AN ABSTRACT OF THE THESIS OF

Shane Uffelman for the degree of Master of Science in Sustainable Forest Management presented on August 12, 2019.

Title: The Impact of Understory Vegetation on the Productivity and Costs of Cut-to-length Thinning Harvest Systems in the Pacific Northwest.

Abstract approved:

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Woodam Chung

The forests in the Pacific Northwest are highly productive for timber and are a major factor in the economies of the region. The Pacific Northwest is the leading producer of lumber and plywood in the country. The use of harvester-forwarder cut-to-length harvest systems as a method for timber harvests in the region is increasing. Understanding which factors affect the productivity and costs of the system can help harvest managers plan harvests more effectively.

This research sought to determine if understory vegetation height affects productivity and stump-to-truck costs in harvester-forwarder cut-to-length thinning harvests. The study was a case study of two harvest units and two sets of harvester-forwarder (PONSSE Scorpion King harvester/Buffalo forwarder and PONSSE Bear harvester/Elephant King forwarder) systems. A detailed time study was completed for all equipment (harvesters, forwarders and loader) to determine which variables affected productivity. Understory vegetation was used as a variable for the harvester

time study and classified into “short” (shorter than 0.91 m), “medium” (between 0.91 m and 2.44 m) and “tall” (above 2.44 m).

Regression results have “tall” understory vegetation reducing productivity of the Scorpion King harvester by 21%, and for the Bear harvester “tall” understory vegetation decreases productivity by 31% compared to “short”. The increase in understory vegetation height resulted in increased stump to truck costs by 12 to 17 % . For more accurate assessment of the influence of understory vegetation on productivity and costs, more field studies need to be completed on a wide range of stand characteristics.

The Impact of Understory Vegetation on the Productivity and Costs of Cut-to-length Thinning Harvest Systems in the Pacific Northwest

by
Shane Uffelman

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APPROVED:

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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.

Shane Uffelman, Author

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CONTRIBUTION OF AUTHORS

Woodam Chung and Shane Uffelman conceived the project concept. Shane Uffelman created the study design, and completed data collection, data analysis and interpretation. Woodam Chung guided data analysis. Shane Uffelman wrote the thesis, with revisions given by Woodam Chung.

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Introduction

The Pacific Northwest (PNW) region of the United States includes Washington, Oregon and part of Idaho. It has a wet climate, and the economies "tended to rely on a few big industries, such as timber" (Encyclopedia Brittanica, 2019).

The forests in the PNW along the Coastal Range and West side of the Cascades are highly productive due to temperate weather conditions, which bring high average rainfall. In Oregon, the Coast Range averages around 190 cm to 228 cm of rain per year up to 508 cm per year. The western slopes of the Cascade Range average up to 190 cm of rainfall per year (National Oceanic and Atmospheric Administration, 2019).

The climate and mountain ranges make Oregon forests highly productive for a variety of merchantable conifers like Douglas fir (*Pseudotsuga menziessi*), grand fir (*Abies grandis*), and western hemlock (*Tsuga heterophylla*) as well as many other species. Various hardwood species such as bigleaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra*) are also common. The productivity of these forests make forestry integral to the economics of the state. In Oregon, timber harvests exceeded 26 million cubic meters (3.8 billion board feet). Of those harvests, 23.8 million cubic meters (3.5 billion board feet) came from the counties in western Oregon (Bureau of Business and Economic Research, 2019) in 2017. Oregon's forest industry provided 61,000 jobs in 2017 and was the leading producer of lumber and plywood in the country (Oregon Forest Resources Institute, 2019).

Harvesting systems and Practices

Approximately 80 percent of western Oregon is forested, and most of that forested land is in the Coastal Range and western Cascades (Campbell et al. 2002). The various terrain conditions and harvest prescriptions have led to an array of different harvesting systems. The conditions and prescriptions will affect whether an aerial, skyline, or ground-based system is used, and if trees are extracted whole tree or cut-to-length.

Aerial logging with helicopters in Oregon began around 1971 (Brown, 2004). As harvests shifted towards second growth forests with smaller trees, the high costs of operations made it uneconomical compared to other systems, especially in thinning operations (Born, 1995). Helicopter logging has remained in use for Christmas tree plantations. The high value of Christmas trees and low payloads allow helicopters to quickly move trees and remain cost effective.

Skyline systems are popular for clear-cuts on steep terrain and include yoaders and yarder towers. This system often uses whole tree extraction and processes the trees on the landing. Yoaders are not as powerful as towers but are more mobile and less expensive, making them useful in units with shorter yarding distances. Yarder towers have a wide range of sizes and power and have high productivity potential but are more expensive to operate than yoders. They are preferred on units with larger trees and longer yarding distances due to their larger drum capacity and potentially higher payloads than yoaders.

Ground-based harvest systems are utilized on flatter terrain (usually with slope less than 35%), although the use of tethered systems attached to equipment has allowed ground-based systems to go on steeper slopes. These systems often utilize mechanized felling machines such as a feller-buncher or a harvester. When using a feller-buncher, a shovel or skidder extracts the whole tree, and the trees are processed into logs at the landing. Shovels costs tend to be higher than skidder costs, but the one pass extraction method of the shovel has “lower impact on the forest floor” (Kizha and Han 2016).

In a harvester-forwarder cut-to-length (CTL) system, harvesters will fell and process trees in the stand. Forwarders extract the logs after harvesters because the forwarders can carry a large load of logs at a single time.

Harvester-forwarder CTL systems are increasing in use around the world due to their safety and productivity (Ferrari et al. 2012, Ponnse 2019). The ergonomics of CTL machines is considered to improve working conditions for loggers (Gerasimov and Sokolov, 2014).

The harvester-forwarder CTL system has not historically been popular in the Pacific Northwest for various reason. One reason is the machines have high initial investment costs. The initial investment for a pair of new machines (a harvester and a forwarder) can easily exceed 1 million dollars. Another reason has been the preference for longer logs at the mills. The mills pay for the logs by scaled volume. The most common log scaling method in the PNW is the Scribner board-foot scale. The Scribner scale only accounts for the wood inside the scaling cylinder (an imaginary cylinder that runs down the length of the log and diameter limited by the small end of the log), the wood outside the cylinder is “over-run”. Shorter logs reduce the amount of taper over-run (Staebler, 1953) which could decrease profits to the mills. Longer logs also give mills more options of what products to make.

Yet harvester and forwarders are increasing in use in the Pacific Northwest. There are around 100 to 120 harvester and forwarders operating in the Pacific Northwest (personal comm. Matt Mattioda, Miller Timber Services). One reason for the increased use of harvesters and forwarders in Oregon is the prevalence of commercial thinning prescriptions for environmental, ecological, and silvicultural reasons. Landowners with long rotation ages use thinnings to promote growth of remaining trees before a future final harvest. On publicly owned lands clear-cut harvests were reduced in the 1980’s due to concern over loss of habitat for wildlife species such as the spotted owl (Burnett and Davis 2002). Thinning operations have since increased to help develop old growth forest structure. Thinnings also help reduce risk of catastrophic fires, by reducing fuel loads and increasing stand health (Graham et al. 1999). Fuel loads had traditionally been reduced with controlled burns, but controlled burns are "becoming a thing of the past due to increased liability concerns" (Bolding and Lanford 2005).

Damage to residual trees during a thinning harvest make the trees subject to deterioration from fungi and insects (Akay et al. 2006). Harvesters and forwarders reduce the risk of residual stand damage during a thinning compared to other harvest methods (Bettinger and Kellogg 1993) and "offers a higher value recovery" (Spinelli and Magagnotti 2010) helping make it a preferable system.

One of the most common ways to evaluate the productivity of a harvest system, or machinery is the use of time studies. Time studies allow for the development of regressions by allowing for breaking down a machine's processes into cycle times and evaluating the variation in cycle times compared to the variables analyzed. These regressions can help determine which variables significantly affect cycle time of a machines operation.

Harvester-forwarder CTL system productivity has been studied extensively around the world from timber harvests to fuel residue extraction. In Kellogg and Bettinger (1994), they used a time study to evaluate the productivity and cost of harvester-forwarder thinning operations in the Cascade Range in Oregon. Green et al. (2019) studied the productivity, cost and soil impacts between a tethered and untethered harvester and forwarder CTL system in the Oregon Coast Range. Spinelli and Magagnotti (2010) compared whole tree and CTL system productivity for biomass removal in the Alps. Goltsev et al. (2010) studied removal of bio-fuels using harvester-forwarder, it was more cost effective than manual methods when dealing with larger sources of biofuel. A study done by Petitmermet (2018) conducted an extensive study to examine the productivity and costs of harvesters and forwarders for removal of bio-char in southern Oregon and to determine if tethering behaved as a fixed or variable cost for operations.

Study Justification and Objectives

Kellogg and Bettinger (1994) acknowledge other that variables may affect productivity of CTL systems and more studies need done in a range of conditions to help identify influencing factors. Forest stands in the Pacific Northwest usually contain abundant understory vegetation (shrubs and herbaceous plants that grow in a forested area) could be a potentially high influencing factor on productivity and costs of CTL harvests. In personal communication with harvester operators and a harvest manager with Miller Timber Services, they expressed that understory vegetation may affect the productivity of their operations, but the impact has not been quantified.

Due to the increase in use of harvester and forwarder CTL systems in the Pacific Northwest, it is important to understand which variables affect productivity and costs of harvester-forwarder CTL operations. Harvester regressions developed in previous CTL studies estimate productivity by tree attributes such as species, DBH, stem volume, and or logs per tree (Kellog and Bettinger 1994, Holtzscher and Lanford 1997, Nurminen et al. 2006, Adebayo et al. 2007 and Ericksson and Lindoos 2014). None of the exististing studies evaluate the impact of understory vegetation. Determining which variables have an impact on productivity can help managers reduce costs by managing for the variable or improved schedule planning.

The climate of the PNW allows understory vegetation to flourish in the forests of the Coastal Range and Western Cascades. Understory vegetation types range from various grasses and ferns to woody stemmed plants like evergreen huckleberry (*Vaccinium ovatum*) and vine maple (*Acer circinatum*). The understory vegetation can be a visual barrier during operations, interfering with an operator's ability to identify which trees to harvest, plan the order in which to harvest the trees or impede operator's ability to see grapple head when reaching for a tree or log. Understory vegetation can also be a physical barrier, forcing an operator to remove the vegetation or can cause delays if vegetation becomes tangled with the equipment.

If understory vegetation affects productivity of the system, the influence should be noticeable in the productivity of the harvester. The harvester is in the stand first, the standing understory vegetation has the greatest potential of being a physical or visual barrier to the equipment influencing its productivity. When the forwarder enters a stand, the harvester will have knocked down or driven over much of the understory vegetation, making its influence on the forwarder productivity unlikely.

The goal of this research is to determine the influence of understory vegetation on harvester productivity in a commercial thinning operation. This will allow estimating the potential change in stump to truck costs due to understory vegetation on in CTL commercial thinnings.

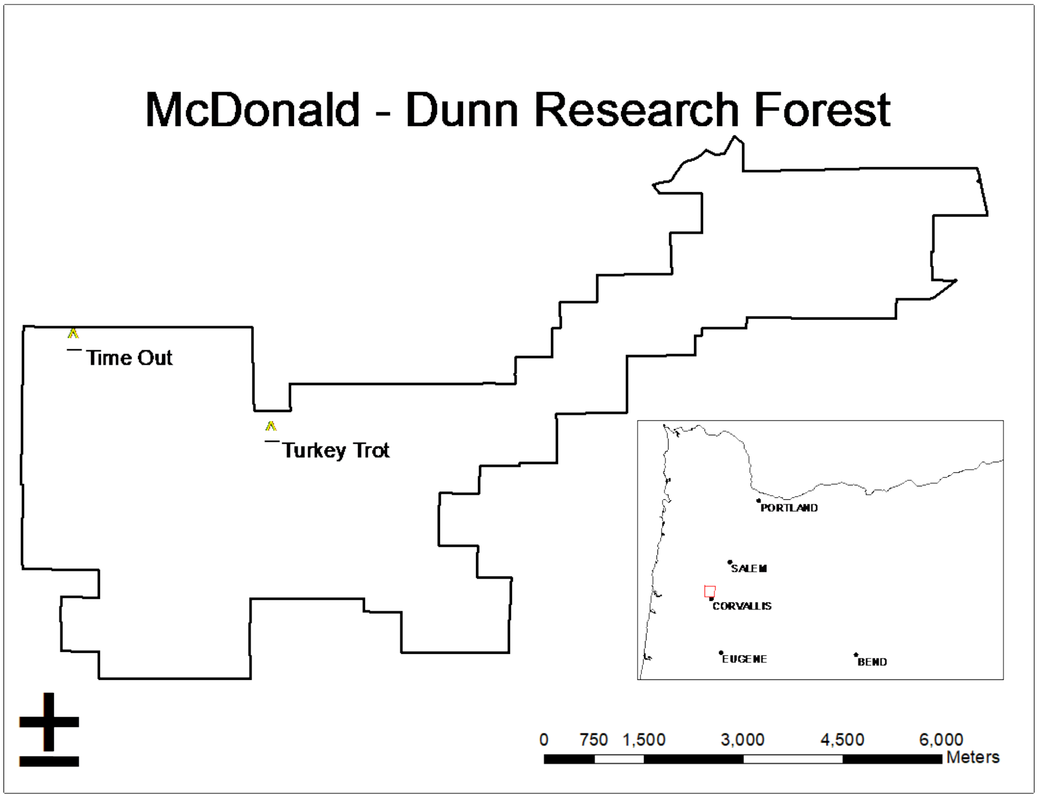
Materials and Methods

Study Area

The study area is located in the McDonald-Dunn Research forest owned by Oregon State University. The research forest falls on the east side of the Coastal Range and western edge of Willamette Valley, northwest of Corvallis, Oregon (Figure 1). The study was performed in two harvest units, Turkey Trot (44.6367° N, 123.3199° W) and Time Out (44.6488° N, 123.3425°

W). Elevation of Turkey Trot is between 195 m and 315m, and Time Out is between 360 m and 490 m.

Figure 1. Research harvest Units "Turkey Trot" and "Time Out" locations in the McDonald-Dunn Research Forest



Turkey Trot is 14.4 ha. Harvester operations were observed on four corridors (C1, C2, C3 and C4), covering about 1.3 ha. The forwarder operated on nine marked corridors covering approximately 2 ha. Two roads passed through the unit, one on the east side boundary and one on the northeast that passes through the middle of the unit. Three landings were used during the study, the first on the east road between corridors 2 and 3. The second landing on the east side of the northern road, and the third further west on the northern road.

Figure 2. "Turkey Trot" harvest unit with road, corridor, and landing locations

Time Out is about 24 ha. Harvester operations were observed on about 1.5 ha on six corridors (1-3 and 6-8). Corridors 4 and 5 were already harvested. The forwarder operations were observed on corridors 2 through 7. One road passed through the unit going east-west. One landing area was during the study, it on the both sides of the road at the bottom of corridor 4. There was a steep cut-bank on the north side of the road and west of corridor 6, which is why corridors 1-3 and 5 do not come to the road.

Figure 3. "Time Out" harvest unit with road, corridor and landing locations

The conifer species in the Turkey Trot unit are Douglas-fir (*Pseudotsuga menziesii*, DF) and Western hemlock (*Tsuga heterophylla*, WH). Grand fir (*Abies grandis*, GF) and DF are the dominant conifer species in the Time Out unit (Table 1).

Table 1. Pre-harvest stand attributes for Turkey Trot and Time Out harvest units.

	Turkey Trot			Time Out		
Species	DF	WH	Total	DF	GF	Total
DBH (cm)	30.0	33.0		28.4	25.4	
Trees/ha	546	395	941	581	741	1322
Volume (m^3/ha)	344.7	439.7	784.4	395.3	440.8	836.2
Basal area (m^2/ha)	38.7	33.9		36.7	37.8	
Relative Density (%)	48	29		47	55	

Unit information and volume calculations were obtained from Oregon State University Research Forest (Brent Klumph, personal communication). Volumes were reported in cubic feet based on 16-foot log lengths and converted to cubic meters with a conversion factor of 0.028 m^3/ft^3. Turkey Trot and Time Out were cruised 1.5 years and 2 months prior to harvests respectively.

The study was an observational case study on CTL commercial thinning harvests completed in June and July of 2018. The weather was generally sunny and dry, with some light rainfall one morning. A combined total of 10 days were spent gathering data on all of the equipment used.

Both units received the same thinning prescription. The prescription was a variable spacing thin from below, with removing ice-damaged, suppressed, diseased, dying and dead trees, and leave dominant and vigorous co-dominant trees. There was no pre-determined harvest volume or leave volume in either unit. Trees were marked before harvest for thinning by the Oregon State University Research Forest.

The most common understory vegetation in Turkey Trot by percent ground cover were vine maple (*Acer circinatum*), ocean spray (*holodiscus discolor*), beaked hazelnut (*Corylus cornuta*) and sword fern (*Polystichum munitum*). The most common understory vegetation in Time Out were sword fern, Oregon grape (*Mahonia aquifolium*), vine maple and grasses.

Harvesting Procedure and Equipment

Harvester operators determined corridor routes in the field. For Turkey Trot, the average slope for the corridors was 21% and average slope distance of 82 m. For Time Out, the average slope was 22% with an average slope distance of 92m.

In the Turkey Trot unit, a Ponsse Scorpion King with a H6 harvester head, harvested and processed the trees. A Ponsse Buffalo forwarder hauled logs from the unit to landings on the roadside. The Scorpion King had one operator (operator “A”) while the forwarder had two (operators “C” and “D”). In the Time Out unit, operator “B” used a Ponsse Bear harvester with a H8 harvester head. Operator “D” used a Ponsse Elephant King forwarder to remove logs from the unit. In both units operator “E” loaded logs onto the mule train log trucks using on a Komatsu 228 USLC loader equipped with a forwarder grapple. All operators were experienced with their equipment.

Table 2. Harvesters, forwarders and loader technical information

	Scorpion King	Bear	Buffalo	Elephant King	Komatsu
Weight (kg)	22,500	24,500	19,800	23,700	23,000
Width (m)	3.08	3	3	3.14	3.8
Length (m)	8.02	8.99	10	10.6	8.89
Clearance (cm)	65	70	68	80	44
Engine power (kw)	210	260	210	210	116
Crane turning angle (deg.)	280	260	360	360	360
Crane reach (m)	10 to 11	9.5 to 11	7.8 to 10	7.6 to 10	8
Harv head opening (cm)	60	74	na	na	na
Harv head feed speed (m/s)	6	5	na	na	na
max load (kg)	na	na	15,000	20,000	15,650

Data Collection

Understory Vegetation

Ground cover from understory vegetation was measured using quadrat method to determine if there is a relationship between ground cover (%) and vegetation height. The quadrat frame was 3.16 m by 3.16 m (10 m^2) as suggested by Baxter (2014) for shrub measurements. Ground cover estimated for each species in the quadrat in increments of 5%. The quadrat plot was classified "short", "medium" or "tall" based on height of the understory vegetation. The height class breaks determined by comparison with harvesters. The quadrat was assigned the tallest understory vegetation class in which there were multiple stems meeting the height criteria.

- Short – shorter than 0.91 m (below top of harvester tracks)
- Medium – between 0.91m and 2.44 m (between harvester tracks and main cab window)
- Tall - taller than 2.44 m (main cab window or taller)

Harvesters, forwarders and the loader operations were recorded with GoPro Hero 4 cameras (GoPro, Inc.). Each machine's operations are separated into cycles, and the cycles are broken down into components. Cycle time minus delays equals delay free cycle time (DFCT). The GoPro Hero 4 cameras also recorded the harvester's onboard computers for log and tree measurements. The corridor lengths and slopes were measured with a TruPulse 360°B laser range finder (Lastertech, Inc).

Harvester

Cycle time for the harvester is the time it takes for the harvester to move to, cut, and process one tree. A Cycle for the harvester starts when the harvester begins to move, or the boom moves toward a tree to begin cutting. A cycle ends when the harvester head finishes processing a tree and releases any slash that remains. If the harvester fells multiple trees consecutively before any are processed, cycle time is the average of the time it takes to fell and process all the trees. If a felled tree is not processed (ex. rotten snag, the tree is too small or non-merchantable), the cycle ends when the grapple releases the tree.

Harvester cycle components are:

- Positioning to cut – Begins when harvester tracks are not moving and boom reaches for a tree. It ends when the harvester head grasps a tree.
- Felling – Begins when the harvester head grasps a tree. It ends after the harvester head has cut down a tree and moved tree from the stump.
- Positioning tree – Begins after felling process when either the harvester boom or harvester moves, dragging the tree into position to be processed. It ends when the harvester has stopped moving and the processing head moves up or down bole of tree.
- Processing – Begins when positioning has ended. It ends when the grapple has cut the tree into logs and released the remainder of the tree or slash.
- Decking – Begins when the harvester grabs a processed log and moves the log into a pile or out of the way. It ends when any other process begins.
- Move – Begins when the machine’s wheels/tracks began moving while grapple is not holding a tree or log. It ends when the machine stops and grapple moves to grab a tree, a log, or understory vegetation.
- Brushing - Begins when the harvester head moves toward understory vegetation to either remove, push down or cut understory vegetation. It ends when the harvester begins any other cycle component.

- Other – Begins when the harvester removes any debris such as stumps, slash (after processor head has already released it at end of processing), knocks down a tree or snag but did not use saw, or any similar activity not covered by the other components.
- Delays – Time that the harvester is not in use for productive purposes due to personal, administrative, mechanical or operational delays.
  - Personal – personal breaks, lunch and other non-work related activities.
  - Administrative – discussions with supervisor or other operators regarding harvest operations.
  - Mechanical – equipment breaking or malfunctioning that required operator to look at or repair equipment.
  - Operational – waiting on other operator/equipment, harvester moving between corridors, stump removal that exceeds 1 minute, loader moving to new landing area.

Independent variables collected for the harvester:

- Diameter at breast height (DBH) – Continuous variable. The diameter of the tree at 1.3 meters from the ground.
- Number of Pieces – Continuous variable. Number of processed logs cut out of a tree.
- Merchantable Tree Volume – Continuous variable. Merchantable volume of harvested trees.
- Species – Categorical variable of trees harvested. The categories are Douglas fir (DF), white fir (WF) which is a combination of grand fir and western hemlock, and hardwoods (HW).
- Average Slope – Continuous variable. Average slope of a corridor.

- Understory Vegetation Class– Categorical variable. Classified the from video into one of three understory vegetation categories during each cycle (“short”, “medium”, or “tall”) by comparing understory vegetation height with the harvester. Understory vegetation classification determined by understory vegetation encountered during harvest cycle between machine and the tree harvested, or growing immediately next to the tree felled by the harvester. The cycle was assigned the tallest understory vegetation class in which multiple stems were encountered during the cycle.
    - Short – shorter than 0.91 m (below top of the track of harvester, Figure 4)
    - Medium – between 0.91 m and 2.44 m (between top of track and main window of the cab, Figure 5)
    - Tall - taller than 2.44 m (Figure 6)

Figure 4. Scorpion King in "short" understory vegetation observed during a harvest cycle

Figure 5. Scorpion King in "medium" understory vegetation observed during harvest cycle

Figure 6. Scorpion King in "tall" understory vegetation observed during harvest cycle

DBH for each tree was estimated using large end diameter (ld), small end diameter (sd) and log length (L) of bottom log, assuming a continuous taper from the base to the top of bottom log (Equation 1). In cases where a harvester fells a tree and does not process it, the DBH for the tree estimated by taking the measurements of sample logs of the same large end diameter and applying their average DBH to unprocessed trees.

(1) $DBH = ld - [((ld - sd)/L) * 1.3]$

The large and small end diameters, and log lengths taken from the harvester's onboard computer monitor. Diameters taken from the monitors are rounded to nearest inch, and then converted to centimeters. Log lengths are measured in feet and then converted to meters.

Tree volume (TV) is the summation of all log volumes (Equation 4). Log volumes (LV) are based on the Huber formula (Equation 3), which only needs a midpoint diameter (md) and log length (L) (Patterson et al. 1993). Assuming a constant taper, midpoint is the average of the small end and large end diameter of the log (Equation 2).

(2) $md = \frac{sd + ld}{2}$

(3) $LV = L * \pi * [\frac{md}{2}]^2$

(4) $TV = \sum_{i=1}^{n} LV_i$

where:

md	midpoint diameter of the log (cm)
sd	small end diameter of the log (cm)
ld	large end diameter of the log (cm)
LV	log volume (m^3)
L	log length (m)

TV tree volume (m^3)

n the number of logs

Measurements taken with the range finder at each break in slope and turn in corridor. The measurements were used to calculate average slope of a corridor and the corridor's length. The range finder measures slope in degrees, which is converted to percent slope using Equation 5.

$$(5) \quad Slope\% = \tan(Slope°) * 100$$

Forwarder

Forwarder cycle time begins when the forwarder starts driving empty from the roadside or landing. The cycle ends when the forwarder is completely unloaded and grapple is at rest on the bunk. Forwarder cycle components are:

- Driving Empty – Travel time of the forwarder when bunk is empty of any logs. It begins when the forwarder begins traveling to a point in the unit to load logs. It ends when the forwarder has stopped and boom moves to begin loading logs onto the bunk.
- Loading – Begins when the boom move to grab logs on the ground. It ends when decking begins or when grapple and boom are at rest and the forwarder begins driving.
- Load Decking – Begins when the grapple releases logs into the bunk, and the grapple head grabs, moves, pushes down logs in the bunk or If grapple removed understory vegetation or other debris from logs in the bunk. It ends when the grapple moves to grab more logs or boom and grapple are at rest and the forwarder begins to move.

- Driving Partially Loaded – Any time forwarder moves with logs in the bunk, but bunk was not "full". Begins when wheels/tracks start moving. It ends when the forwarder has stopped and boom moves to grab logs.
- Driving Loaded – Forwarder travel time in which the bunk was "full". The bunk is "full" when the last log is loaded onto the bunk and forwarder begins driving to the landing. It ends when the forwarder stops at the landing and boom begins to move to unload logs. If the forwarder moves again after unloading begins but while logs are still in bunk, it is still driving loaded.
- Unloading – Begins when the forwarder has stopped next to a landing and the boom moves to unload logs from bunk to the landing deck. Unloading ends when unload decking begins or when the bunk was completely empty and the grapple was in a secure resting position inside bunk.
- Unload Decking - When grapple adjusts logs on or next to decking pile. Ended when grapple returned to bunk to grab more logs or unloading ended.

Independent variables for forwarder:

The rangefinder was used to measure slope and slope distance in corridors and along roads by measuring from one break in slope or turn in corridor to the next. A numbered marker was placed on the nearest tree to the measurement.

- Average Slope – Continuous variable. The weighted average slope (Equation 6) of the forwarder's route during a cycle. All slopes were treated as positive.

$$(6)\quad \text{Weighted average slope (\%)} = \sum_{i=1}^{n} S_{\mathrm{i}} * D_{\mathrm{i}} \;/\; \sum_{i=1}^{n} D_{\mathrm{i}}$$

Where:

S the slope segment between markers in which the forwarder travelled (%)

D the slope distance segment between markers in which the forwarder travelled (m)

n the number of segments in which the forwarder travelled during the cycle

- Travel Distance Empty – Continuous variable. Slope distance traveled while bunk is empty. Determined by comparting position of forwarder with markers at start of travel and where the forwarder stopped to begin loading.
- Travel Distance Partial – Continuous variable. Distance the forwarder travels while partially loaded. A partial load is when the forwarder is carrying logs in the bunk and hadn't headed back to a landing to unload. Determined by comparing position of the forwarder with markers at start of travel after getting first log loaded and where the forwarder stopped to load the last log before heading to the landing to unload.
- Travel Distance Full – Continuous variable. Distance the forwarder travels while "full". A "full" load is any amount of logs in the forwarder when it heads to a landing to unload. Determined by comparing the nearest marker when the forwarder is "full" and the landing in which it unloads the logs.
- Total Distance – Continuous variable. Sum of the empty, partial and full distances on a cycle.
- Total Pieces – Continuous variable. Total number of logs loaded on forwarder during a cycle.
- Number of Load Swings – Continuous variable. The number of times grapple swung out to grab logs when loading the forwarder per cycle.

- Number of Unload Swings – Continuous variable. The number of times grapple swung from forwarder bunk to log deck when unloading the forwarder per cycle.
- Sorts – Categorical variable of whether one or multiple log sort types are loaded onto the forwarder.
- Volume – The estimated volume of the full load (m^3). Calculated by multiplying the number of pieces on the load with the average log volume of that sort. If multiple sorts are on a load, the number of each sort is counted and multiplied by its corresponding average log volume.

Loader

Loading cycle time starts when the truck is parked and the loader begins positioning boom and grapple to unload the second trailer from the mule-train log truck. The cycle ends when the last log is loaded onto the second trailer and the grapple was placed onto the ground. Each truck was loaded with only one log sort. Loading cycle components are:

- First Setup – The time to unload the second trailer of the mule train off the first, and for the first trailer to be prepared to load. It begins when the truck is parked and the boom/grapple begin to move to the truck to remove the trailer. It ends when the trailer is placed out of the way and loader began loading the first trailer.
- Loading – Loading occurs twice per truck, first the front trailer and second the back trailer. Loading begins when the grapple starts moving towards log deck to grab logs. Loading ends when the machine reaches for the second trailer to attach it, or when the last log was placed on the second trailer and the grapple is placed on the ground.

- Second setup – The cycle time to connect and set up the second trailer after the first trailer has been loaded. It began when the first trailer was loaded and the loader moved toward or reached for the second trailer. The cycle ended when the trailer was attached and loader reached for log deck to begin loading.
- Move – Begins when the loader tracks move and ends when tracks stop moving and boom begins moving.

Independent variables for the loader:

- Total Pieces – Continuous variable. Total number of logs loaded on the truck during the cycle.
- Number of Load Swings – Continuous variable. The total number of times the loader grabs logs from the decking area to load on the truck.
- Volume – The estimated volume of the full load (m^3). Calculated by multiplying the number of pieces on the load with the average log volume of that sort.

Analysis

Any cycle in which there was not a complete observation (missing one or more of the cycle components, or log measurements) on the camera were removed from the dataset.

RStudio ver. 3.5.0 (RStudio, Inc.) was used to analyze the data and develop the machine regressions for DFCT. Variables were compared for correlations. If two variables were determined to have high correlation values (> 0.85) one of the variables would be removed from model. Backwards stepwise method was used to select final model for the harvester and loader.

Due to small sample sizes for the forwarder, and to limit model overfitting, models were limited to three variables with several variable combinations compared to determine which model to use.

Production costs were determined using a machine cost model developed by Ackerman et al. (2014).The machine costs and rates (Table 3) were determined from a combination of personal communications with Ponsse dealership, personal communication with Matt Mattioda (logging manager of Miller Timber services) , Petitmermet (2018) and Green et al. (2019).

Table 3. Equipment costs and rates used in Ackerman model to determine harvest system costs

	Scorpion King	Bear	Buffalo	Elephant King	Komastu
Purchase Price ($)	$ 690,000	$ 720,000	$ 490,000	$ 650,000	$ 230,000
Salvage Value (%)	35%	35%	40%	40%	50%
Interest	15%	15%	15%	15%	15%
Fuel ($/liter)	$ 0.87	$ 0.87	$ 0.87	$ 0.87	$ 0.87
Fuel Use (l/pmh)	28	31	24	26	24
Lube and Oil (% of fuel)	15%	15%	15%	15%	15%
Utilization Rate	85%	85%	80%	80%	70%
Repair and Maintenance (%)	100%	100%	100%	100%	100%
Expected Life (years)	5	5	5	5	5
Labor ($/hr)	$ 24.00	$ 24.00	$ 24.00	$ 24.00	$ 24.00
Fringe Benefits (% of labor)	45%	45%	45%	45%	45%
Operator Transport ($/yr)	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00	$ 10,000.00
Overhead	10%	10%	10%	10%	10%
smh per year	2080	2080	2080	2080	2080

Results

<u>*Understory Vegetation*</u>

Ground cover increased in both units as understory vegetation class height increased. Turkey Trot averaged 39 % ground cover in “short” plots (Table 4). Trailing blackberry (*Rubus ursinus*) was the most common species in these plots averaging 13 % ground cover, followed by Salal (*Gaultheria shallon*). “Medium” plots in Turkey Trot averaged 74 % ground cover. Vine maple and ocean spray were the most common for these plots averaging 34 % and 15 % ground cover respectively. “Tall” plots averaged 87 % ground cover. The species with highest average ground cover in “tall” plots were vine maple (34 %) and beaked hazel (24 %).

Time Out averaged 55 % ground cover in “short” plots, grass (15 %) and sword fern (13 %) were the most common. In “medium” plots averaged 78 % ground cover with vine maple as most common at 40 % followed by sword fern at 9 %. “Tall” plots averaged 82.5 % cover, with beaked hazel the most averaging 26 % ground cover followed by vine maple at 14 %.

Table 4. % ground cover by understory vegetation class and unit

	Turkey Trot			**Time Out**		
	short	medium	tall	short	medium	tall
mean	39	74	87	55	78	82.5
median	20	65	70	55	82.5	82.5
range (min)	15	50	60	5	55	70
range (max)	100	100	120	110	95	95
SD	35.4	22.2	30.3	30.1	16.1	9.4
SE	15.8	9.9	13.6	10.7	7.2	3.8
95% CI lower	83.0	101.6	124.7	80.2	97.9	92.3
95% CI upper	-5.0	46.4	49.3	29.8	58.1	72.7
n	5	5	5	8	5	6

<u>*Time Study*</u>

Harvester

The average harvested tree from Turkey Trot had a DBH of 18.6 cm and 2.1 logs per tree (Table 5). Comparatively trees harvested from Time Out had an average DBH of 25.1 cm and 2.8 logs per tree (Table 6). On average trees in Turkey Trot had a merchantable volume of 0.28 m^3, while the trees in Time Out averaged 0.71 m^3. The merchantable volume primarily came from Douglas fir for both units. Douglas fir made up 96 % of the harvested trees in Turkey Trot and 94 % in Time Out. The scorpion King had 452 cycles and the Bear had 229 cycles that were analyzed.

Table 5. Slope percent, tree size and volume statistics for trees harvested in Turkey Trot unit by Ponsse Scorpion King

Tree and Slope Statistics for Scorpion King Harvest Cycles

	DBH (cm)	Pieces	Merchantable Volume / tree (m^3)	Average Corridor Slope
mean	18.6	2.1	0.28	20.9
median	17.8	2	0.21	20.4
range(min)	5	0	0	14.8
range(max)	40	4	1.54	28.1
sd	8.08	1.2	0.3	5.6
se	0.38	0.1	0.0	2.4
95% CI lower	18.0	2.0	0.2	20.9
95% CI upper	19.2	2.2	0.4	20.9
n	452	452	452	4

Table 6. Slope percent, tree size and volume statistics for trees harvested in Time Out unit by Ponsse Bear

Tree and Slope statistics for Bear Harvest Cycles

	DBH (cm)	Pieces	Merchantable Volume / tree (m^3)	Average Corridor Slope (%)
mean	25.1	2.8	0.7	21.6
median	24.8	3	0.56	20.4
range(min)	6.8	0	0	9.2
range(max)	48.8	5	2.77	34.2
sd	9.09	1.61	0.63	10.04
se	0.60	0.11	0.04	4.10
95% CI lower	23.9	2.6	0.5	21.6
95% CI upper	26.3	3.0	0.9	21.7
n	229	229	229	6

Delay free cycle time (DFCT) for the Ponsse Scorpion King averaged 41 seconds on 452 cycles. Decking had the largest average (42 seconds) of cycle time components, but only occurred during 4% of the cycles. The average cycle time for cycles in both “short” and “medium” understory vegetation was 38 seconds. The average cycle time for cycles in “tall” understory vegetation was 49 seconds, a 29% increase in average cycle time.

Table 7. Cycle-time component statistics for Ponsse Scorpion King (time is in sec.)

Ponsse Scorpion King Cycle Element Statistics									
	Move	Position Cut	Fell	Position Tree	Process	Brush	Deck	Other	Cycle Time
mean	9	4	4	6	16	16	42	13	41
median	5	4	3	3	12	14	34	9	33
range(min)	0	1	1	0	4	4	18	3	6
range(max)	156	27	55	71	116	45	105	51	225
sd	16.3	2.8	4.0	6.8	12.7	9.8	22.0	11.3	31.2
se	0.9	0.2	0.2	0.4	0.7	1.6	5.3	2.0	1.7
95% CI lower	8	4	3	5	14	0	31	9	38
95% CI Upper	11	5	4	6	17	19	53	16	44
n	452	452	452	452	390	38	17	33	452
% of cycles	100%	100%	100%	100%	86%	8%	4%	7%	100%

Table 8. Average observed cycle time by understory vegetation class for Ponsse Scorpion King

Average Scorpion King Cycle Time by Understory Vegetaion Class			
	Average Cycle Time (s)	% increase from "short"	# of cycles
Short	37.6	-	170
Medium	37.9	1%	137
Tall	48.5	29%	145

Average DFCT for the Ponsse Bear from 229 cycles was 59 seconds. Decking had the largest average mean time (29 seconds) of all cycle time components, but occurred on only 2% of the cycles. The average DFCT for cycles in “short” understory vegetation 56 seconds and 63 seconds for cycles in “medium” understory vegetation. That is a 14% higher average DFCT for cycles in “medium” compared “short”. Cycles in “tall” understory vegetation had an average DFCT of 72 seconds, which is 29% higher cycle time compared with cycles in “short”.

Table 9. Cycle time component statistics. for Ponsse Bear (time is in sec.)

Ponsse Bear Cycle Element Statistics									
	Move	Position Cut	Fell	Position Tree	Process	Brush	Deck	Other	Cycle Time
mean	12	9	6	8	23	24	29	18	59
median	6	7	5	5	19	18.5	23.5	16	48
range(min)	0	1	1	1	4	12	8	5	10
range(max)	124	136	28	47	120	46	64	54	250
sd	17.9	9.6	4.0	6.8	15.6	15.3	18.1	10.9	37.9
se	1.2	0.6	0.3	0.5	1.1	7.6	5.2	1.8	2.5
95% CI lower	10	7	5	7	21	0	18	14	54
95% CI Upper	14	10	6	8	25	48	41	21	64
n	229	229	229	229	201	4	12	37	229
% of cycles	100%	100%	100%	100%	88%	2%	5%	16%	100%

Table 10. Average observed cycle times by understory vegetation class for Ponsse Buffalo

Average Bear Cycle Time by Understory Vegetaion Class

	Average Cycle Time (s)	% increase from "short"	# of cycles
Short	55.7	-	164
Medium	63.4	14%	42
Tall	72	29%	23

Forwarder

There were 18 observed cycles for the Ponsse Buffalo, and 13 cycles for the Ponsse Elephant King. The average chip 'n saw log from Turkey Trot was 0.14 m^3, and the average sawlog was 0.51 m^3. No pulp log was produced from Turkey Trot. In Time Out, the average pulp log was 0.24 m^3, chip n saw log was 0.2 m^3 and the average sawlog was 0.71 m^3.

Table 11. Log volumes in m^3 by log sort and harvest unit

	Turkey Trot		Time Out		
	Chip n Saw	Saw Log	Pulp	Chip n Saw	Saw log
mean	0.14	0.51	0.24	0.20	0.71
median	0.12	0.50	0.23	0.18	0.70
range(min)	0.03	0.44	0.08	0.03	0.41
range(max)	0.44	0.64	0.39	0.48	1.27
sd	0.08	0.08	0.11	0.11	0.22
95% CI Lower	0.14	0.45	0.18	0.19	0.65
95% CI Upper	0.15	0.57	0.30	0.21	0.76
se	0.00	0.03	0.03	0.01	0.03
n	959	9	13	610	58

The mean total travel distance was 291 m for the Buffalo and 381 m for the Elephant King. The largest contributor to the total distance for both machines was travel distance empty, which was 51 % of total distance for the Buffalo and 44 % for the Elephant King.

The Buffalo had an average load of 88 logs with an average volume of 12.9 m^3. The Elephant King had an average load of 62 logs with an average volume of 14.6 m^3. The Elephant King having lower number of logs per cycle and higher volume was due to the bigger logs in the Time Out unit.

Table 12. Independent variable statistics for Ponsse Buffalo forwarder in Turkey Trot harvest unit

Ponsse Buffalo Variable Statistics

	Average Slope (%)	Travel Dist. Empty (m)	Travel Dist. Partial (m)	Travel Dist. Full (m)	Total Dist. (m)	Total Pieces	# of Load Swings	# of Unload Swings	Volume (m^3)
mean	15.1	148	71	73	291	88.4	27.6	10.1	12.9
median	15.1	126	50	49	255	94.5	30.5	11.0	13.6
range(min)	0.0	9	0	3	12	5.0	1.0	1.0	0.7
range(max)	30.4	320	234	243	562	121.0	38.0	14.0	18.6
sd	6.6	91.5	65.7	70.9	171.1	32.2	10.2	3.6	5.1
95% CI Lower	12	102	38	38	259	72	23	8	10
95% CI Upper	18	193	103	108	377	104	29	12	15
se	1.5	21.6	15.5	16.7	40.3	7.6	2.4	0.8	1.2
n	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0

Table 13. Independent variable statistics for Ponsse Elephant King in Time Out unit

Elephant King Variable Statistics

	Average Slope (%)	Travel Dist. Empty (m)	Travel Dist. Partial (m)	Travel Dist. Full (m)	Total Dist. (m)	Total Pieces	# of Load Swings	# of Unload Swings	Volume (m^3)
mean	21.5	168	90	123	381	61.9	23.0	12.4	14.6
median	21.7	189	64	117	399	72.0	24.0	12.0	14.5
range(min)	17.4	3	13	15	217	15.0	14.0	11.0	10.1
range(max)	26.0	261	236	244	540	79.0	29.0	19.0	23.4
sd	2.6	70.2	70.2	81.5	112.2	22.0	4.2	2.2	3.1
95% CI Lower	20	125	47	74	339	49	20	11	13
95% CI Upper	23	210	132	173	449	75	24	14	16
se	0.7	19.5	19.5	22.6	31.1	6.1	1.2	0.6	0.9
n	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0

The Buffalo had an average cycle time of 30.7 minutes. The largest contributors on average to the cycle time were loading and unloading at 13.7 and 4.8 minutes respectively. Driving empty had the longest average time of all drive time components at 3.2 minutes. The average total drive time was 7.5 minutes.

Table 14. Cycle component statistics for Ponsse Buffalo forwarder during observed cycles in Time Out unit (time is in min.)

Ponsse Buffalo Cycle Component Statistics

	Driving Empty	Driving Partially Loaded	Driving Loaded	Loading	Load Decking	Unloading	Unload Decking	Other	Cycle Time
mean	3.2	2.3	2.0	13.7	2.5	4.8	1.4	0.8	30.7
median	2.8	1.7	1.4	14.9	2.4	5.2	0.6	0.3	34.6
range(min)	0.5	0.0	0.2	0.7	0.1	0.2	0.0	0.0	2.0
range(max)	5.9	5.5	7.1	20.0	5.9	6.7	3.5	3.6	43.4
sd	1.8	1.5	1.9	5.2	1.9	1.7	1.4	1.0	11.4
95% CI Lower	2.3	1.5	1.0	11.2	1.5	3.9	0.7	0.3	25.1
95% CI Upper	4.1	3.0	3.0	16.3	3.4	5.6	1.9	1.3	36.4
se	0.4	0.4	0.5	1.2	0.5	0.4	0.3	0.2	2.7
n	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0

The Elephant had an average cycle of 27.7 minutes. The largest contributors to cycle time were loading and unloading (mean of 10.0 minutes and 5.4 minutes, respectively). Driving empty was the largest contributor to drive time with an average of 4.0 minutes.

Table 15. Cycle component statistics for Ponsse Elephant King forwarder during observed cycles in Time Out unit (time is in min.)

Ponsse Elephant King Cycle Component Statistics

	Driving Empty	Driving Partially Loaded	Driving Loaded	Loading	Load Decking	Unloading	Unload Decking	Other	Cycle Time
mean	4.0	2.4	3.3	10.0	1.1	5.4	1.0	0.6	27.7
median	4.4	2.1	3.5	10.8	0.9	4.9	0.8	0.3	26.5
range(min)	0.3	0.7	0.8	5.6	0.1	4.3	0.0	0.0	21.1
range(max)	6.3	5.7	6.4	12.2	2.0	9.2	4.3	1.9	38.4
sd	1.6	1.6	2.0	1.9	0.6	1.3	1.1	0.6	4.8
95% CI Lower	3.1	1.5	2.1	8.9	-0.2	4.6	0.3	0.2	24.8
95% CI Upper	5.0	3.4	4.5	11.2	1.4	6.1	1.4	0.9	30.6
se	0.4	0.5	0.6	0.5	0.2	0.4	0.3	0.2	1.3
n	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0

Loader

There were twenty-one observed cycles for the Komatsu loader; nine were from Turkey Trot unit and twelve from Timeout. Chip ‘n saw loads made up nineteen of the cycles, the other two were sawlog loads and no pulp log loads were observed. The average truckload had 184 logs and a volume of 32.2 m^3 (Table 16). The average chip ‘n saw load was 200 logs and 33.3 m^3, while the average saw log load averaged 33 logs and 23.4 m^3.

Table 16. Komastu loading variable statistics

Loading Variable Statistics

	Number of Load Swings	Total Pieces	Volume (m^3)
mean	21.7	183.6	32.2
median	23.0	179.0	32.8
range(min)	13.0	32.0	22.7
range(max)	30.0	282.0	39.5
sd	4.0	63.3	4.1
95% CI Lower	19.9	154.8	30.4
95% CI Upper	23.5	212.4	34.1
se	0.9	13.8	0.9
n	21	21	21

The average DFCT for all trucks loaded was 21.8 minutes. The average time for trucks loaded with chip ‘n saw logs was 22.2 min and 18.2 min for sawlog loads. Loading time was the largest contributor to cycle times with an average time spent loading of 10.7 min. Time spent decking logs on the truck was the second largest contributor on average followed by setup of the second trailer.

Table 17. Cycle component statistics for Komastu loader. Time is in min.

Loading Cycle Component Statistics

	Setup 1	Setup 2	Move	Load	Decking	Other	cycle time
mean	1.3	3.4	1.2	10.7	4.7	0.6	21.8
median	1.4	3.5	1.0	10.3	4.2	0.4	21.7
range(min)	0.4	1.5	0.1	6.9	1.5	0.0	13.4
range(max)	2.7	5.2	2.8	15.5	10.2	2.1	34.9
sd	0.6	0.9	0.8	2.0	2.5	0.6	5.2
95% CI Lower	1.0	3.0	0.8	9.8	3.6	0.3	19.4
95% CI Upper	1.5	3.8	1.6	11.6	5.8	0.9	24.2
se	0.1	0.2	0.2	0.4	0.5	0.1	1.1
n	21	21	21	21	21	21	21

Limited log truck availability resulted with the loader having the lowest observed utilization rate (25%). The observed utilization rates were not used in the cost model due low number of days observing each machine resulting in uncertainty of utilization rates being an accurate representative. Other than the loader, no machine had more than two days of observations. The Bear had only one day of observations and had a long mechanical delay causing a very low utilization rate (44%) that is unlikely to represent the true utilization.

Table 18. Observed utilization for all equipment

	Study time (hrs.)	Productive time (hrs.)	Delays (hrs.)	Utilization rate
Scorpion King	6.05	5.39	0.66	89%
Bear	6.02	2.66	3.36	44%
Buffalo	10.76	9.36	1.40	87%
Elephant King	7.85	6.01	1.84	77%
Komatsu	30.97	7.64	23.33	25%

Regression Models

The difference between average “DBH”, “number of pieces per tree” and “tree volumes” in units Turkey Trot and Time Out, as well as the differences in machine capabilities of Ponsse Scorpion King and Ponsse Bear resulted in separate analysis of both machines.

The final model for Scorpion King had the variables “DBH”, “pieces”, “short” and “tall” vegetation class. The variable “merchantable tree volume” was removed from the model consideration due to a high correlation (0.87) with “DBH”. White fir and hardwoods were not statistically different (p-value of 0.85 and 0.13 respectively before removal from the model) from Douglas fir, so “species” were removed from the model. Slope had a p-value of 0.42 when removed from the model (Table 19). With “short” understory vegetation as the intercept, I failed to find a statistical difference between “short” from “medium” understory vegetation (p-value = 0.29).

Table 19. Variable’s p-value and model adjusted R-squared and Residual SE before variable removal from regression for Scorpion King

Variables removed from Ponsse Scorpion King Regression

Variable	p-value	Adj-R squared	Residual SE
Slope	0.42	0.35	0.531
Hardwood	0.13	0.35	0.530
White fir	0.78	0.35	0.531
Medium Vegetation	0.29	0.35	0.530

The response variable “cycle time” was log transformed so that the response variable have a more standard distribution for the regression analysis. The final regression was back-transformed for ease of use.

Scorpion King

cycle time =		p-value
	e ^ (2.459172	< 2e-16
+	0.03718 * DBH	4.11e-10
+	0.130268 * Pieces	3.98e-05
+	0.245997 * Tall)	5.76e-06

Residual SE: 0.5312 on 448 degrees of freedom (DF)
Adjusted R-squared: 0.3491
F-statistic: 81.63 on 3 and 448 DF, p-value: < 2.2e-16

Where:

- the intercept is "short" understory vegetation class
- "DBH" is in cm
- "Pieces" is the number of logs cut from a tree
- "Tall" is binary (1 if cycle is in "tall" understory vegetation, 0 if it is in "short" or "medium")

The final model for the Bear consisted of "DBH", "pieces", "slope" and all three understory vegetation classes. "Merchantable tree volume" had a high correlation (0.88) with "DBH" and "DBH" was chosen for use in model consideration. "Medium" and "tall" understory vegetation were not statistically different from each other. The final model has an adjusted R-squared of 0.46.

White fir was not significantly different (p-value 0.08) from Douglas-fir, but hardwood s were (p-value 0.02). However, due to the low number of hardwoods (13) and white fir (4) harv est cycles observed, "species" were removed from the model. Removing species lowered the adj usted R-squared by 0.01 and increased residual standard error from 0.425 to 0.427. With "short" understory vegetation as the intercept, “medium” and “tall” vegetation were found to be significa nt (p-values of 0.0004 and 9.42e-05 respectively)

Table 20. Variables p-value, and model adjusted R-squared and residual SE before variable removal from harvester regression

Variables removed from Ponsse Bear Regression

Variable	p-value	Adj-R squared	Residual SE
Hardwood	0.02	0.46	0.427
White fir	0.08	0.47	0.425

The response variable “cycle time” was log transformed so that the response variable has a more standard distribution for the regression analysis. The final regression was back-transformed for ease of use.

Bear
cycle time =

		p-value
	e^(3.233918	< 2e-16
+	0.024073 * DBH	1.14e-08
+	0.107303 * Pieces	5.73e-06
-	0.014517 * Slope	8.64e-06
+	0.287977 * Medium	0.000420
+	0.380826 * Tall)	0.000174

Residual SE: 0.4316 on 223 DF
Adjusted R-squared: 0.4498
F-statistic: 38.28 on 5 and 223 DF, p-value: < 2.2e-16

Where:

- the intercept is “short” understory vegetation class
- “DBH” is in cm
- “Pieces” is the number of logs cut from a tree
- “Slope” is average slope (%)

- "Medium" is binary (1 if cycle is in "medium" understory vegetation, 0 if it is in "short" or "tall")
- "Tall" is binary (1 if cycle is in "tall" understory vegetation, 0 if it is in "short" or "medium")

Forwarder

A two-sided t-test analysis of the "operator" and "number of sorts" relative to cycle time for Ponsse Buffalo forwarder had p-values of 0.75 and 0.19 respectively, and therefore the two variables were removed from model consideration. "Volume" had high correlations with "number of unload swings" (0.88), "number of load swings" (0.91), and "total pieces" (0.99), so "volume" was chosen for model consideration over the others. "Travel empty distance" and "total distance" had a high correlation value (0.91). "Total distance" was selected for use in model consideration. The remaining variables for model consideration were "travel distance partial", "travel distance full", "total distance", "volume", and "average slope".

The final model selected for the Buffalo has the variables "volume" and "total distance" with an adjusted R-squared of 0.93 with a residual standard error of 3.143.

Buffalo

cycle time (min) =		p-value
	0.35521	0.874
+	1.753856 * Volume	1.21e-10
+	0.008161 * Total distance	3.92e-05

Residual SE: 3.143 on 15 DF
Adjusted R-squared: 0.9255
F-statistic: 106.6 on 2 and 15 DF, p-value: < 1.356e-09

For the Elephant King a two-sided t-test analysis of whether “sorts” relative to cycle time resulted in a p-value of 0.81 therefore “sorts” was removed from model consideration. There is a highest correlation between variables was “total distance” and “travel distance empty” (0.83). All other variables were used in model consideration.

The final model for the Elephant King has the variables “number of load swings” and “total distance” with an R-squared adjusted of 0.81 and residual standard error of 2.061.

Elephant King

cycle time =		p-value
	-2.2221	0.60398
+	0.005048 * Total distance	0.01892
+	0.83283 * # of unload swings	0.02602
+	0.581602 * # of load swings	0.00393

Residual SE: 2.061 on 9 DF
Adjusted R-squared: 0.8132
F-statistic: 18.42 on 3 and 9 DF, p-value: <0.00003506

Where:

- “Total distance” is the total traveled slope distance during a cycle (m).
- “Number of unload swings” is number of times the boom swings a load of logs from the bunk to the decking area during a cycle.
- “Number of load swings” is number of times the boom swings a load of logs to the bunk during a cycle.

Loader

“Number of pieces” had a p-value of 0.25, and “volume” had a p-value of 0.14 before they were removed from the regression (Table 21). The selected model had the variable “number of load swings” and had an adjusted R-squared of 0.65.

Table 21. Variables p-value, and model adjusted R-squared and residual SE before variable removal from loader regression

Variable	p-value	Residual SE	Adj-R squared
Volume	0.14036	3.256	0.615
Number of pieces	0.24567	3.422	0.5747

Komatsu

cycle time =		p-value
	-0.4833	0.905
+	1.0269 * # of load swings	1.85e-05

Residual SE: 3.255 on 19 DF
Adjusted R-squared: 0.6084
F-statistic: 32.07 on 1 and 19 DF, p-value: < 21.849e-05

Where:

- “Number of load swings” is number of times the boom swings a load of logs to the truck during a cycle.

Productivity and Costs

We used the mean values of the observed variables in each regression to estimate the mean DFCT for each machine. The estimated productivity for each machine (m^3/PMH) is the mean observed volume per cycle for each machine multiplied by the estimated number of cycles per hour. With assumed utilization rates for the harvesters (85%), forwarders (80%) and the loader (70%), machine productivity per scheduled machine hour (SMH) were calculated.

Using the average variable measurements from Turkey Trot, the estimated DFCT for the Scorpion King in "short" understory is 31 seconds (Table 22). The estimated cycle time in "tall" understory is 39 seconds, a 26% increase in cycle time.

Table 22. Estimated DFCT (s) for Ponsse Scorpion King by understory vegetation class.

Scorpion King Cycle Time Estimation	
short	31
tall	39
% increase	26%

Using the average variable measurements from Time out, the estimated cycle time for the Bear in "short" understory vegetation is 46 seconds (Table 23). The estimated cycle time in "tall" understory vegetation is 67 seconds, a 46% increase in cycle time.

Table 23. Estimated DFCT (s) by understory vegetation class for Ponsse Bear

Bear Cycle Time Estimation	
short	46
tall	67
% increase	46%

The Scorpion King harvester was estimated to produce 27.7 m^3/SMH (Table 24) when operating in "short" understory vegetation and 22.0 m^3/SMH in "tall" understory vegetation (a 21% decrease in productivity). The estimated productivity for the Bear harvester in "short" understory vegetation is 45.1 m^3/SMH and 30.9 in "tall" understory vegetation (31% decrease).

Table 24. Estimated harvester productivity and percent change in productivity between understory vegetation classes

	Scorpion King		Bear	
	medium	tall	short	tall
Production (m^3/PMH)	32.6	25.9	53	36.4
Utilization Rate	85%	85%	85%	85%
Production (m^3/SMH)	27.7	22.0	45.1	30.9
% change		-21%		-31%

Using the mean variables for the Buffalo, the estimated cycle time is 25.4 minutes (Table 25) and productivity of 24.4 m^3/SMH (Table 26). The estimated DFCT for the Elephant King is 23.4 minutes (Table 25) and productivity of 29.9 m^3/SMH (Table 26). The estimated DFCT for the Komastu loader is 21.8 minutes (Table 25). The productivity for the loader is 64.0 m^3/SMH (Table 26).

Table 25. Estimated DFCT times (min) for the Ponsse forwarders and Komastu loader

Buffalo	Elephant King	Komastu
25.4 min	23.4 min	21.8 min

Table 26. Estimated productivity of Ponsse forwarders and Komatsu loader

	Buffalo	Elephant King	Komastu
Production (m^3/PMH)	30.5	37.4	91.4
Utilization	80%	80%	70%
Production (m^3/SMH)	24.4	29.9	64.0

While maintaining the observed machine pair of Scorpion King and Buffalo, the decrease in productivity for the Scorpion King, increasing understory vegetation height from “short” to “tall” understory vegetation switches the forwarder from constraining productivity to the harvester. For the second pair of machines (Bear and Elephant King), the forwarder is the most constraining regardless of understory vegetation class. The loader has a much higher productivity than both harvesters and forwarders even with a lower utilization rate.

The total cost for the Scorpion King is \$ 180.88/PMH (Table 27). The lower productivity from cycles in "tall" understory vegetation compared to "short" increased the cost from \$ 5.55/ m^3 to \$ 6.98/ m^3 (a 26% increase). The total cost for the Buffalo was \$ 149.26/PMH or \$ 4.89/ m^3. The Komastu had a cost of \$ 117.93/PMH or \$ 1.29/ m^3. The stump to truck costs in "short" understory vegetation was \$ 11.73/ m^3 and \$ 13.17/ m^3 in "tall" vegetation. That was an estimated increase of \$ 1.44/m^3 or 12% in stump to truck costs from an increase in vegetation height.

Table 27. Estimated machine costs for CTL equipment used in "Turkey Trot" unit

	Scorpion King		Buffalo	Komastu
	short	tall		
Fixed cost (\$/PMH)	\$ 94.06	\$ 94.06	\$ 66.67	\$ 31.76
Variable cost (\$/PMH)	\$ 28.01	\$ 28.01	\$ 24.01	\$ 24.01
Operator cost (\$/PMH)	\$ 46.60	\$ 46.60	\$ 49.51	\$ 56.58
Overhead cost (\$/PMH)	\$ 12.21	\$ 12.21	\$ 9.07	\$ 5.58
Total cost (\$/PMH)	\$ 180.88	\$ 180.88	\$ 149.26	\$ 117.93
Total cost (\$/m^3)	\$ 5.55	\$ 6.98	\$ 4.89	\$ 1.29
Stump to truck (\$/m^3)	\$ 11.73	\$ 13.17		

The total cost for the Bear is \$ 188.68/PMH (Table 28). The lower productivity from cycles in "tall" understory vegetation compared to "short" understory vegetation increased the cost from \$ 3.56/ m^3 to \$ 5.18/ m^3 (46% increase). The total cost for the Elephant King was \$ 175.41/PMH or \$ 4.69/ m^3. The estimated stump to truck costs in "short" understory vegetation was \$ 9.54/m^3 and \$ 11.16/m^3 in "tall" vegetation. That was an estimated increase of \$ 1.62 or 12 % in costs from an increase in vegetation height.

Table 28. Estimated machine costs for CTL equipment used in "Time Out" unit

	Bear		Elephant King	Komastu
	short	tall		
Fixed cost ($/PMH)	$ 98.14	$ 98.14	$ 88.44	$ 31.76
Variable cost ($/PMH)	$ 31.02	$ 31.02	$ 26.01	$ 24.01
Operator cost ($/PMH)	$ 46.60	$ 46.60	$ 49.51	$ 56.58
Overhead cost ($/PMH)	$ 12.92	$ 12.92	$ 11.45	$ 5.58
Total cost ($/PMH)	$ 188.68	$ 188.68	$ 175.41	$ 117.93
Total cost ($/m^3)	$ 3.56	$ 5.18	$ 4.69	$ 1.29
Stump to truck ($/m^3)	$ 9.54	$ 11.16		

Discussion

It was assumed that if understory vegetation height had an impact on machine productivity, it would only be to the harvesters. While the forwarders may not have the direct impacts of vegetation on their productivity, they might have indirect impacts that were not accounted for in this study. Nurminen et al. (2006) said harvesters and forwarders should be analyzed together because the harvester will define the working environment for the forwarder (i.e. logs in a pile or spread out). Understory vegetation might impact the harvesters ability to define a more productive work environment for the forwarder by making it difficult to stack logs together or getting stems stuck between logs making the forwarder reach more times with the grapple to pick up all the logs.

The Scorpion King and Bear harvesters have an increase in average cycle time as understory vegetation height increases in both observed and the models. There was no observed difference on average DFCT going from “short” to “medium” for the Scorpion King, but there was going form “medium” to “tall”. The model for the Scorpion King agreed with the observations, showing no significant difference between “short” and “medium”. Meanwhile there was an observed difference of average DFCT amongst all height classes for the Bear.

Recent studies on CTL systems in Oregon by Petitmermet (2018) and Green et al. (2019) which were both done in Oregon using the Bear and Elephant King allow for production comparisons of these machines with this study. However, neither study examined the effects of understory vegetation on machine productivity.

The productivity for the harvester in this study was a higher than Petitmermet (2018) had observed. Differences in harvester productivity may be due to location of the study. That study sites of Petiterment (2018) were in southern Oregon, with dominant species being ponderosa pine (*Pinus ponderosa)* and white firs.

Although Green et al. (2019) and this study were both conducted in the same forest, the harvester productivity were quite different, with that study estimating the Bear harvester to be twice as productive. Differences may have been caused from larger trees in the Green et al. (2019), with Douglas fir trees averaging 10 cm larger at DBH compared to this study.

Forwarder productivity for the three studies were similar. Petitmermet (2018) defined a forwarder cycle differently than other studies. Instead of treating the forward going out and returning as a cycle, a cycle was considered completed when log extraction from a single corridor was complete. The point being the loads coming on a corridor are not independent of each other; wherever the operator ends on one load determines where they start the next load. While an intriguing method, the forwarder operator often grabbing logs from multiple corridors on a single turn made the method impractical. Overall the productivity and costs were similar to both studies with the exception of the harvester costs per unit volume of log (m^3) compared to Green et al. (2019). That is due to the large difference in productivity.

An assumption made for the costs is that each machine's productivity in a system is independent of each other and therefore a decrease in productivity of a harvester from understory vegetation would not affect the productivity of the other machines in the system. In the case of the Scorpion King, the decrease in productivity switches the least limiting machine in the system from the forwarder to the harvester. If the decrease is not planned for the Scorpion King could bottle neck the system increasing costs by making the forwarder wait and decreasing utilization.

As being two case studies, this study had several limitations. First, this study did not directly account for the influence of understory vegetation density on machine productivity, it was assumed that density and understory vegetation height were highly correlated. Evidence of this is the vegetative cruise showing the average ground cover (%) increase from the shortest class to the tallest in both units. Second, the operational season was limited to a dry summer. During summer harvests, the soils are usually dry and the vegetation is fully leafed (allowing vegetation to be visual barrier). In a winter harvest, the soils can be wet or covered in snow effecting the traction of the machines and most understory vegetation has lost its leaves making it less visually impactful. This could drastically reduce the impact of understory vegetation on winter harvests compared to summer harvests. Third, tree density is a potentially confounding variable in relation to understory vegetation, which was not addressed explicitly in this study. Density will play a role in canopy closure. Less dense stands could allow more light to reach the forest floor, which can promote more understory vegetation. The farther spaced trees also means more distance for the harvester to cover. With the limited study size, it was difficult in our study to separate effects from harvested tree density and the understory vegetation classes.

Conclusion

While the study is limited in scope due to it being a case study on a couple units with a few different pieces of equipment, it does begin to allow insight to the effects of understory vegetation on productivity and costs of CTL systems. The models show a decrease in productivity as understory vegetation height increases which can lead to increased operating costs. Logging contractors using CTL systems can use this to better estimate harvest unit production, and reduce costs by having a more efficient harvest schedule. Timber sale administrators can use this to get a better valuation of stump to truck costs for a harvest unit, in turn have more accurate stand valuation.

The limitations of the study mean future research encompassing a wider range of machines and environments is needed to determine more precisely how much influence understory vegetation has on harvesting systems.

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