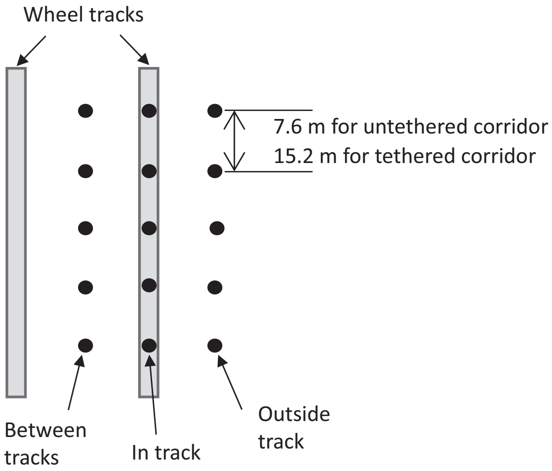

Figure 2. Untethered and tethered corridor sampling schematic.

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 approximately 7.6 m intervals for the untethered corridor, 29 sample locations at roughly 15.2 m intervals for the tethered corridor).

At each sample location, bulk density and penetration resistance samples were taken between the wheel tracks, in the machine wheel track, and outside of the machine tracks (termed "sub-locations" hereafter) (Figure 2) to capture: 1) the influence of machine passes on bulk density at the soil surface, and 2) how the spatial (vertical and horizontal) impact of these machines behaves (termed "zone of influence" hereafter). For bulk density sampling, a 164-cm^3 cylindrical soil core was used to collect samples which was 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.

Penetration resistance measurements were taken at each sample location and sub-location from 10 to 50 cm 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.

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 samples), clay (3 samples), sandy clay loam (2 samples), and loam (1 samples) textural classes. Corridor A only had one medium-textured sample (A23) while the rest were all fine-textured across both corridors.

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.

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 near the study area recorded 0.48 cm of rain three days prior to our first day of data collection, but no rain prior to that for 57 days. Average and standard error of moisture content ranged between 21–25% and 0.006–0.011%, respectively, for the untethered corridor, and 22–26% and 0.010–0.024% for the tethered corridor across all days of data collection.

Data Analysis

Productivity and Cost

All data analysis was completed using Microsoft Excel 2016 and R software (version 3.6.0). 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.

Production per productive machine hour (PMH) for harvesting was estimated using estimates of time cycles from DFCT equations, average piece size and average number of pieces per tree. Cycles per hour and cubic volume per PMH were then determined using these inputs. Forwarding productivity was similarly estimated using DFCT equations for time cycle and average volume per cycle.

For both the harvester and forwarder, production per PMH was converted into production per scheduled machine hour (SMH) by applying either the pre-determined utilization rates of individual machines for uncoupled operations (Table 1), or a utilization rate of each function in the system for coupled operations. Uncoupled operations assume that individual machines work independently without being influenced by the production rates of other machines. In coupled operations, however, all machines in the system are assumed to work collaboratively, and therefore the productivity of each function in the system depends on the productivity of the bottleneck function. This function utilization rate for coupled operations is calculated as the bottleneck function productivity per SMH divided by the individual machine productivity per PMH. This utilization rate is then applied to a machine production per PMH in order to convert into production per SMH.

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 also include impact from harvesting.

Results

Productivity and Cost

Our time study data showed that the average delay-free cycle times (DFCT) of the harvester were 0.98 and 1.30 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 operations. 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 volumes and lower pulp volumes than the untethered corridor. Sawlog volume was carried in every turn for both corridors, whereas pulp volume was carried in three turns on the untethered corridor and one turn on the tethered corridor. Although the actual payloads could not be determined, we estimate full or close to full payloads as most of the turns had full bunks of wood during transport.

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; however, this was after our data collection thus we only have an estimate for this delay. 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 (two from the harvester, 16 from the forwarder). All 27 observed delays across both corridors were less than six minutes in length. Operational delays were the most frequent at 74% of total delays (20 occurrences);personal delays were less frequent at 22% of delays (six occurrences), and administrative delays were least common at just 4% (one occurrence). Observed total delay times were 0.1% of total observed machine time for the untethered harvester and 1.4% for the untethered forwarder. For tethered operations, total delay times were 1.5% of total observed machine time for the harvester and 10.8% for the forwarder, which is why we conservatively used a utilization rate for tethered operations that was 10% lower than that for untethered operations. This difference also contributed to estimated production cost differences.

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). Table 4 shows analysis of variance (ANOVA) for the regression models

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).

	Untethered Harvester	Tethered Harvester	Untethered Forwarder	Tethered Forwarder
N	110	168	8	8
DFCT (min)	0.98 ± 0.1	1.30 ± 0.1	30.60 ± 2.9	40.01 ± 3.9
dbh (cm)	29.7 ± 1.0	29.4 ± 0.7	N/A	N/A
DBS (m)	7.15 ± 1.0	4.11 ± 0.5	N/A	N/A
Pieces/Tree	3.35 ± 0.1	3.38 ± 0.1	N/A	N/A
Dist. (m)	N/A	N/A	172.5 ± 19.4	302.5 ± 37.1
SVT (m^3)	N/A	N/A	14.7 ± 4.0	18.7 ± 3.1
PVT (m^3)	N/A	N/A	4.8 ± 2.6	2.0 ± 2.0

Table 3. Summary results and significance of multiple linear regression models developed to estimate mean delay free cycle times (dbh = diameter at breast height, DBS = Distance Between Stops, SVT = Sawlog Volume Total, PVT = Pulp Volume Total).

		Coefficients	N	MSE	R Square	F	Significance F
Untethered Harvester	Intercept	-0.112	110	0.14	0.50	35.53	<0.001
	dbh (cm)	0.023					
	DBS (m)	0.022					
	# Pieces	0.076					
Tethered Harvester	Intercept	-0.200	168	0.97	0.23	16.30	<0.001
	dbh (cm)	0.039					
	DBS (m)	0.056					
	# Pieces	0.037					
Untethered Forwarder	Intercept	-7.500	8	9.14	0.92	15.85	0.011
	Dist. (m)	0.092					
	SVT (m^3)	0.946					
	PVT (m^3)	1.742					
Tethered Forwarder	Intercept	-17.356	8	58.44	0.73	3.54	0.127
	Dist. (m)	0.108					
	SVT (m^3)	1.136					
	PVT (m^3)	1.786					

obtained. The untethered and tethered harvester analysis both showed dbh and DBS to be significant. For the forwarder cycle time regression models, forwarding distance was significant for both tethered and untethered operations, while pulp volume was only significant for untethered forwarding. Though the R-square for untethered forwarding was rather high, the operator was very experienced and able to maintain a consistent work pace on the gentler terrain of the untethered corridor. F significance showed the tethered forwarder model a poor explanation of the observed data, with a *P*-value of 0.127, whereas the other three models all showed significance (*P*-values < 0.05) (Table 3). Though eight forwarder cycles per corridor may not be sufficient to develop regression models, we include the analysis and discussion of forwarding as it provides a holistic view of these operations for the purpose of comparison between tethered and untethered operations.

When using the derived regression models with the same value 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 ± 0.07 minutes at a 95% confidence level compared to 1.37 ± 0.15 minutes tethered, likely owing to the higher weight give to DBS in the tethered model.

When comparing forwarding productivity regression using the same independent variables to both corridors (turn distance of 200 m, which was chosen arbitrarily 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 ± 23.2 minutes compared to 32.6 ± 3.46 minutes for the untethered forwarder; however, the difference was within the margin of error.

Untethered and tethered harvesting showed estimated productivity values of 115 and 79 m^3/PMH, respectively, whereas forwarding productivity was estimated at 36 and 43 m^3/PMH for untethered and tethered, respectively. Critical productivity assumptions for this work lie in volume estimation techniques (both the manual collection of measuring logs and electronically through the machine calibration for the harvester head), and that productivity was derived through regression techniques and equations.

As different operating conditions can heavily influence machine productivity, and in light of our productivity assumptions, we present two analyses in order to observe a possible 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, whereas 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 (machines work independently from each other), harvester productivity was estimated at 92 and 55 m^3/SMH untethered and tethered, respectively. Forwarder productivity was estimated at 29 and 30 m^3/SMH untethered and tethered, respectively. Total unit cost was \$13.19/m^3 and \$15.34/m^3 untethered and tethered, respectively (Table 5).

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 29 m^3/SMH, compared to 30 m^3/SMH for the tethered system (Table 6). Total unit cost was \$17.40/m^3 for the untethered corridor and \$18.13/m^3 for the

Table 4. Analysis of Variance (ANOVA) for the delay free cycle time regression models (* significant at p < 0.05, ** significant at p < 0.01, * significant at p < 0.001, dbh = diameter at breast height, DBS = Distance Between Stops, SVT = Sawlog Volume Total, PVT = Pulp Volume Total).**

		df	Sum of squares	Mean squares	F	*P*-value
Untethered Harvester	dbh (cm) ***	1	8.59	8.59	62.34	<0.001
	DBS (m) ***	1	5.73	5.73	41.58	<0.001
	# Pieces	1	0.37	0.37	2.68	0.105
	Residuals	106	14.60	0.14		
Tethered Harvester	dbh (cm) ***	1	24.08	24.08	24.81	<0.001
	DBS (m) ***	1	23.17	23.17	23.17	<0.001
	# Pieces	1	0.20	0.20	0.20	0.654
	Residuals	164	159.12	0.97		
Untethered Forwarder	Dist. (m)*	1	171.57	171.57	18.77	0.012
	SVT (m^3)	1	2.71	2.71	0.30	0.615
	PVT (m^3)**	1	260.28	260.28	28.47	0.006
	Residuals	4	36.56	9.14		
Tethered Forwarder	Dist. (m)*	1	462.0	462.0	7.91	0.048
	SVT (m^3)	1	31.70	31.70	0.54	0.503
	PVT (m^3)	1	126.4	126.4	2.16	0.215
	Residuals	4	233.8	58.44		

Table 5. Uncoupled system costs and productivity summary.

		Untethered		Tethered	
		Harvester	Forwarder	Harvester	Forwarder
Productivity (m^3/SMH)		92.36	28.75	55.31	29.78
Fixed Costs	\$/SMH	133.55	116.93	137.52	122.49
Variable Costs	\$/SMH	140.70	121.29	137.87	121.00
Operator Costs	\$/SMH	42.30	42.30	42.30	42.30
Total	\$/SMH	316.55	280.52	317.69	285.79
	\$/m^3	3.43	9.76	5.74	9.60
System Total	\$/SMH	597.07		603.48	
	\$/m^3	13.19		15.34	

tethered corridor, with harvesting accounting for 44% and 47% of total unit cost for untethered and tethered, respectively.

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. Independent variables such as

Table 6. Coupled system costs and productivity summary.

		Untethered		Tethered	
		Harvester	Forwarder	Harvester	Forwarder
Productivity (m^3/SMH)		28.75	28.75	29.78	29.78
Fixed Costs	\$/SMH	133.55	116.93	137.52	122.49
Variable Costs	\$/SMH	43.80	121.29	74.23	121.00
Operator Costs	\$/SMH	42.30	42.30	42.30	42.30
Total	\$/SMH	219.65	280.52	254.05	285.79
	\$/m^3	7.64	9.76	8.53	9.60
System Total	\$/SMH	500.17		539.84	
	\$/m^3	17.40		18.13	

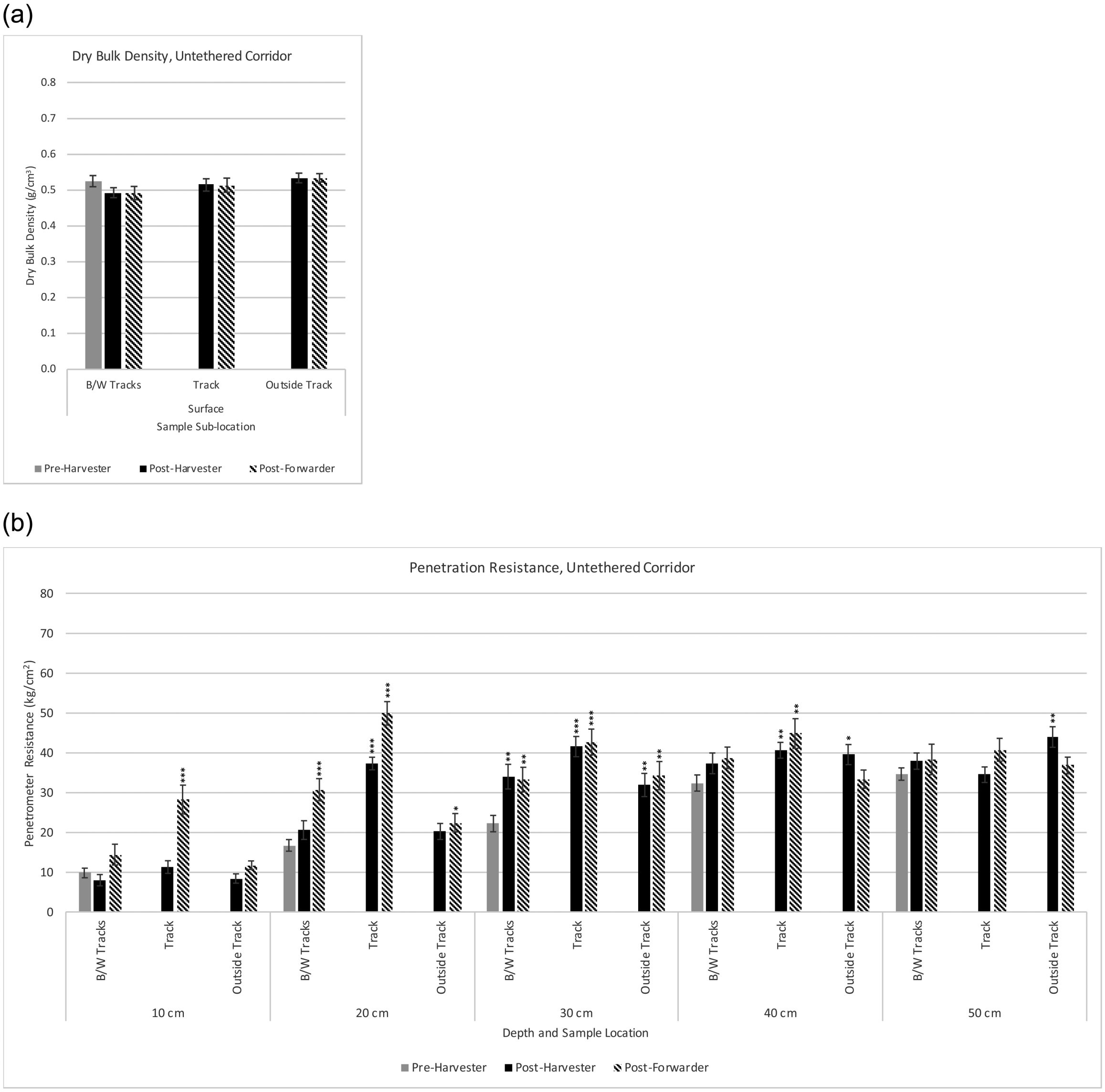

Figure 3. Average dry bulk density for untethered corridor (a) and tethered corridor (c) and penetration resistance for untethered corridor (b) and tethered corridor (d) with error bars and significance (* significant at $p < 0.05$, ** significant at $p < 0.01$, * significant at $p < 0.001$) (B/W = Between).**

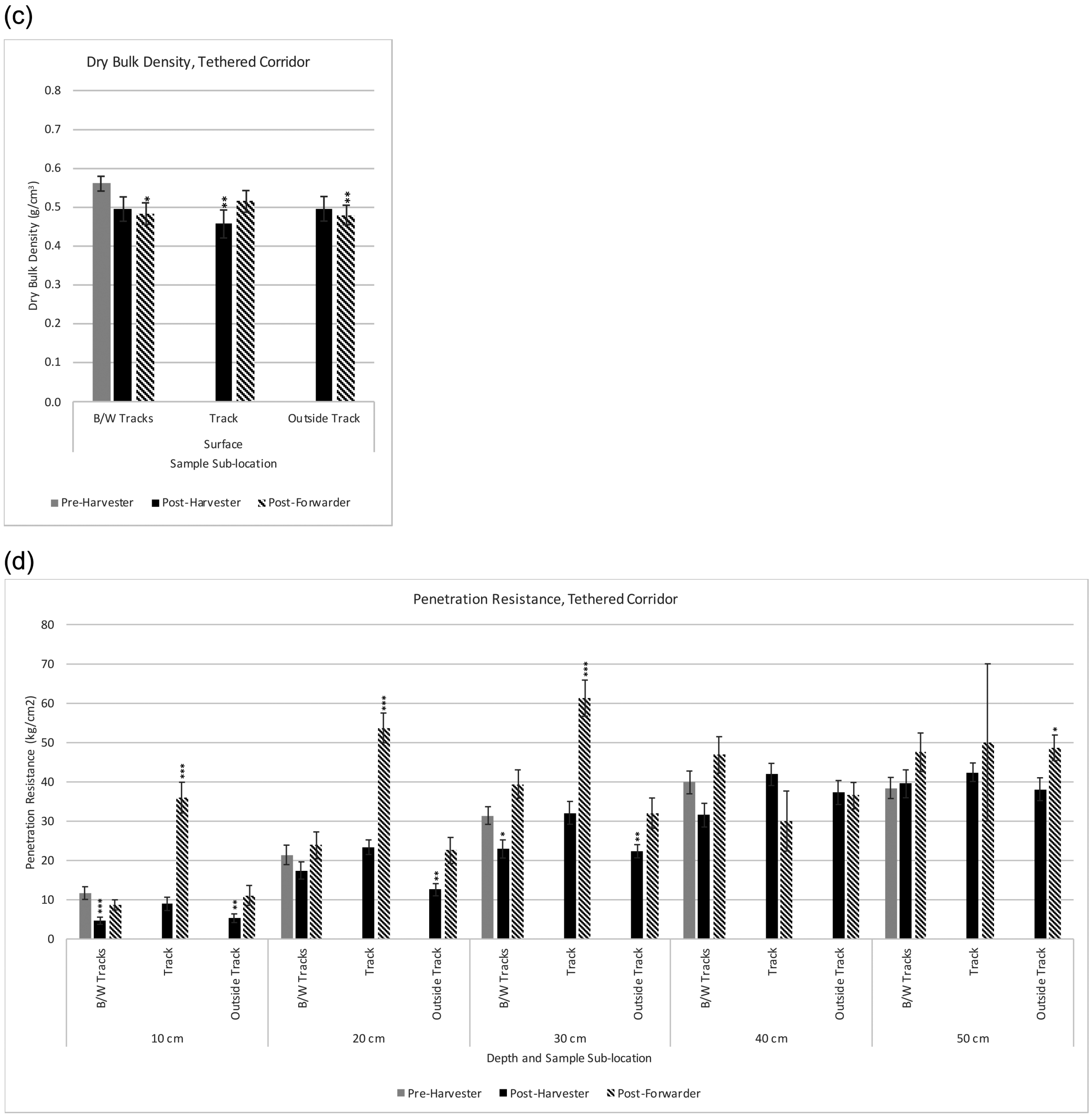

Figure 3. Continued

machine passes, slope, slash and original condition are discussed in subsequent text.

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 c). 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 = 0.003]), whereas track measurements showed increases from 20–40 cm (from 16.7 to 37.3 kg/cm^2 [P-value < 0.001], 22.2 to 41.5 kg/cm^2 [P-value < 0.001], and 32.4 to 40.6 kg/cm^2 [P-value > 0.05] penetration resistance, respectively) and outside tracks revealed significant increases from 30–50 cm (from 22.2 to 31.9 kg/cm^2 [P-value = 0.009], 32.4 to 39.5 kg/cm^2 [P-value = 0.032], and 34.6 to 43.9 kg/cm^2 [P-value = 0.004] penetration resistance, respectively) (Figures 3b and 4a). Although 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 within the 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 kg/cm^2 [P-value < 0.001], and 22.2 to 33.2 kg/cm^2 [P-value = 0.0047] penetration resistance, respectively), whereas track measurements showed increases at 10, 20, 30 and 40 cm (from 9.8 to 28.2 kg/cm^2 [P-value < 0.001], 16.7 to 49.8 kg/cm^2 [P-value < 0.001], 22.2 to 42.7 kg/cm^2 [P-value < 0.001], and 32.4 to 44.8 kg/cm^2 [P-value = 0.007] penetration resistance, respectively). Outside track measurements had significant increases at 20 and 30 cm (from 16.7 to 22.4 kg/cm^2 [P-value = 0.044] and 22.2 to 34.2 kg/cm^2 [P-value > 0.005] penetration resistance, respectively) (Figures 3b, 4c). Increases, although not significant, were observed at all other sample sub-locations post-forwarder.

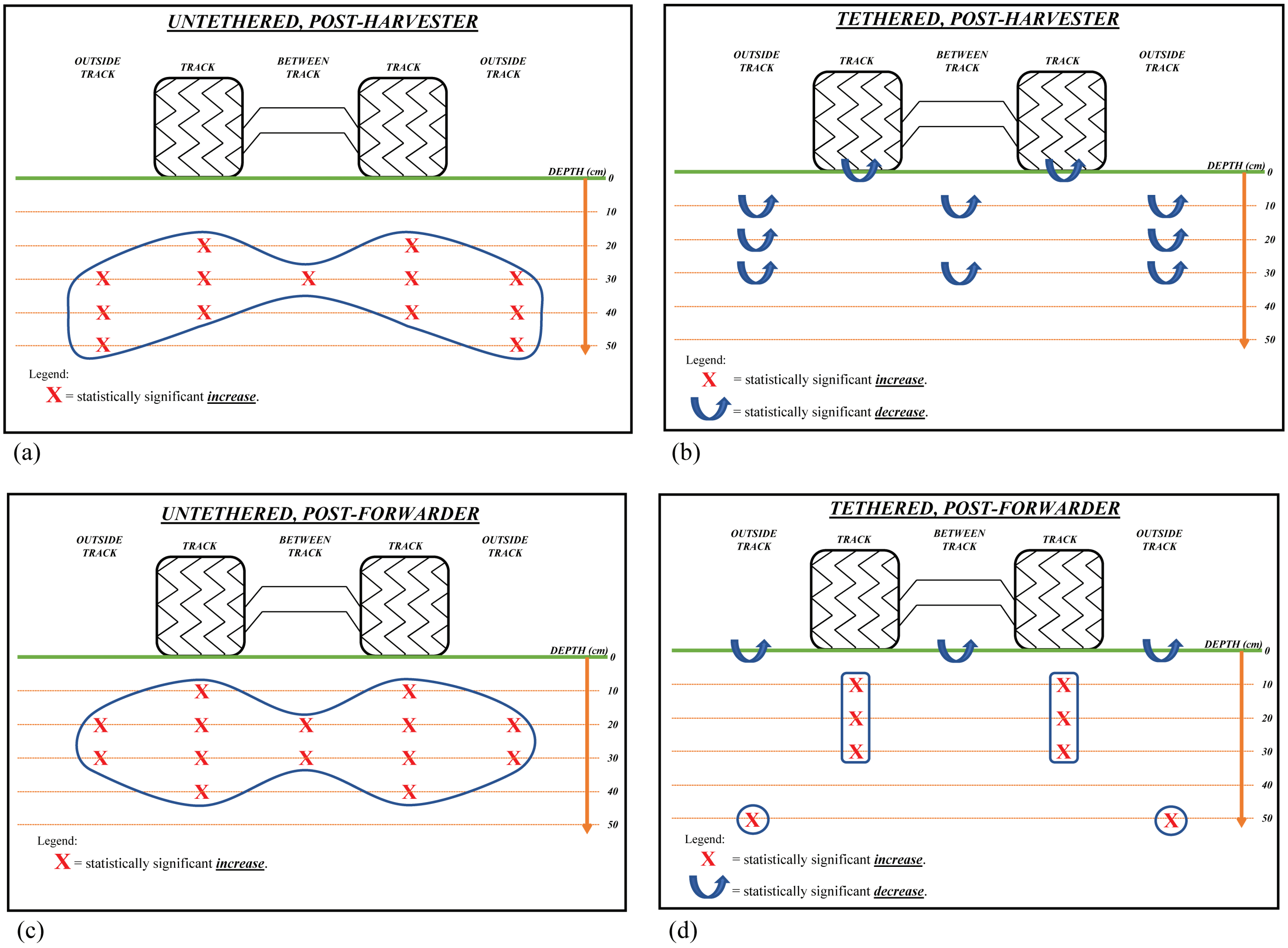

Figure 4. Bubble Disturbance Images showing statistically significant increases/decreases in soil density because of untethered harvesting (a) and forwarding (c), and tethered harvesting (b) and forwarding (d).

No 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 post-forwarder tracks and between tracks) were observed (Figure 3a). No reductions in penetration resistance were seen at any sub-locations as a result of untethered forwarding (Figures 3b, 4c).

The tethered post-harvester showed significant *decreases* in penetration resistance from 10, 20 and 30 cm outside tracks (from 11.7 to 5.3 kg/cm^2 [P-value = 0.002], 21.4 to 12.5 kg/cm^2 [P-value = 0.004], and 31.4 to 22.3 kg/cm^2 [P-value = 0.002], respectively) and from 10 and 30 cm between tracks (from 11.7 to 4.6 kg/cm^2 [P-value < 0.001], and 31.4 to 22.9 kg/cm^2 [P-value = 0.011], respectively) (Figures 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] (Figures 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).

The tethered post-forwarder showed an increase in penetration resistance in track measurements from 10, 20 and 30 cm (from 11.7 to 36.0 kg/cm^2 [P-value < 0.001], from 21.4 to 53.7 kg/cm^2 [P-value < 0.001], and 31.4 to 61.3 kg/cm^2 [P-value < 0.001], respectively) and outside track measurements at 50 cm (from 38.4 to 48.6 kg/cm^2 [P-value = 0.021]) (Figures 3d, 4d). Insignificant increases were observed at 10 cm outside tracks; at 20 and 30 cm both between and outside tracks; at 40 and 50 cm between tracks, and at 50 cm within the track (Figure 3d). Insignificant decreases were observed at 10 cm between tracks and at 40 cm both within 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 g/cm^3 [P-value = 0.012] and 0.48 g/cm^3 [P-value = 0.0054], respectively) (Figures 3c, 4d) after tethered forwarding. Track dry bulk density also decreased from 0.56 to 0.51 g/cm^3 (P-value = 0.134) (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 2007).

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 < 0.05). Both slope and number of machine passes were not significant at any locations (*P*-values > 0.05) (Table 7).

Post-forwarder vertical depths of slash were measured at each sample location for both corridors and not found to be statistically significantly different between the two corridors (*P*-value = 0.078, 1.33 cm untethered corridor, 3.55 cm tethered corridor), so slash was excluded from any analysis in this research.

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 the 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 1980s and 1990s with less advanced technology, and thus it is difficult to make direct comparisons with the previous studies.

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.

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, these include 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 in Figure 4a–d. 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 (Brais and Camire 1998, Han et al. 2009), 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 resistance and peak pressures. Sessions et al. (2017) highlighted that the tether more evenly distributes the 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 8), which may be partly attributed to higher pre-harvest penetration resistance on the tethered corridor.

Table 7. 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 sample size (N), *P*-value of each independent variable, Model R Square, MSE, Model F, and F Significance (BT = Between Track, T = Track, OT = Outside Track).

	Post-Forwarder Untethered			Post-Forwarder Tethered		
	BT	T	OT	BT	T	OT
N	28	29	29	28	28	28
Original Condition	0.001	<0.001	<0.001	0.019	0.028	<0.001
Slope	0.050	0.086	0.097	0.401	0.865	0.267
Passes	0.437	0.132	0.932	0.579	0.567	0.059
R Square	0.44	0.64	0.44	0.31	0.34	0.43
MSE	0.1568	0.2065	0.0930	0.1256	0.2315	0.1097
Model F	6.1836	14.6145	6.5921	4.4247	8.6473	7.5614
F Significance	0.003	<0.001	0.002	0.01	<0.001	0.001

Previous research has highlighted the influence of initial soil density when testing for compaction in forest harvesting (Hillel 1998, Powers et al. 2005, Jamshidi et al. 2008). 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 = 0.003). 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 (Figures 5 and 6), particularly with the 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 whereas denser materials tend to dilate, similar to what was observed here, particularly after tethered harvesting between and outside wheel tracks (Table 8, Figures 3d and 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.

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. Although 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 c, 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 (Figures 3d, 4b). Jansson and Johansson (1998) observed a similar decrease in bulk density

Table 8. 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	0.51	1	Untethered Track	1.06
2	Untethered Outside Track	0.30	2	Tethered Track	0.89
3	Untethered Between Tracks	0.22	3	Untethered Between Tracks	0.41
4	Tethered Track	0.07	4	Untethered Outside Track	0.27
5	Tethered Between Tracks	-0.15	5	Tethered Between Tracks	0.18
6	Tethered Outside Track	-0.17	6	Tethered Outside Track	0.11

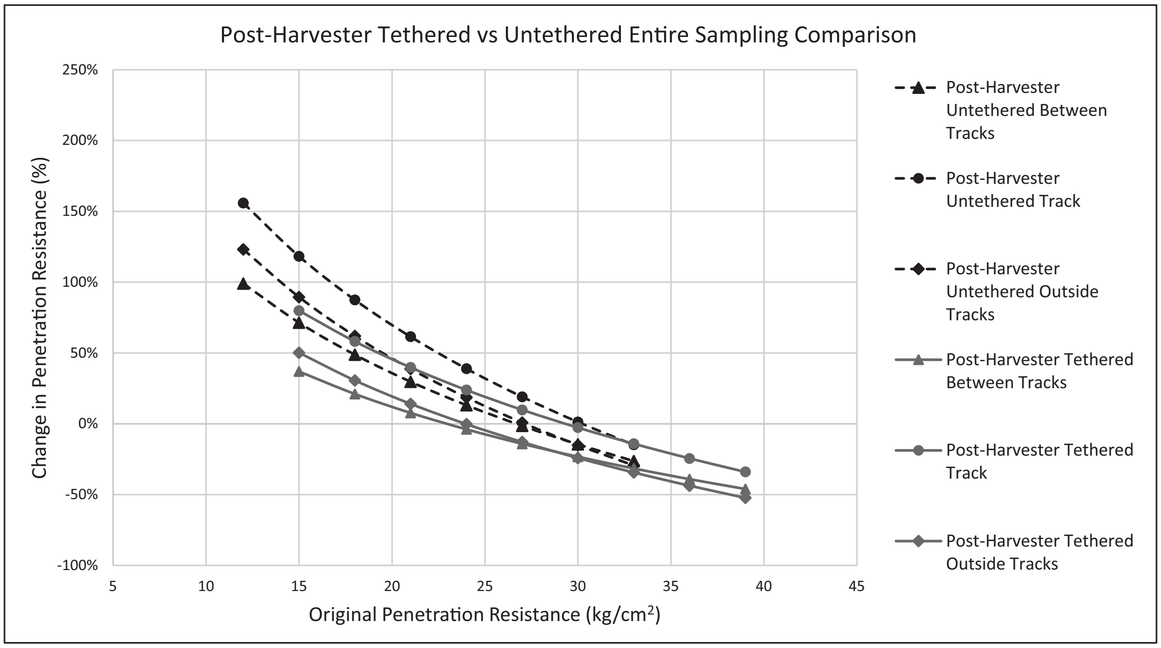

Figure 5. Post-harvester percent increase in penetration resistance based on original penetration resistance.

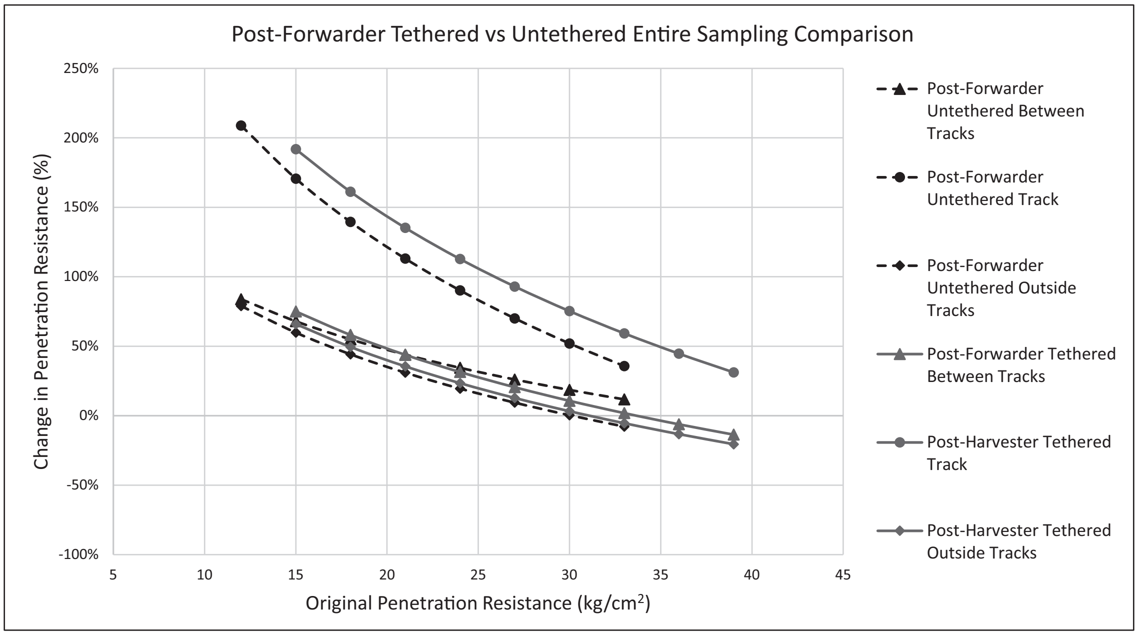

Figure 6. Post-forwarder percent increase in penetration resistance based on original penetration resistance.

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). Although 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 and track wander would 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 was unconfined and subsequently displaced with equipment travel (Figure 4d), a product of the initially higher soil density.

Although previous research highlighted the importance of machine passes and ground slope when considering compaction (Wallbrink et al. 2002, Agherkakli et al. 2010), our regression results showed passes were not significant in either corridor (*P*-values > 0.05) (Table 7). 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.

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 7). 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 45 cm 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, possibly 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 is 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, it 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.

Endnote

1. Mention of trade names is for information only and does not constitute an endorsement any state, federal or funding agency.

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