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Title: Tires, Tracks, and Tethering: Idaho Steep Slope Harvesting

Abstract approved:

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Woodam Chung

Steep slope timber harvesting often falls under scrutiny of labor, safety, and operational challenges, but is beginning to advance past these barriers through substantial technological progression. Across previous decades, large advancements of technology have occurred in ground-based timber harvesting systems, giving mechanized options to every phase of timber harvesting. These progressions have created outcomes including, but not limited to, improved worker safety and reduced risk, increased productivity and reduced harvest cost, while also increasing consistent harvest output through seasonal conditions. Timber harvesting methods on steep slopes historically involved motor-manual tree felling and labor-intensive extraction, but are now giving way to mechanization in steep slope harvesting.

Tether-assist technology is now bringing the decades of progression from ground-based harvesting systems onto steep slopes. With the ability of ground-based harvesting systems to now traverse slopes steeper than previously possible, there is much to learn of their impacts and relationships with the landscape. Previously developed state and federal government policies in the Pacific Northwest (PNW), within the United States of America (USA), limit ground-based harvesting equipment on steep slopes. Different levels of regulation come into application by means of restriction for traditional ground based harvesting equipment above specified slope

thresholds, in addition to extra requirements and some restrictions for tether-assist technology.

This research is a case study showcasing soil impacts of traditional steep slope cable harvesting systems alongside developing tether-assist ground-based harvesting systems in similar terrain and timber conditions. Felling methods vary from motor-manual to mechanized directional felling head, while extraction methods incorporate grapple skidder, shovel, and cable logging, each exhibiting a different interaction with the site. Pre-harvest and post-harvest observations were collected of bulk density and penetrometer resistance for impact characterization and comparison. Bulk density measures work to capture differences in top-soil disturbance, while penetrometer resistance captures soil profile differences at increased depths. Sampling consisted of pre-operation and post-operation measurements taken at repeated locations on an established grid, allowing for paired testing of observations.

The results from this study have shown differences in harvest system and operational area impacts, with each configuration contributing a unique distribution of soil impact to the harvest area. Through a variety of cable, tracked, and rubber tire equipment, this is to be expected due to the differing contact relationships and payload interactions with the soils in the harvest area. Machine passes and spatial distribution of machine activity was also found to be variable between harvest system configurations.

These differing outcomes led to support traditional trends found in ground-based harvesting soil disturbance studies, with grapple skidding exhibiting the greatest impacts followed by shovel, and cable logging. Although trends in the data led to this comparative conclusion, significant differences were not found between either of the tether-assisted skidder or shovel systems. Further development of tethered logging system research is necessary, as trends may be similar to flat ground, yet additional forces via tether tension and extra payload may be entering new magnitudes.

Tires, Tracks, and Tethering: Idaho Steep Slope Harvesting

by
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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.

Austin R. Finster, Author

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Introduction

Global demand for wood products coupled with a desire for sustainable harvest practices continues to support technological advancement, and operational refinement in timber harvesting systems. Amongst timber harvesting operations, a variety of harvest system configurations allow for a broad range of operational advantages and disadvantages. These advantages and disadvantages that appear in timber harvests often hinge on site conditions, timber to be harvested, and machine configurations implemented, all of which are variables assessed by land managers and logging contractors.

Historically, timber harvesting systems have been divided into two distinct groups of ground based, and cable harvesting systems, depending on terrain to be harvested. Ground based timber harvesting systems have been restricted by steep slopes above 40% (Brame & Jimenez, 2019), and government regulations in the past. In timber harvesting operations containing slopes beyond the 40% threshold, cable harvesting systems can be found in operation. Currently, a young technology referred to as tethered harvesting systems are being developed and implemented to bridge the operational gap between ground-based harvest systems and cable harvesting systems. Tethered harvesting systems aim to remove the constraint of steep slopes, allowing modified ground-based systems to operate in areas that they couldn't access prior in traditional operation. Ground based equipment used in tethered configuration provides the opportunity of mechanizing previously manual operations with proven safety and cost improvements (Visser & Stampfer, 2015).

Background

Traditional Steep Slope Logging

Logging on steep slopes (greater than 40%) has previously necessitated motor-manual tree felling to be completed by workers on the ground using chainsaws (Brame & Jimenez, 2019). Extraction of the trees and logs cut by these workers on the ground is subsequently conducted by cable harvesting systems through the yarding process. These systems utilize a variety of cables, winches, and brakes to partially or fully suspend fallen trees and or logs into the air for extraction to a determined location. A small variety of machines are used for cable harvesting depending on the demands of the harvest site. In applications that require long distance yarding of trees and logs or large payloads, large tower yarders or swing yarders may be used (Olund, 2001). In cases of shorter yarding distances or smaller payloads, machines such as yoders may be used for cable harvesting extraction. The essential components of these systems are some sort of elevated spar pole or boom to provide lift to the payload, as well as winches and cables for suspending and transporting the necessary payload (Studier & Binkley, 1974). This study utilized a smaller cable logging method involving a yoder with both mechanized and non-mechanized carriages for log extraction.

> Yoder - Typically a log loader with a minimum of 2 drums mounted at the base of the boom. Lines from each drum run through sheaves mounted on the boom or heel rack to facilitate multiple cable logging configurations (OSHA O. , 2010).

Ground Based Logging: Whole Tree

On slopes below 40%, ground based timber harvesting systems have been implemented in a variety of configurations. Modern applications of ground based harvesting systems allow for mechanization of all harvest processes, leading to increased productivity and safety compared to non-mechanized methods. Tree felling is completed by mechanized feller-buncher, with extraction of felled trees being completed through use of a skidder or logging shovel to predetermined locations. In this study, the traditional extraction machines of a grapple skidder and logging shovel were each used, but in a modified tethered operation from conventional operation.

> Grapple Skidder - Rubber tired four-wheel-drive machine consisting of a front dozer blade and maneuverable grappling device on the back of the machine. The grapple on the back of the machine allows the operator to close the grapple on the trunk of previously felled trees to transport them to a predetermined landing for drop off (OSHA, 1995).

> Logging Shovel - Specially designed log loader utilized for rough terrain traversing to access and swing logs within harvest unit towards predetermined landing. Log loaders use grapple arms as positive means to handle logs (OSHA O. , 2010) and are outfitted with duty specific booms, grapples, undercarriages, and guarding in comparison to similar excavator machines.

Feller-Buncher - Purpose built forestry swing machine with metal tracks, compact body, and specialized cutting head for grabbing and felling trees. Cutting heads either utilizing a rotating disc saw or grapple and guide bar configuration for manipulating and felling trees.

Tethered Logging

Tethered logging systems have seen application across a variety of configurations in ground based harvesting systems. From a simple standpoint, tethered systems rely on a cable and winch system applied to traditional ground-based equipment to act as a traction aid on steep slopes. These traction aids allow the ground-based machines to traverse steeper slopes than operating in an untethered fashion. With previous maximum slope limitations applied to ground based machinery in various policies and legislation, these limits are now being met and exceeded by this new technology.

Tethered Logging System - Equipment configuration used to allow ground based harvesting equipment to operate on slopes steeper than traditionally traversed. Systems typically consist of a feller-buncher or shovel operating on the slope, anchored to a machine based winch via cable at the top of the slope (Chase et al., 2019). Tethering capabilities are now expanding to rubber tire skidders as well. Tethered logging systems are usually classified in 1 of 2 categories identified as dynamic or passive (Ellgard, 2015). Dynamic tether systems utilize a machine working on the slope and a separate base machine up slope that houses a winch and associated cable. Passive systems in contrast utilize an onboard winch integrated to the machine working on the slope.

New technology in tethered timber harvesting equipment has gained attention for worker safety benefits, as well as positive logging production increases, yet lacks analysis of site and soil impacts compared to traditional steep slope harvesting methods. Much of the current research surrounding soil disturbance and tethered systems has either had a narrow scope of machinery studied, or mostly been qualitative in soil disturbance metrics. As ground-based systems are being adapted to steep slopes through the use of tethered harvesting systems, there is interest in understanding their relationship to the landscape on slopes they have not previously traversed. Ground based timber harvesting systems have long been criticized for creating negative soil impacts, especially in terms of compaction, with detriment to soil health and loss of long-term soil productivity (Froehlich & McNabb, 1983). Viewpoints and findings of soil disturbance due to timber harvesting greatly vary across soil types, forest types, and logging systems implemented, therefore creating a need for inquiry and research.

Research Questions

This study aims to further explain and address the soil disturbance differences and relationships in traditional and developing steep slope harvesting systems through side-by-side comparison of 4 different steep slope harvest corridors and harvest systems. Corridor A and B represent emerging technology of tethered ground-based equipment on steep slopes, while Corridor C and D represent traditional and advanced cable logging methods, respectively, found on steep-slopes. Corridor A will utilize a feller-buncher for the felling of trees, followed by a rubber tire grapple skidder for subsequent extraction, with each machine utilizing tethering to a base machine. Corridor B will utilize a feller-buncher for the felling of trees, followed by a steel tracked logging shovel, with each machine utilizing tethering to a base machine. Corridor C represents traditional cable logging methods through the use of motor-manual chainsaw hand falling of trees, followed by extraction by yoder with manual chokers. Corridor D represents advancing cable logging methods with tree felling completed by a tethered feller-buncher, and extraction by yoder with grapple carriage.

We specifically explore:

- What are the characteristics and trends within and between traditional steep slope cable logging and tethered logging systems on soil compaction?
- How does harvest corridor compaction compare between corridors subject to tethered steel track shovel logging and tethered rubber tire grapple skidding extraction methods?

Hypotheses

Ho: Tethered logging systems will present greater amounts of soil compaction than traditional cable logging systems on steep slope harvest units.

H_1: Tethered shovel logging will result in less soil compaction than tethered grapple skidder use in steep slope harvest units.

Research Objectives

The objective of the research and study design used in this case is to quantify and characterize the difference in soil compaction between and within multiple steep slope harvesting systems. This research will not only characterize and compare traditional and developing steep slope harvesting systems, but additionally explore differences in tethered steel-tracked shovel logging operation and tethered rubber-tired skidder operation.

Literature review

Soil compaction following timber harvest is often of interest with potential impacts on seedling establishment and vigor with potential for restricted root growth and reduced productivity (Williamson & Neilsen, 2000). Due to the nature of an external force being applied to the soil during operations, all harvest systems will exhibit changes in physical soil properties, but the degree of change varies with harvesting equipment, technique, intensity, and soil properties (Reisinger et al., 1988). Ground based timber harvesting equipment has carried a stigma of high potential to create negative soil impacts and decreases in long term site productivity, although many factors in addition to harvest system type are influential. Studies across multiple forest types have aimed to quantify and observe timber harvesting machine impacts relative to forests, with a large focus on ground-based timber harvesting equipment (Miller et al., 2004; Crawford et al., 2021).

Ground based harvesting not only has machine presence on the ground, but also has a variable operating pattern and number of machine passes on given areas. Previous studies surrounding ground based harvesting systems utilizing crawler tractors and rubber tired-skidders used for log extraction indicated as much as 20 to 35 percent of the harvest unit being subject to compaction (Adams, 1990). Although these areas may not be compacted to a detriment, it illustrates the relevance of machine coverage on the harvest unit with most compaction occurring within early machine passes (Han et al., 2006) up to the 10 to 15 pass threshold (Cambi et al. 2015).

Efforts for limiting soil disturbance from ground-based logging operations have often been connected to the machine-to-soil interface (Sheridan, 2003). This interface has been characterized by various combinations on forestry machines, including rubber tires, steel tracks, and additional steel tracks or chains over rubber tires. Machine to soil contact differences of either rubber tire or steel track contact have been shown to interact differently in terms of soil impact (Sakai et al., 2008), although there are inconsistent findings of distinct compaction, there are differing trends in soil impact distribution (Williamson & Neilsen, 2000; Jansson & Johansson, 1998; Atherton, 2019).

The impacts of harvest system trail coverage on harvest sites (Miller et al., 2004), as well as increasing machine size (Green, 2019; Hakansson & Reeder, 1994), continues to facilitate research of soil compaction on harvest sites (Crawford et al., 2021) with an increasing presence of mechanized equipment in recent decades (Cambi et al., 2015). Compaction in forest soils from heavy equipment is especially relevant due to their susceptibility of compaction characterized by the loose, friable structure and high porosity of forest soils (Crawford et al., 2021). Natural ameliorative processes may not quickly restore soils, leaving compacted soils with 5 to 15% stand growth losses for as long as 30 years in some areas (Froehlich & McNabb, 1983) following harvest operations. Contrasting findings suggest compacted soils may aid in young stand establishment through increased water holding capacity (Ares et al., 2005), yet results are very site, soil, and species specific.

Traditional steep slope logging methods involving cable yarding have had favor for their absence or minimization of machines traversing the harvest unit with soil contact. Cable yarding allows for full suspension of logs into the air or partial suspension of logs in the air, allowing one end of logs during extraction to drag on the ground. Full suspension cable yarding has been found to have a lesser amount of soil disturbance and compaction compared to ground-based equipment (Allen et al., 1999; Reeves et al., 2011), yet is not always possible. Due to site and logging equipment constraints, partial suspension can occur of log payloads resulting in increased mineral soil exposure and rutting (Youngblood, 2000) contributing to a diversity of soil disturbances. Soil disturbance in cable logging systems on steep slopes may be less characterized by compaction, yet have other impactful modes of disturbance associated with their extraction and payload patterns (Allen et al., 1999). Due to long linear extraction patterns in cable logging, soil displacement and rutting may increase erosion susceptibility in cable logging systems due to soil scarification and exposure (Cambi et al., 2015).

Tethered timber harvesting innovation and technology is now allowing mechanized ground-based equipment onto slopes historically accessible only by motor-manual tree felling and labor-intensive cable logging (Visser & Stampfer, 2015). Original commercial implementation of tethered harvesting equipment was spurred by the need for increased trafficability of loaded forwarders in soft soils on adverse slopes (Oberer, 2012) in cut-to-length harvest systems, with expansion to harvesters following initial harvester application (Visser & Stampfer, 2015). These developments mark the initial driver of tethered equipment as soil protection, although the technology has produced byproducts of improvements in productivity and safety (Holzfeind et al., 2020). Commercial development of whole tree tethered systems was minimal until 2006 (Cavalli & Amishev, 2019) with the advent of Trinder Engineering's "ClimbMax " machine (Holzfeind et al., 2020). Numerous studies have worked to previously characterize soil disturbance of ground-based harvest operations on slopes below 40%, and cable logging operations on slopes greater than 40% (Reeves et al., 2011; Crawford et al., 2021), yet little has been done to characterize soil disturbance of whole tree ground based machines now being utilized in tethered systems (Visser & Stampfer, 2015). Theoretical models have been under development for soil interactions (Sessions et al., 2017) and stability with tethered harvest systems (Visser & Stampfer, 2015) as further research of their soil disturbance characteristics occur. Rutting, erosion, and soil densification associated with tethered logging operations in their emergence have been summarized as similar to impacts found in gentle terrain, yet application and advancement of these machines continues to outpace research on various sites and soils necessitating further environmental analysis (Holzfeind et al., 2020).

Research has begun comparing soil disturbance of tethered and untethered harvesting methods for various comparisons of felling and extraction. Chase et al. (2019) observed that winch assisted harvest systems with tethered felling and extraction compared to cable logging created a greater amount of soil disturbance, yet it was comparable to accepted untethered ground-based harvest system impacts. Multiple studies have examined the soil impacts of implementing tethered felling in contrast to motor-manual felling, followed by cable extraction on steep slopes with no significant soil impact differences (Chase et al., 2019; Green, 2019; Amishev & Evanson, 2010; Evanson et al., 2013). Increased traction and decreased rutting are marked as potential benefits of tethered whole tree harvest systems, thereby limiting adverse effects on forest soils (Holzfeind et al., 2020).

Multiple methods of steep-slope whole tree extraction are present between cable logging and tethered ground-based harvest systems. Tethered ground-based harvest systems utilize either steel-tracked or rubber-tired machine platforms for felling and extraction, with each type resulting in different trends of soil disturbance (Atherton, 2019). Tethered rubber tire harvesting equipment has been studied in relation to soil compaction (Green, 2019), yet has largely been focused around cut-to-length systems incorporating harvester and forwarder pairs in short wood harvesting. Tethered grapple skidders are beginning to gain popularity for their ease of use and operation in steep areas difficult to extract though traditional cable logging methods (Pedofsky & Visser, 2019). Additionally, tethered steel track swing machines are being increasingly utilized in whole-tree harvesting for felling and shovel logging (Sessions et al., 2017; Visser & Berkett, 2015) yet lack comparison to alternative steep slope logging methods. There have been developments in theoretical stability and machine to soil relationships (Sessions et al., 2017;

Belart et al., 2018) of steel tracked tethered machinery, as well as comparisons to untethered operations (Chase et al., 2019), but no comparison of multiple whole tree tethered logging methods.

Methods

Study Area

This study took place on the Greenhorn Timber Sale administered by the United States Forest Service (USFS) on the St. Joseph National Forest, managed by the Nez Perce Clearwater National Forests. Our study area was chosen due to its ability to facilitate adjacent harvest corridors under similar slope, soil, timber, and aspect conditions. Coordinates for the Greenhorn Timber Sale study area in which our observed corridors are located 46.99 N, 116.59 W. Elevation at the site ranges from approximately 3000 - 3500 feet, with an average temperature of 43 degrees Fahrenheit and an average rainfall 40 inches.

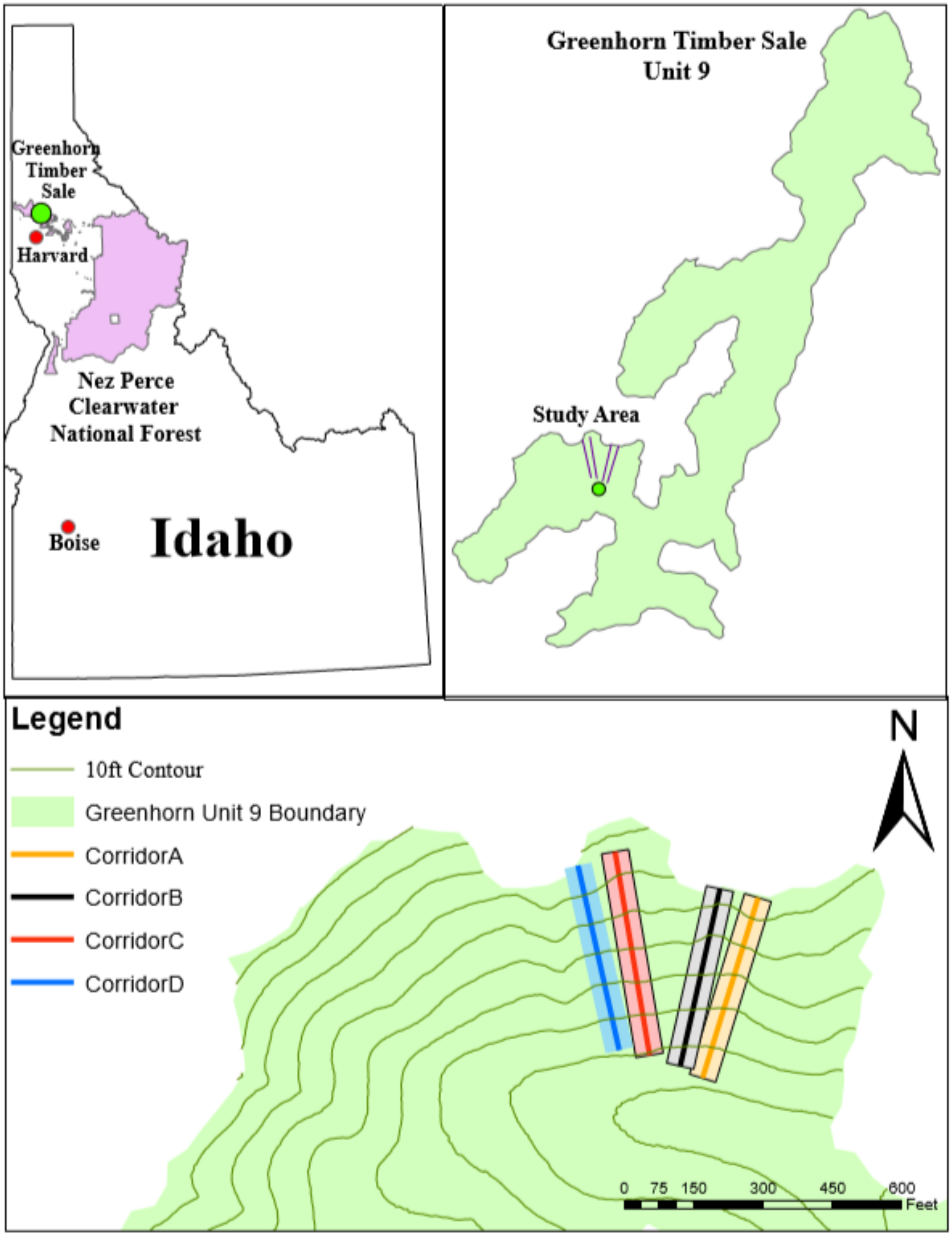


Figure 1: Study site within the Nez Perce-Clearwater National Forest near Harvard, Idaho.

Site Soils

Soils on the site are of the Andisols order, classified as a Flewsie-Bouldercreek Complex (Wilkenshaw et al., 2021) Soils in this region are characterized by a prominent Mt. Mazama ash cap that comprises approximately 30cm of the upper soil horizons. The soil profile from 0 to 50 cm in depth appeared to be fairly homogenous, characterized by fine textured soils and little to no presence of rock or gravel material. These soils are well drained with parent material derived from volcanic ash in the upper horizons and quartzite and gneiss in the lower horizons. Due to their ash over loam composition and skeletal nature, they are fairly susceptible to common soil impacts such as compaction, displacement, and erosion if severely disturbed (Wilkenshaw et al., 2021).

Forest Composition

The silvicultural prescription of this stewardship timber sale was a regeneration harvest with select leave trees to facilitate conditions favorable to restoring white pine, and other early seral tree species. Furthermore, the harvest operation aimed to balance successional stages on the landscape and promote more resilient forest conditions for future forest development.

Inventory data was provided by the Nez Perce-Clearwater USFS staff (Larson & Craig, 2021). The data consisted of 15 variable radius plots dispersed across the unit of the sale that the research area is located in. A variable radius plot design was utilized and measured at a forty basal-area-factor (40 BAF). Only one plot fell within the corridor study area, but others nearby were of similar timber type. To expand the inventory population, 3 additional plots were selected based upon similar aspect and similar tree canopy qualities observed from aerial photos. These plots lent themselves to improve our inventory calculations and data resolution apart from the overall timber sale averages comprised of all 15 plots of multiple conifer stand types.

Stocking of merchantable timber to be harvested included Douglas-fir (*Pseudotsuga menziesii)*, Western Red Cedar (*Thuja plicata*), Grand Fir (*Abies grandis*), Western Larch (*Larix cccidentalis*), Ponderosa Pine (*Pinus ponderosa*), and Western Hemlock (*Tsuga heterophylla*) (Figure 2). An average DBH was observed of 14.8 inches, with an average total tree height of 78.2 feet (Table 2). The site was mostly dominated by Western Red Cedar, followed by Grand Fir, and Douglas-fir, with other species found in much lower amounts (Figure 2). Dominant overstory trees averaged heights of approximately 90-110 feet in height, followed by developing mid-story structure and dispersed understory structure.

Table 1 Inventory Data: Four 40-BAF variable radius plots used for inventory. (GF: Grand Fir, H: Western Hemlock, C: Western Red Cedar, L: Western Larch, DF: Douglas-fir, PP: Ponderosa Pine).

Plot ID	Species	DBH (in)	Tree height (ft)
8	DF	15.6	68
8	DF	18.4	83
8	PP	19.6	106
8	DF	20.5	113
8	PP	20.8	110
9	C	12.5	56
9	C	13.3	67
9	C	14.4	70
9	H	16.9	90
12	GF	8.8	40
12	GF	12.7	62
12	H	12.8	55
12	L	14.1	91
12	C	18.9	71
13	C	8.5	43
13	C	10.4	62
13	C	10.9	74
13	C	12.8	78
13	C	13.6	71
13	DF	14.4	80
13	C	14.6	80
13	GF	15.2	99
13	GF	16.5	91
13	GF	19	116
Average		14.8	78.2

Table 2: Average forest stand attributes in study area.

DBH (in)	Tree Height (ft)	Stand Density (TPA)	Volume per Tree (ft3)	Volume per Acre (ft3)
14.8	78.2	240	46.8	11,232

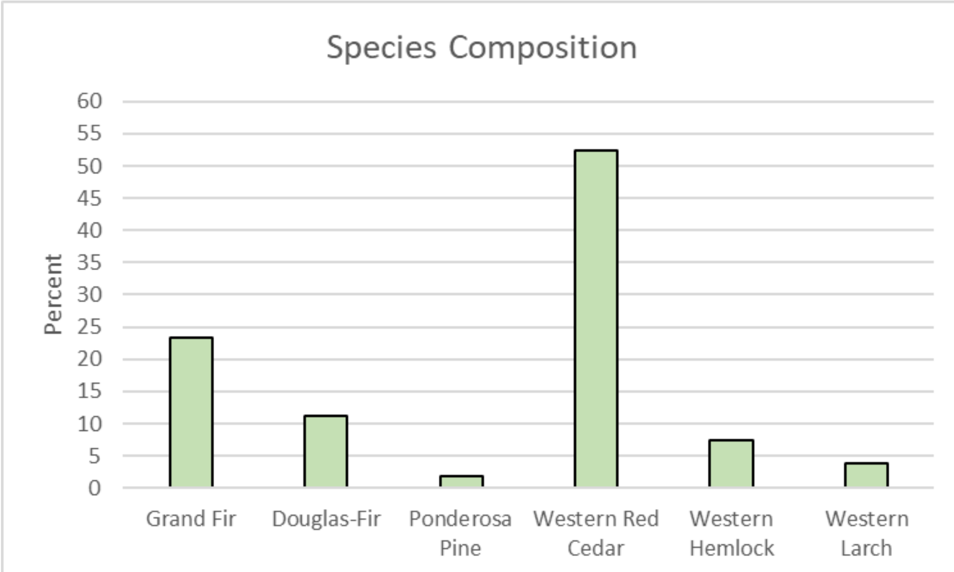


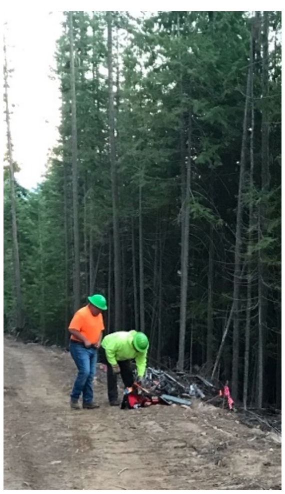
Figure 2: Study Site Species Composition

Harvest Systems

Systems Utilized

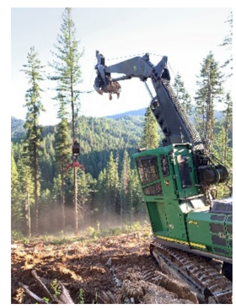
Steep slope felling operations were completed either by the traditional method of motor-manual hand falling, or by the use of a tethered felling system (Table 3). The traditional motor-manual method was conducted through the use of two timber fallers. These fallers fell trees directly downhill in a tree length fashion using professional grade Husqvarna chainsaws in the 70cc size class. Alternatively, the tethered felling system represented the developing method of felling through a tethered feller-buncher being used in tandem with a base machine at the top of the slope. This system utilizes two pieces of historically non-steep slope equipment in conjunction with modifications to allow steep slope operation by anchoring the feller-buncher working on the slope to a stationary excavator higher up on the slope via cable. In this case a TimberPro TL 765 was utilized as the feller buncher, tethered to a CAT 330 excavator with an integrated tethering system from Summit Attachments.

Table 3 Timber Felling Methods

Motor-manual Hand Falling (Corridor C)	**Tethered Felling System** (Corridor A, B, D)
2 Timber Fallers 	TimberPro TL765 (84,800 lbs) 
2 70cc Chainsaws 	CAT 330 with Summit Tether Package (68,100 lbs) 

Four different extraction methods (Table 4) were used for skidding, shoveling, and yarding trees out of the harvest unit area to a landing at the top of the slope. Tethered skidding utilized a tethered John Deere 948L-II grapple skidder for uphill tree extraction. Tethered shovel logging utilized a John Deere 3756G swing machine for uphill extraction. The same John Deere 3756G swing machine was utilized for the cable logging operations as a yoder with one corridor utilizing a manual gravity fed carriage with chokers, while the other utilized a Summit Attachments grapple carriage. Lastly, a Caterpillar 330 excavator was used as the tethering base machine with winch, radio, and boom modifications from Summit Attachments.

Table 4: Timber Extraction Systems

Tethered Grapple Skidding (Corridor A)	**Tethered Shovel Logging** (Corridor B)	**Traditional Cable Logging** (Corridor C)	**Advanced Cable Logging** (Corridor D)
John Deere 948L-II (49,570 lbs) 	John Deere 3756G (107,200 lbs) 	John Deere 3756G Gravity Carriage & Chokers 	John Deere 3756G Summit SG80 Grapple Carriage 
CAT 330 (68,100 lbs) 	CAT 330 (68,100 lbs) 		CAT 330 (68,100 lbs) 

Operators

All machine operators involved in the study were professionals with 15+ years of experience in the logging industry. The same operator was utilized for the tethered TimberPro TL765 feller-buncher across corridors utilizing the tethered cutting method throughout the study. Similarly, another highly experienced operator was utilized for the John Deere 3756G swing machine in the tethered shovel logging operation, as well as in the cable logging yoder configuration. The tethered John Deere 948L-II grapple skidder had another separate and experienced operator. The skidder operator also manually operated the CAT 330 base machine with modifications from Summit Attachments during the tethered shovel logging operation. Although this function is typically automated, it occurred due to the lack of automatic tether synchronization radios on the John Deere 3756G. The feller-buncher operator had the most experience operating on tether with the TimberPro TL765 as it is largely used by the contractor for felling cable logging units as well. The crew had experience with tethering the John Deere 948L-II grapple skidder commonly, followed by slightly less experience tethering the John Deere 3756G swing machine for shovel logging.

Data Collection

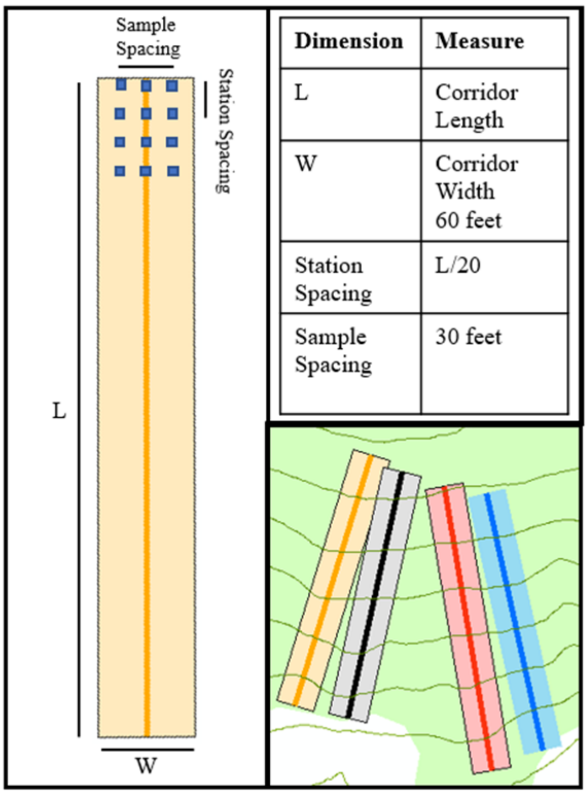
Study Design

This study contained four harvest corridors and harvest method combinations in adjacent locations, with similar size, aspect, ground condition, and timber in the preharvest condition (Table 5). Each of these harvest corridors were prescribed the same post-harvest condition to be met through a regeneration harvest treatment removing all but selected leave trees. Due to the similarity of conditions, timber, and terrain, these four harvest corridors were chosen for adjacent comparison. Furthermore, each of the harvest corridors have an average slope approaching the current regulatory threshold of 40% slope for ground based harvesting equipment. Approaching this threshold allows for comparison of tethered ground-based harvest methods on slopes that would traditionally facilitate cable logging methods or be on the edge of operability for ground-based methods. Corridor C and Corridor D required a slightly different orientation in comparison to Corridor A and Corridor B (Figure 1) due to cable logging constraints and the orientation of the slope.

Table 5:Harvest Corridor/Treatment Assignments & Specifications

Corridor	**Felling Method**	**Extraction Method**	**Average Slope %**	**Dimensions**
A	Tethered TimberPro 765C Feller-Buncher	Tethered John Deere 948 LII Grapple Skidder	39	Width: 60 ft Length: 427 ft
B	Tethered TimberPro 765C Feller-Buncher	Tethered John Deere 3756G Shovel	38	Width: 60 ft Length: 421 ft
C	Motor Manual Hand Felling	John Deere 3756G Yoder with gravity carriage	37	Width: 60 ft Length: 512 ft
D	Tethered TimberPro 765C Feller-Buncher	John Deere 3756G Yoder with Summit SG80 Grapple Carriage	39	Width: 60 ft Length: 501 ft

Each of the harvest corridors and their associated harvest system were sampled using a systematic gridded plot layout across each corridor. The intent of this systematic grid approach is to capture the soil disturbance that occurred across the individual harvested corridor. The harvest systems involved have widely different interactions with harvest corridor soils, with some having contact through rubber tires, steel tracks, or limited contact in aerial suspension. Additionally, whole tree felling and extraction patterns varied through our harvest unit further showing the need to characterize soil disturbance across the operable area in contrast to specific locations or machine tracks.



Dimension	Measure
L	Corridor Length
W	Corridor Width 60 feet
Station Spacing	L/20
Sample Spacing	30 feet

Figure 3: Study & Sampling Design

This systematic grid layout contained 20 equally spaced stations along the length of each corridor (Figure 3). This approach provided coverage on the site to support an adequate sample size per corridor, as well as capture operational interactions between harvest systems and the site. Each one of these stations contained 3 sample locations, with one in the center, and the others on the left and right offset by 15 feet from the center location (Figure 3). These sample locations resulted in a station of 3 equally spaced samples across a 30-foot width. These offset distances were chosen due to the approximately 60-foot width of harvest corridors. From an operational standpoint, a corridor width of 60 feet was fitting between cable logging and tethered logging systems on the basis of average boom reach lengths and cable logging corridor capabilities.

Soil Measurements

Soil density measurements were taken in mineral soil with the O-horizon cleared, through the use of bulk density measurements of soil 0-6cm in depth, as well as penetrometer measurements at 10cm increments between 10cm and 50cm in depth. These metrics were chosen as they allow for characterization of the preharvest and postharvest soil profile condition (Miller et al., 2001), even in machine trafficked areas.

Soil moisture can largely impact the behavior of forest soils in their susceptibility to compaction (Lull, 1951). Data collected during this study was not subject to any precipitation events between preharvest sample collection, harvest operations, or postharvest sample collection. Due to this and the similarity of weather across the duration of the study, soil moisture conditions are assumed to be consistent throughout sample collection. The intervals of soil sample collection and harvest operations were as seen in (Table 7). Soil moisture conditions were as follows (Table 6), with Corridor A pre-harvest measurements removed due to instrument error.

Table 6 Gravimetric Moisture Content- Study Corridors

Average Gravimetric Moisture Content		
Corridor	**Pre-Harvest GMC%**	**Post-Harvest GMC%**
A	NA	59.2%
B	46.6%	49.8%
C	51.9%	54.3%
D	56.3%	46.1%

Table 7: Study Sampling and Operations Schedule

Corridor A	**Corridor B**	**Corridor C**	**Corridor D**
Pre-Harvest Sampling July 9th	*Pre-Harvest Sampling July 9th*	*Pre-Harvest Sampling July 8th*	*Pre-Harvest Sampling July 7th*
Felling July 13th	*Felling July 14th*	*Felling July 13th*	*Felling July 14th*
Extraction July 14th	*Extraction July 14th*	*Extraction July 15th*	*Extraction July 16th*
Post-Harvest Sampling July 20th	*Post-Harvest Sampling July 21st/22nd*	*Post-Harvest Sampling July 22nd/23rd*	*Post-Harvest Sampling July 19th*

Sampling Protocol

At each sampling location, all woody debris and organic matter was cleared from the sampling area to provide an approximate 1 square foot area of exposed mineral soil, and then measurements of bulk density and penetrometer resistance were recorded to characterize the soil profile between 0 and 50 cm in depth.

Bulk density measurements were taken using a 164 cm^3 cylindrical soil core 6cm in depth. The core was placed onto the surface of the mineral soil and driven into the ground till flush with the surface soil. Careful extraction of the sample followed through excavation of soil core and lifting as needed. If samples were partial or fell apart on removal from the ground, they were disposed of and resampled. Upon collection in the field, bulk density samples were placed into an individual plastic bag, followed by a second plastic bag, then tied shut to prevent moisture loss or sample contamination.

Penetrometer measurements were taken using a Humboldt Manufacturing digital static cone penetrometer equipped with a 60-degree, 1.5cm^2 area cone. Penetrometer measurements were taken at each sampling location cleared to mineral soil, but adjacent to and away from the immediately disturbed bulk density sample location. Penetrometer values were recorded at 10cm increments between 10cm, and 50cm in depth. In the event of root strikes or obstructions, the penetrometer was removed and reset for another sample in an unsampled area of the location.

Measurements were conducted prior to harvest operations as well as following harvest operations. Sample stations were located through the recording of azimuths and distances from reference points within the harvest unit. These azimuths and distances allowed for the establishment of preharvest plots and measurements, as well as their repeated sampling after harvest operations.

Data Analysis

Sample Processing

Bulk density samples require oven drying and processing following collection in the field. These samples were transported from the field back to a soil drying lab in which they were further dried and processed. This drying process included being baked in an oven with other samples at a temperature of 105 degrees Celsius until completely dry. Samples were checked during the oven drying process every 24-48 hours till moisture loss was concluded and weight change did not exceed one-hundredth of a gram from prior dried weight. Dried sample weights were recorded and then divided by their volume (164 $cm^{3)}$ to obtain bulk density. These bulk density figures then open the potential for observing the differences in soil density between pre-harvest and post-harvest bulk density across all 4 harvest units in the 0-6 cm range of the soil profile.

Statistical Modeling

RStudio was utilized for all statistical modeling included in this study. Initial condition comparisons were implemented with Kruskal-Wallis hypothesis testing of soil preconditions within and between corridors, as well as paired t-tests for within corridor pre-harvest and post-harvest analysis. Following condition comparisons, corridor results were analyzed through multiple linear regression analysis. Later predictions and comparisons were made through the use of multiple linear regression models at a fixed production level between corridors using fixed parameter values.

Data was screened for samples missing matched pairs of pre and post measurements in bulk density and penetrometer resistance, and removed if present. This allowed for the retention of repeated measure data in matched pairs.

Kruskal-Wallis

Initial characterization of the soil conditions allow for an understanding of pre-harvest soil conditions for later characterization of factor affects. In order to compare preharvest soil condition equivalence between corridors, the Kruskal-Wallis test was implemented by depth. The Kruskal-Wallis test was necessary opposed to ANOVA analysis due to the inability to satisfy the assumption of normality with the collected data.

Paired T-tests

In order to observe harvest operation impacts at a finer resolution, Paired T-Tests were carried out between pre- and post-harvest operations for each corridor. These comparisons were made to illustrate results past only the basis of corridor. Bulk density comparisons work to further include position within corridor (Figure 10). Penetrometer resistance utilizes position as well as depth (Figure 11) to further provide insight to the differences estimated between pre- and post-operation soil conditions.

MLR Regression

Multiple linear regression modeling utilized post-harvest soil measurements as the response variable, with parameters of the model as seen in Table 8. Model parameters included the class variable of depth (Depth), the number of extraction cycles (Cycles), and the average at the given depth of the precondition measurement for the associated model (Pre_BD, Pre_Resist).

Table 8: Multiple Linear Regression Models

Model	Response	Parameters
MLR Bulk Density	Post Harvest Bulk Density (Post_BD)	Depth + Cycles + Pre_BD
MLR Penetrometer Resistance	Post Harvest Penetrometer Resistance (Post_Resist)	Depth + Cycles + Pre_Resist

These models work to capture differing effects from harvest system and corridor combinations, while accounting for machine passes through the Cycles variable. Each harvest system exhibits a different number of harvest cycles, and therefore machine passes to extract a given amount of harvest volume, as well as the number of machine passes traversing each sample station. We define a machine cycle as the activity required for a machine or carriage to travel to a log pickup point and return to the landing. These differences in harvest cycles are related to mechanical differences in payload capacity and transportation of each harvest system type. In order to capture cycle frequency, GPS units were installed inside machine cabs and on the grapple carriage to capture extraction cycle data for Corridor A, B, and D (Figure 4). Corridor C utilized a simple gravity-returned carriage without a secure area for GPS, therefore cycles were estimated using manual time study records.

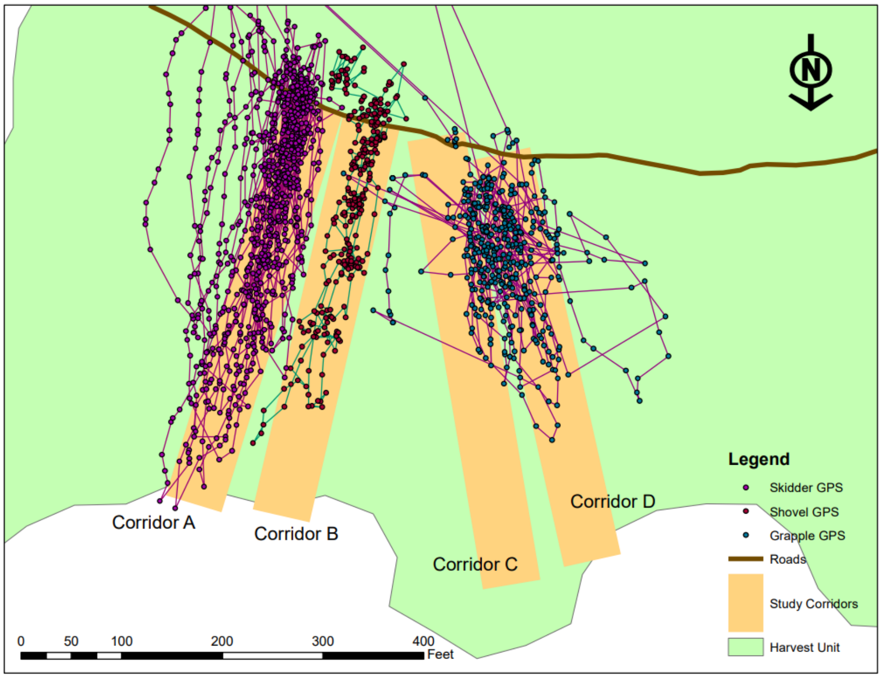


Figure 4: GPS Machine Tracks

MLR Regression Predictions

Multiple linear regression was utilized to model the disturbance characteristics of each individual corridor, and then predict post-harvest soil metrics given a fixed production level. These results work to incorporate machine pass frequency through the amount of extraction cycles needed per given amount of harvest volume. Bulk density regression analysis includes models built for each corridor utilizing the following parameters of harvest cycles (Cycles) to include machine passes, and pre-harvest bulk density (Pre_BD) to include the initial soil condition at the 0-6cm range of the soil profile. Penetrometer resistance regression analysis includes models built for each corridor including parameters of soil measurement depth (Depth), harvest cycles (Cycles) to include machine passes, and pre-harvest penetrometer resistance (Pre_Resist) to include initial soil conditions in the 10-50cm range of the soil profile.

Utilizing the GPS tracks of machine passes in Figure 4, the number of cycles (one cycle is equal to two machine passes) were recorded along the corridor at each sample station. Through collection of additional productivity data, an average piece count was established for each corridor on a per extraction cycle basis. Coupling of cycle frequency, as well as extracted volume per cycle allowed for the further comparison amongst corridors given a fixed amount of volume moved. With each corridor being subject to different harvest system combinations, and their inherent soil interaction differences, comparison given a fixed amount of volume allows insight to the impacts observed.

Due to harvest extraction piece counts ranging widely between corridors (n= 52 – 150) from different operational limitations, model predictions were analyzed at the harvest extraction level of 50 trees, with one tree representing one piece for a comparison between corridors (Table 9). The described models (Table 8) utilize depth as a class variable, pre-harvest soil metrics as an average at the given depth across corridors (Table 10 & 11), and cycles as a calculated input for the harvest extraction level. The number of cycles is determined by the average piece count per cycle, and therefore the number of cycles needed to achieve the fixed level of production (Table 9).

Table 9: Machine Extraction and Cycle Information

Corridor	A	B	C	D
Average Pieces/Cycle	4	18.05	2.65	2.07
Cycles to extract 50 trees	12.5	2.77	18.87	24.07

Table 10: Bulk Density Prediction Variables Values

Corridor	Cycles	Pre-Harvest Bulk Density (g/cm^3)
A	12.50	0.41
B	2.77	0.41
C	18.87	0.41
D	24.07	0.41

Table 11: Penetrometer Resistance Prediction Variable Values

Corridor	Depth (cm)	Cycles	Pre-Harvest Penetrometer Resistance (kg/cm^2)
	10	12.5	4.34
	20	12.5	4.90
	30	12.5	5.76
	40	12.5	6.84
A	50	12.5	11.26
	10	2.77	4.34
	20	2.77	4.90
	30	2.77	5.76
	40	2.77	6.84
B	50	2.77	11.26
	10	18.87	4.34
	20	18.87	4.90
	30	18.87	5.76
	40	18.87	6.84
C	50	18.87	11.26
	10	24.07	4.34
	20	24.07	4.90
	30	24.07	5.76
	40	24.07	6.84
D	50	24.07	11.26

Results

Pre-Harvest Conditions

As shown in Figure 5, observed pre-harvest soil conditions characterized by bulk density exhibit similar measurements across positions within each corridor. With the exception of Corridor A in the left side position having an uneven Inter-Quartile-Range (IQR) distribution, the magnitude and variability of measurements are similar ranging between .352 g/cm^3 and .482 g/cm^3.

Figure 6, 7, 8, and 9 characterize preharvest soil conditions further by increasing depth and multiple positions of left, center, and right, by corridor. As expected through soil densification with depth, soil penetrometer measurement variability and magnitude increase with soil measurement depth. Initial conditions by depth are similar, with observed penetrometer resistance measurements at 10cm in depth

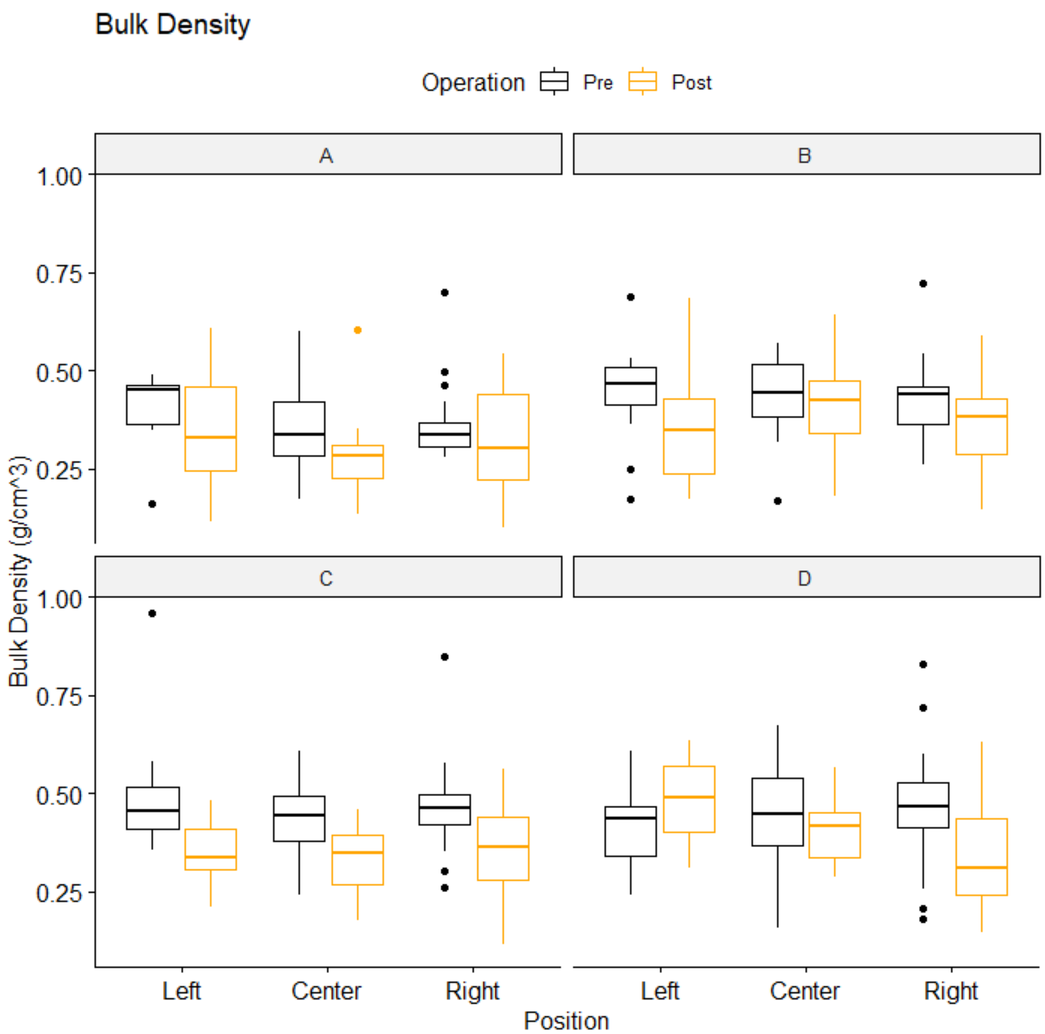


Figure 5: Bulk Density - Observed Data

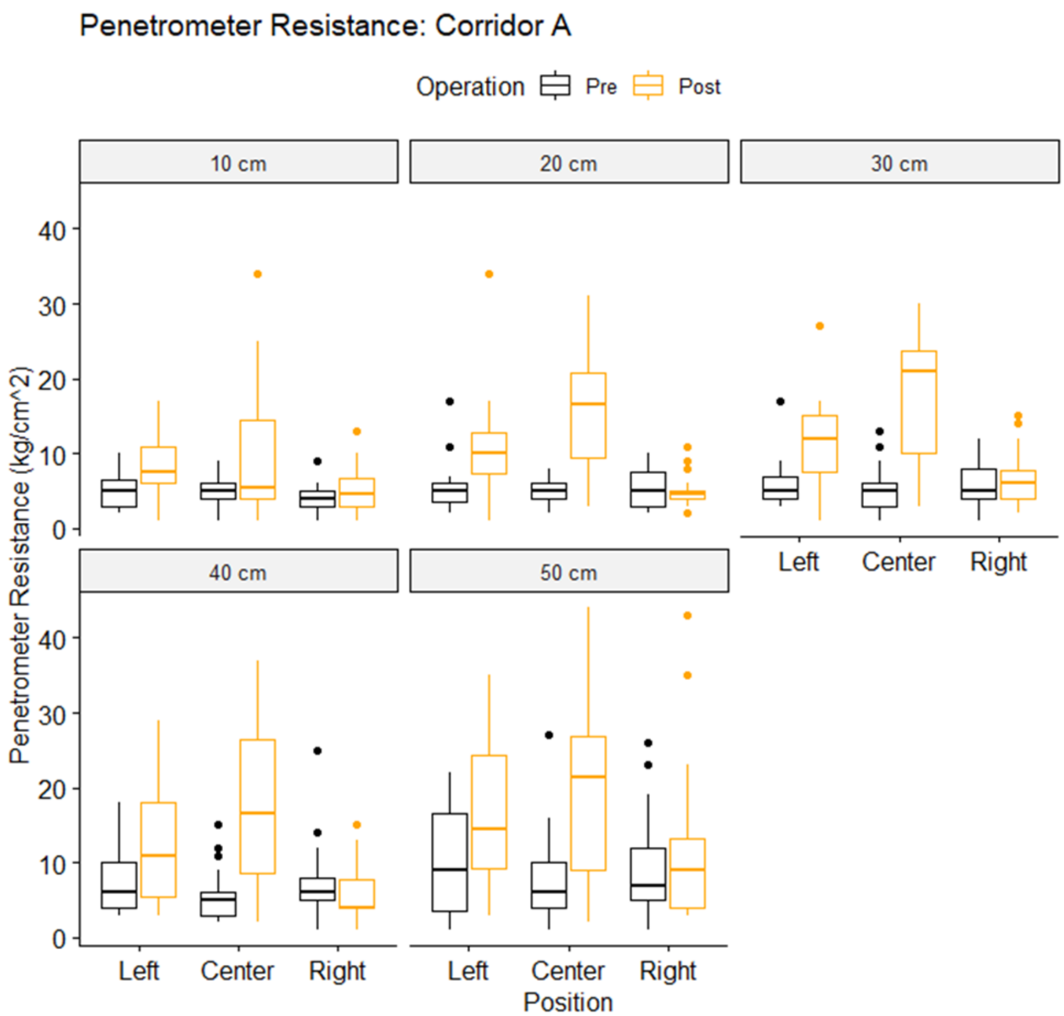


Figure 6:Penetrometer Resistance - Corridor A

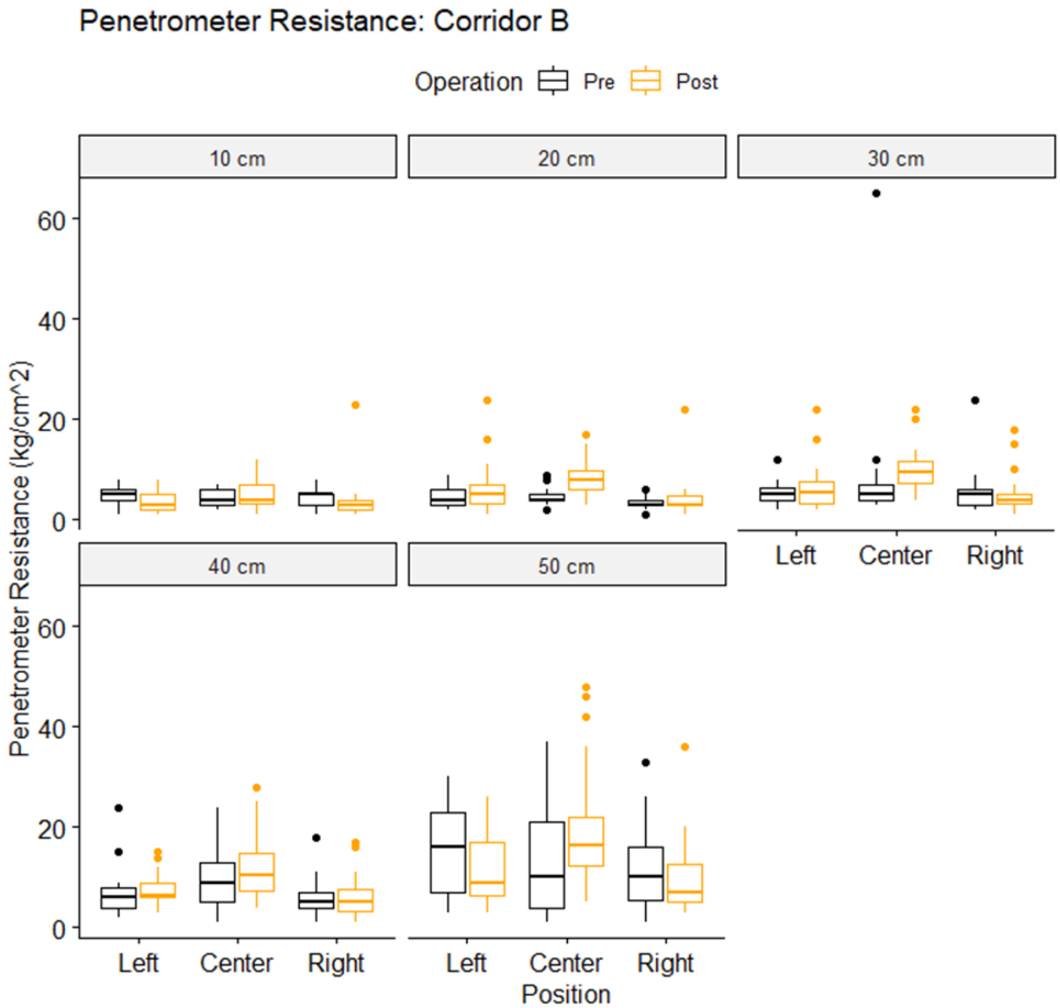


Figure 7: Penetrometer Resistance - Corridor B

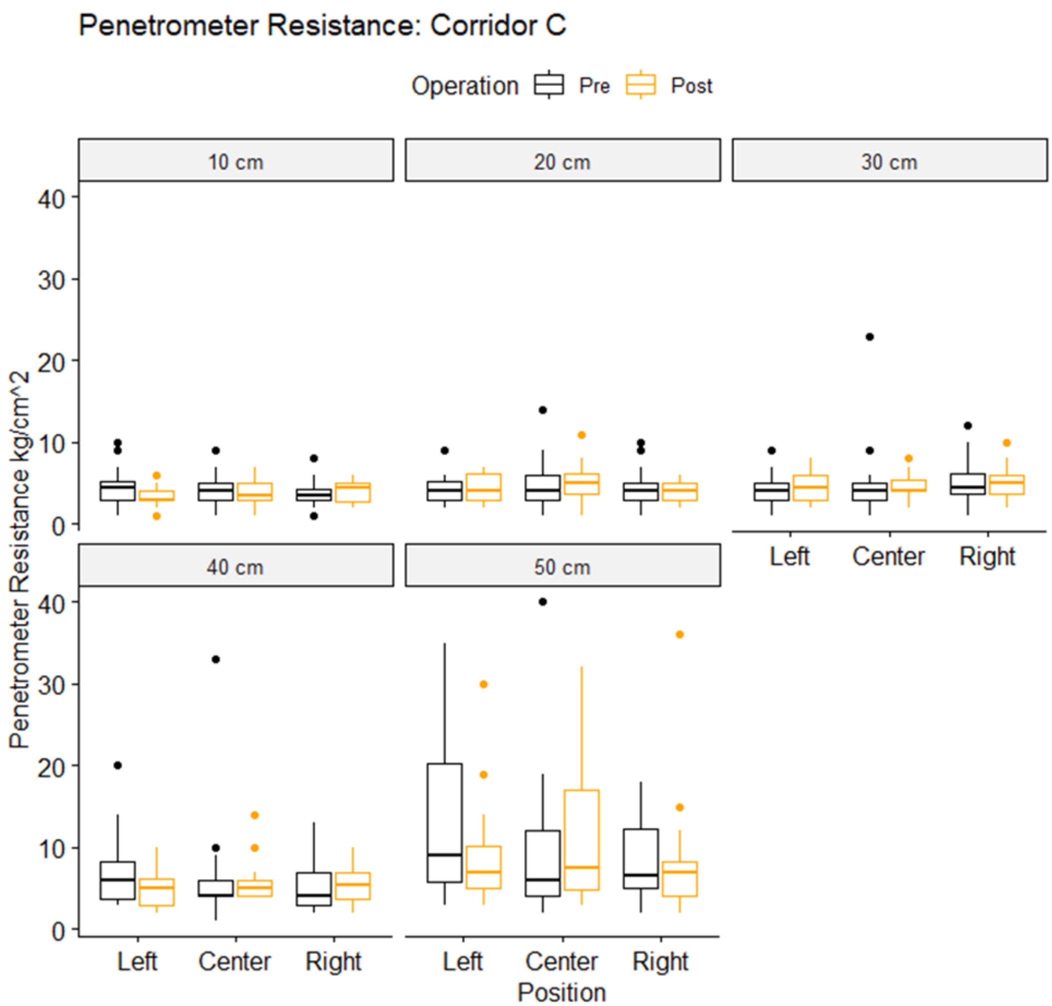


Figure 8: Penetrometer Resistance - Corridor C

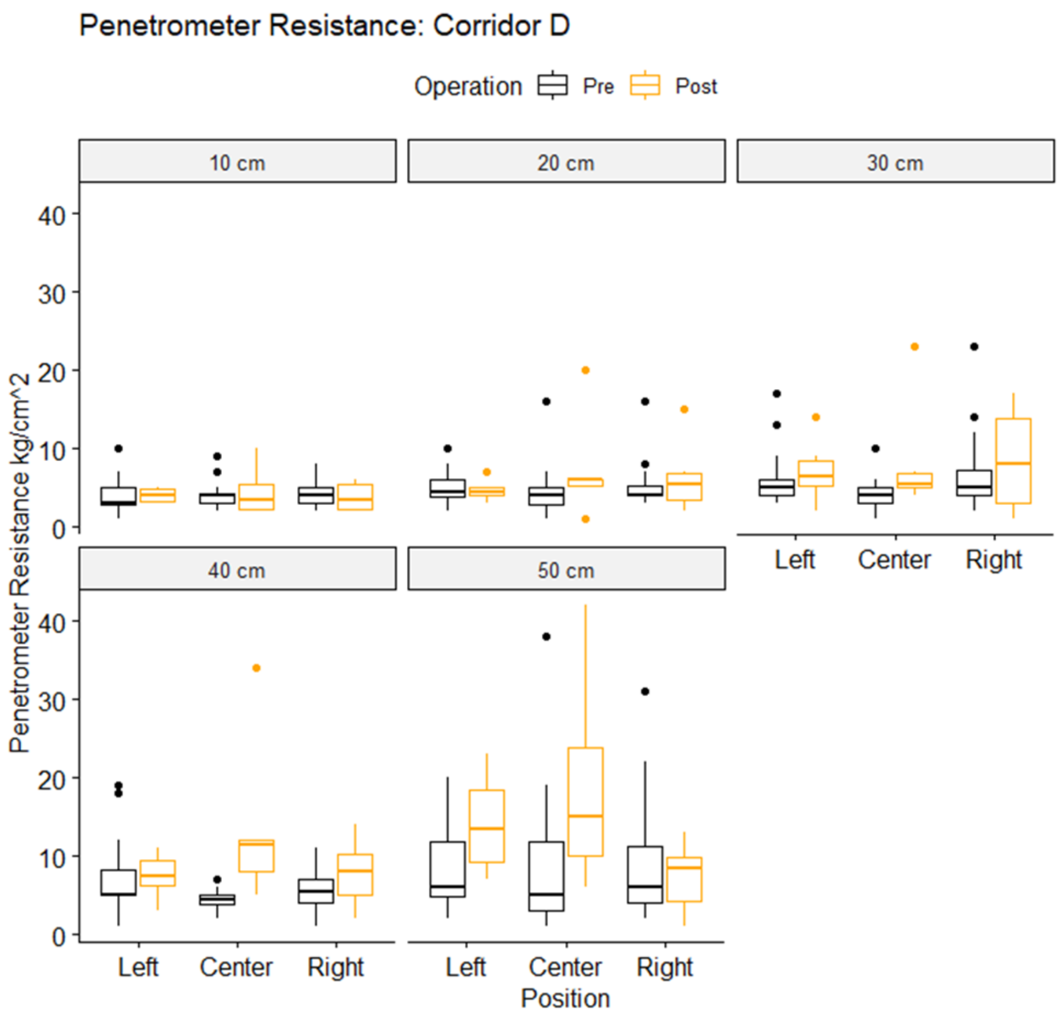


Figure 9: Penetrometer Resistance - Corridor D

Pre-Harvest Equivalence

Comparisons produced by Kruskal-Wallis testing across corridor mean values by depth before treatment, seen in Table 12, show similarities and statistically significant differences in the soil profile.

Table 12: Kruskal-Wallis Test Results Across Treatments

Measurement	Depth (cm)	Chi-Sq	df	P-Value
Bulk Density	0-6	22.154	3	6.06E-05 ***
Penetrometer Resistance	10	7.7065	3	0.05248
	20	4.2066	3	0.24
	30	4.304	3	0.2305
	40	7.2819	3	0.06343
	50	12.973	3	0.004696 **

As seen in Table 12, at the depth of zero to six centimeters represented by bulk density, there is a significant difference present amongst corridors ($p < .001$) The soil profile then exhibits similarity without significant differences throughout the profile from 10 to 40 centimeters in depth, till a significant difference is measured at 50 centimeters in depth ($P=.004696$).

Within Group Pre-Harvest and Post-Harvest Comparisons

In order to observe harvest operation impacts at a finer resolution, Paired T-Tests were carried out between pre- and post-harvest operations for each corridor. These results are seen for bulk density comparisons below in Figure 10, and penetrometer resistance in Figure 11.

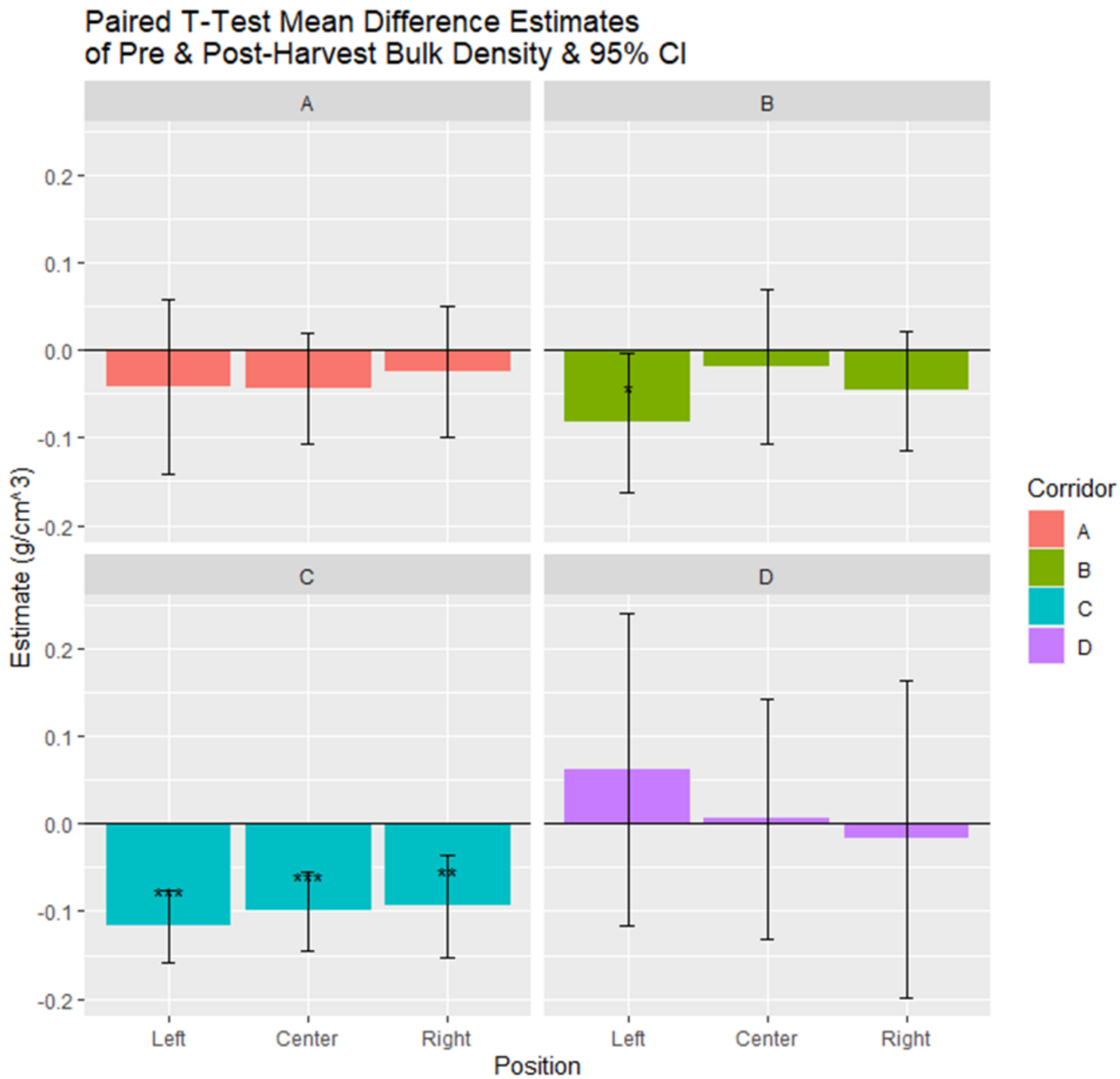


Figure 10: Bulk Density Paired T-test results

Bulk density results were incorporated by position of left, center, and right in the corridor to examine differences in soil disturbance distribution within each harvest corridor. As shown above, Corridor A reveals estimated mean change within the left and center positions more prominently than the right, with values across the corridor signifying a decrease of bulk density, and therefore a decrease in soil compaction. Corridor B exhibits large estimated changes in the left and right positions of the corridor, with a significant change (P=.04) in bulk density noted in the left position, signifying a reduction in soil compaction with all estimates being sub-zero.

Corridor C showcased decreases in bulk density, at left, center, and right respectively. Corridor D followed a unique pattern with increases and decreases at the left and right positions, while illustrating a similar magnitude of estimated change as Corridor C as well. A majority of the comparisons point to estimated decreases of means in bulk density, with the exception of left and center positions in Corridor C and D, showcasing an overall trend of reduction in bulk density values, and a loosening of soil in the 0-6 cm range.

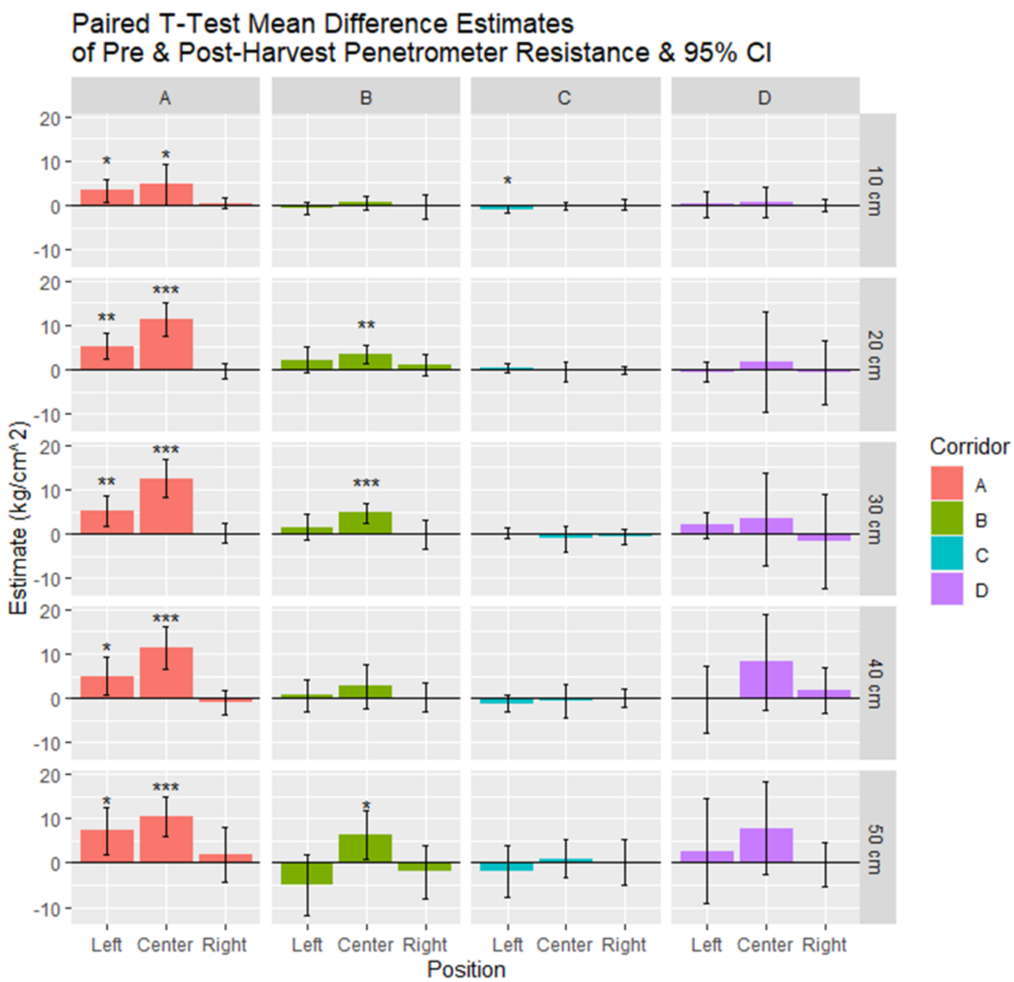


Figure 11: Penetrometer Resistance Paired T-test results

Similar to bulk density results, penetrometer resistance results were incorporated by position of left, center, and right in the corridor to examine differences in soil disturbance distribution within each harvest corridor. Corridor A exhibits a dominant increase trend in the center and left position, with significant changes throughout the soil profile from 10 to 50cm in depth. This trend of significant increase in the left side position is quantified by an estimated difference of 3.28 Kg/cm^2 at 10cm (p-value =.02), 5.33 Kg/cm^2 at 20cm (p-value < .01), 5.28 Kg/cm^2 at 30cm (p-value = .01), 4.94 Kg/cm^2 at 40cm (p-value = .03), and 7.17 Kg/cm^2 at 50cm in depth (p-value = .01). The trend is further seen in the center with increased magnitudes of estimated change with 7.72 Kg/cm^2 at 10cm (p-value=.05), 11.28 Kg/cm^2 at 20cm (p-value < .01), 12.56 Kg/cm^2 at 30cm (p-value < .01), 11.50 Kg/cm^2 at 40cm (p-value < .01), and 10.39 Kg/cm^2 at 50cm in depth (p-value < .01).

Corridor B has a variable pattern with penetrometer resistance increases visible in the center of the corridor, along with scattered left side change. Corridor B is also variable in terms of observation trend consistency by depth. In the upper layers of the soil horizon as measured at 10cm, change is estimated to be minimal as well as at lower layers at 40 cm in depth. Significant difference findings in Corridor B are evident with increasing estimated change found in the center position of the corridor at 20cm, 30cm, and again at 50cm in depth. Each of these significant change depth estimates reflect an increase in penetrometer resistance with values of 3.50 Kg/cm^2 at 20cm (p-value <.01), 4.72 Kg/cm^2 at 30 cm (p-value <. 01), and 6.39 Kg/cm^2 at 50cm in depth (p-value = .02).

Corridor C exhibits minimal estimated change, yet showcases decreasing trends of small magnitude overall. Corridor C is marked by significant decrease at 10cm in the left side position of .94 Kg/cm^2 (p-value = .05). No other depths or positions in Corridor C were found to exhibit significant estimated change.

Corridor D was included in paired t-testing and plotting, although it contains a small sample size. Corridor D exhibits a dominant trend of center position penetrometer resistance increases, that approximately increase in magnitude with increasing depth. Although trends are observed within the paired t-tests of Corridor D, there are no statistically significant changes observed or reported.

	Corridor A	Corridor B	Corridor C	Corridor D
0-6 cm	↓	↓*	↓***	↑
10 cm	↑**	↓	↓	↑
20 cm	↑***	↑**	↓	↑
30 cm	↑***	↑**	↓	↑
40 cm	↑***	↑	↓	↑
50 cm	↑***	↓	↓	↑

Key

↑ : Increased Compaction

↓ : Decreased Compaction

* : P-Value < .05

** : P-Value < .01

***: P-Value < .001

Figure 12: Paired T-test Corridor Soil Profile Compaction Map - Grouped Averages

When samples were grouped by corridor regardless of sample locations, analysis of within corridor comparisons through paired t-tests revealed that a variety of impacts occurred on the harvest site between pre-harvest and post-harvest conditions (Figure 12). Soil densification through compaction is shown within each corridor as the result of paired t-test analysis between pre-harvest and post-harvest conditions by mean value estimated change for each individual corridor. Corridor A exhibited a decrease in bulk density, with significant increases in penetrometer resistance throughout the rest of the corridor. Corridor B exhibited a significant decrease in bulk density with significant increases in penetrometer resistance at 20cm and 30cm. Corridor C exhibited a significant decrease in bulk density with decreases throughout the rest of the soil profile. Corridor D showed increases in compaction, but did not showcase any indication of statistically significant change.

<u>Post-Harvest Comparisons: Multiple Linear Regression</u>

Multiple linear regression was utilized to model the disturbance characteristics of each individual corridor. Table 13 and 14, respectively, showcase model information for regression analysis of bulk density and penetrometer resistance.

Table 13: Bulk Density Multiple Linear Regression Results

		Coefficients	P-value	R-Squared	F	F Significance
	Intercept***	0.3811	<.001			
	Cycles	-0.0009	0.590			
Corridor A	Pre_BD	-0.1507	0.504	0.02	0.46	0.633
	Intercept***	0.4236	<.001			
	Cycles	-0.0067	0.709			
Corridor B	Pre_BD	-0.0842	0.700	0.01	0.24	0.792
	Intercept	0.0581	0.528			
	Cycles	-0.0001	0.900			
Corridor C	Pre_BD**	0.6439	0.002	0.20	5.49	0.007
	Intercept	0.0272	0.895			
	Cycles	0.0103	0.105			
Corridor D	Pre_BD	0.4980	0.173	0.21	1.95	0.177

Bulk density regression models (Table 11) provided a poor explanation of the observed data from Corridor A, B, and D given the F significance values (>0.05). In addition, no parameters from Corridor A,B, or D models gave indication of independent variables being significant. The bulk density model for Corridor C gave a better explanation of the observed data based upon the F significance value (.007), as well as the significant parameter of pre-harvest bulk density (p-value = .002).

Penetrometer resistance regression analysis below incorporates additional layers of depth past bulk density, showcasing results from 10 to 50cm in depth (Table 12).

Table 14: Penetrometer Resistance Multiple Linear Regression Results

		Coefficients	P-value	R-Squared	F	F Significance
	Intercept	1.1200	0.415			
	Depth***	0.1559	<.001			
	Cycles***	0.2585	<.001			
Corridor A	Pre_Resist*	0.2541	0.032	0.22	24.42	<.001
	Intercept	0.3814	0.747			
	Depth***	0.1837	<.001			
	Cycles	0.6432	0.097			
Corridor B	Pre_Resist*	0.1591	0.029	0.21	23.59	<.001
	Intercept	0.9192	0.200			
	Depth***	0.0965	<.001			
	Cycles	0.0153	0.415			
Corridor C	Pre_Resist***	0.2572	<.001	0.25	25.63	<.001
	Intercept	-3.2525	0.220			
	Depth***	0.1834	<.001			
	Cycles	0.2305	0.051			
Corridor D	Pre_Resist*	0.2690	0.028	0.27	10.59	<.001

Corridor A,B,C, and D penetrometer resistance models provide explanation of the observed data with F significance values all lesser than .001 (Table 14). The model for Corridor A indicates significance of all variables in the model of Depth (p-value < .001), Cycles (p-value < . 001), and Pre_Resist (p-value = .032). The models for Corridor B, C, and D indicate significance in variables of Depth (p-values <.001), and Pre_Resist (p-values = .029, <.001, .028).

Multiple Linear Regression Predictions

Predictions were calculated at a fixed production point of 50 trees extracted. In order to make this production comparison between Corridor A, B, C and D, individual corridor models included the values in Figure 13 for bulk density predictions, and Figure 14 for penetrometer resistance predictions.

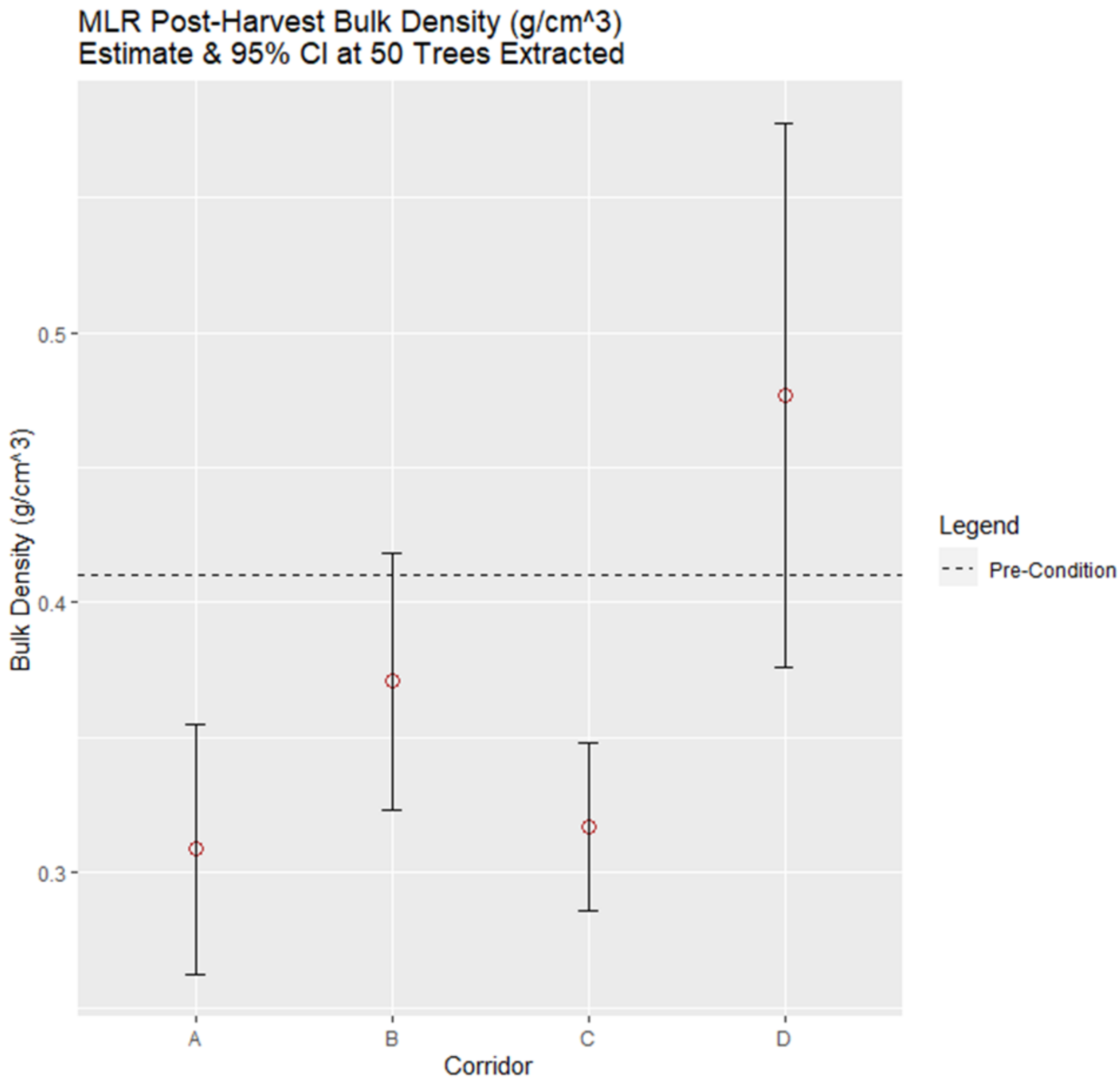


Figure 13: Bulk Density - MLR Estimates & 95% CI for 50 Trees Extracted

Bulk density regression outcomes as seen in Figure 13 make predictions of a Corridor A value of .34 g/cm^3, Corridor B value of .37 g/cm^3, Corridor C value of .32 g/cm^3, and Corridor D value of .48 g/cm^3. These results further support the trends previously found in paired t-testing with Corridor A loosening soil, while presenting new trends for Corridor B and C in comparison to their expected outcomes based off of paired t-tests. Corridor D was included in modeling due to interest in comparative trends, yet contained too small of a sample size to uphold statistical conclusions and comparisons. Predictions for Corridor A, B, and C show a relative decrease in bulk density from the precondition line within Figure 13. Corridor A shows the greatest deviation from the observed precondition level, followed by Corridor C, and then Corridor B.

The results below (Figure 14) continue to show model post-harvest penetrometer resistance predictions by depth.

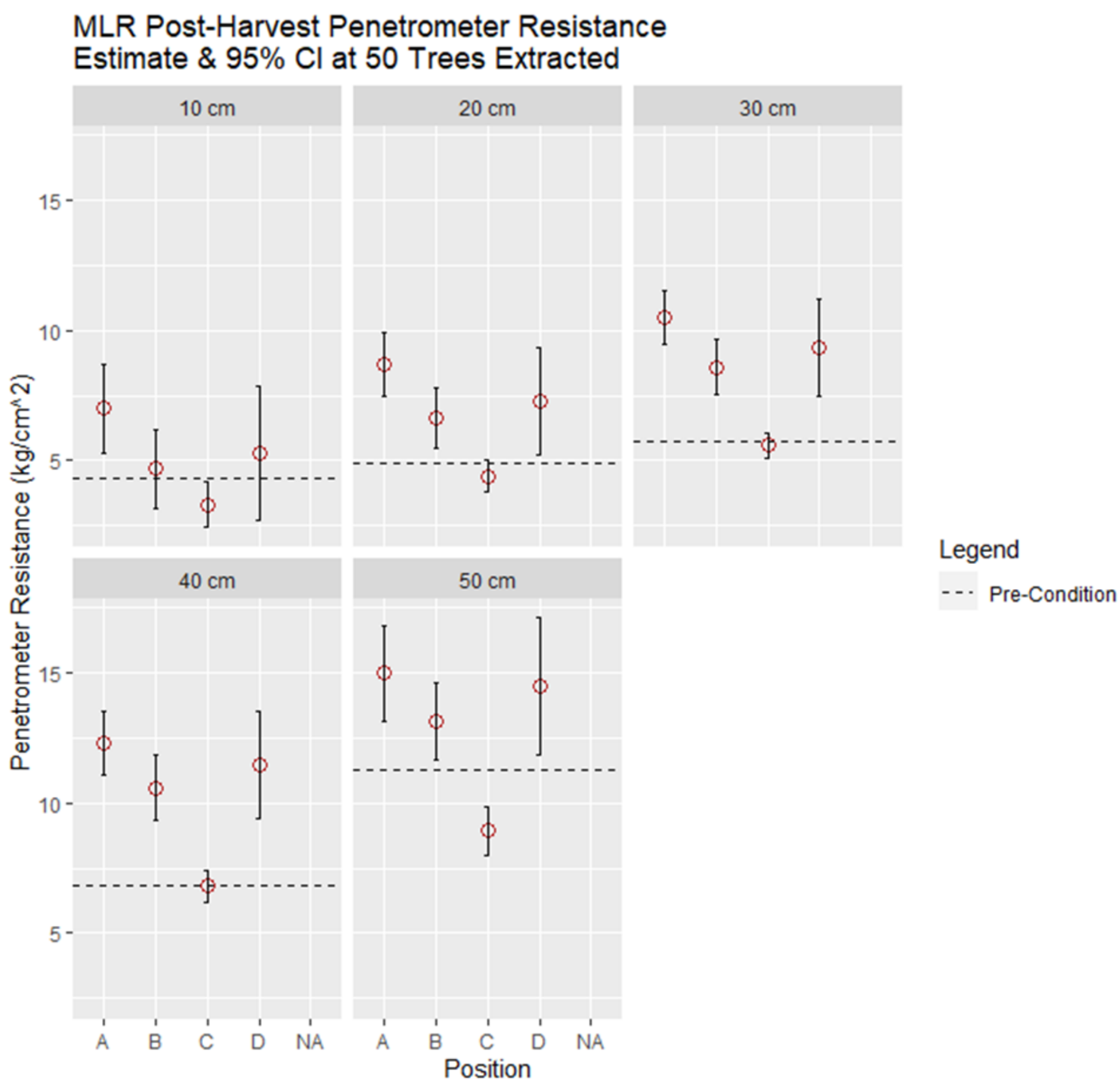


Figure 14: Penetrometer Resistance Prediction - MLR Estimates & 95% CI at 50 Trees Extracted

Predictions for each Corridor and depth from 10-50 cm can be seen in Figure 14. Corridor A exhibits similar trends as seen in paired t-tests previously, showing a larger predicted post-harvest value across depths compared to other corridors. Corridor B follows Corridor A with values lesser than Corridor A, but still comparatively greater than predictions for Corridor C. Corridor D was included in modeling across corridors and depths due to interest in comparative trends, yet contained too small of a sample size to uphold statistical conclusions and comparisons.

Prediction results at 10cm in depth showcased Corridor A (7.01 Kg/cm^2) as the highest predicted post-harvest penetrometer resistance followed by Corridor B (4.69 Kg/cm^2), and Corridor C (3.29 Kg/cm^2). Prediction results at 20cm maintain this trend with Corridor A (8.71 Kg/cm^2) being the highest, followed by Corridor B (6.62 Kg/cm^2), and Corridor C (4.40 Kg/cm^2). Prediction results at 30 cm in depth continue this trend, and also show a beginning separation between Corridor A (10.49 Kg/cm^2) and B (8.59 Kg/cm^2) apart from Corridor C (5.58 Kg/cm^2). This increasing gap continues at 40 cm with Corridor A (12.32 Kg/cm^2) and B (10.60 Kg/cm^2) being further away from Corridor C (11.47 Kg/cm^2). Predictions at 50 cm in depth maintain the previous trends with Corridor A (15.01 Kg/cm^2) having the highest predicted penetrometer resistance value followed by Corridor B (13.14 Kg/cm^2), with an increasingly prominent gap between Corridor C (8.93 Kg/cm^2).

In comparison to pre-harvest conditions, only Corridor C predictions show a decrease in penetrometer resistance throughout depths, while the other Corridor predictions were all above the pre-harvest conditions (Figure 14). Corridor D values showcase wide confidence intervals surrounding predictions, with 10cm predictions near the original precondition, while all deeper depth intervals show more prominent increases from the precondition.

Figures

Table 15: Observed Bulk Density Values

		Pre-Harvest		Post-Harvest	
Corridor	**Position**	**n**	**Mean ± SD**	**n**	**Mean ± SD**
	Center	21	0.352 ± 0.11	18	0.287 ± 0.10
	Left	13	0.409 ± 0.09	18	0.348 ± 0.15
A	Right	19	0.365 ± 0.10	18	0.322 ± 0.13
	Center	21	0.441 ± 0.10	18	0.406 ± 0.12
	Left	19	0.449 ± 0.11	18	0.353 ± 0.14
B	Right	19	0.428 ± 0.10	18	0.365 ± 0.12
	Center	21	0.432 ± 0.09	16	0.334 ± 0.08
	Left	20	0.482 ± 0.13	16	0.346 ± 0.08
C	Right	20	0.461 ± 0.12	16	0.353 ± 0.13
	Center	20	0.438 ± 0.12	6	0.41 ± 0.10
	Left	20	0.417 ± 0.10	6	0.483 ± 0.12
D	Right	20	0.466 ± 0.15	6	0.348 ± 0.18

Table 16: Observed Penetrometer Resistance Values

		Pre-Harvest						Post-Harvest					
		Left		Center		Right		Left		Center		Right	
Corridor	**Depth (cm)**	**n**	**Mean ± SD**	**n**	**Mean ± SD**	**n**	**Mean ± SD**	**n**	**Mean ± SD**	**n**	**Mean ± SD**	**n**	**Mean ± SD**
	10	19	5.05 ± 2.37	21	4.81 ± 2.04	19	4.05 ± 1.87	18	8.39 ± 4.83	18	9.39 ± 9.25	18	5.06 ± 3.28
	20	19	5.63 ± 3.52	21	4.76 ± 1.73	19	5.21 ± 2.72	18	11.1 ± 7.08	18	16.2 ± 8.4	18	5.11 ± 2.19
	30	19	6.21 ± 4.2	21	5.24 ± 2.93	19	6.26 ± 3.05	18	11.6 ± 5.99	18	17.9 ± 8.84	18	6.5 ± 3.82
	40	19	7.47 ± 4.23	21	5.71 ± 3.39	19	7.53 ± 5.21	18	12.5 ± 7.42	18	17.2 ± 10.9	18	6.28 ± 3.85
A	50	19	10.1 ± 7.22	21	7.76 ± 6.02	19	9.95 ± 7.89	18	16.8 ± 10.1	18	19.1 ± 11.9	18	12.1 ± 11.2
	10	19	4.58 ± 1.87	21	4.57 ± 1.5	19	4.47 ± 1.65	18	3.67 ± 2.28	18	5.22 ± 2.94	18	4.11 ± 4.89
	20	19	4.68 ± 2.08	21	4.52 ± 1.66	19	3.53 ± 1.35	18	6.61 ± 5.72	18	8.22 ± 3.89	18	4.56 ± 4.55
	30	19	5.37 ± 2.29	21	8.43 ± 13.1	19	5.68 ± 4.76	18	6.83 ± 5.12	18	10.3 ± 4.76	18	5.61 ± 4.43
	40	19	7.32 ± 5.4	21	9.71 ± 6.62	19	6.11 ± 3.81	18	7.94 ± 3.52	18	12.1 ± 6.63	18	6.44 ± 4.58
B	50	19	16.1 ± 9.21	21	12.9 ± 10	19	12.1 ± 8.43	18	11.6 ± 7.26	18	20.5 ± 13.5	18	10.4 ± 8.21
	10	20	4.6 ± 2.35	21	4.05 ± 2.01	20	3.75 ± 1.55	16	3.31 ± 1.3	16	3.81 ± 1.52	16	3.88 ± 1.41
	20	20	4.35 ± 1.69	21	4.95 ± 3.02	20	4.3 ± 2.25	16	4.62 ± 1.93	16	5.19 ± 2.46	16	4.06 ± 1.18
	30	20	4.35 ± 1.79	21	5.19 ± 4.57	20	5.25 ± 2.61	16	4.5 ± 1.93	16	4.75 ± 1.65	16	5.19 ± 2.1
	40	20	7 ± 4.52	21	6.1 ± 6.52	20	5 ± 2.9	16	5.06 ± 2.17	16	5.81 ± 2.69	16	5.5 ± 2.37
C	50	20	12.2 ± 8.74	21	9.38 ± 8.7	20	8.3 ± 4.71	16	9.44 ± 6.78	16	11.8 ± 8.99	16	8.31 ± 8.17
	10	20	3.85 ± 2.18	20	4.05 ± 1.82	20	3.9 ± 1.48	6	4 ± 0.894	6	4.5 ± 3.08	6	3.83 ± 1.83
	20	20	4.9 ± 2.13	20	4.3 ± 3.16	20	5.2 ± 2.91	6	4.67 ± 1.37	6	7.33 ± 6.5	6	6.33 ± 4.63
	30	20	5.95 ± 3.5	20	4.4 ± 2.28	20	6.6 ± 4.92	6	7.17 ± 4.07	6	8.33 ± 7.26	6	8.5 ± 6.92
	40	20	7.1 ± 4.59	20	4.25 ± 1.45	20	5.6 ± 2.23	6	7.5 ± 2.88	6	13.5 ± 10.4	6	7.83 ± 4.4
D	50	20	8.8 ± 5.96	20	8.45 ± 8.98	20	8.9 ± 7.4	6	14.2 ± 6.37	6	18.8 ± 13.3	6	7.33 ± 4.5

Table 17: Paired T-test Penetrometer Resistance Results

		Left						Center						Right					
Corridor	**Depth**	**Estimate**	**T-stat**	**P-Value**	**df**	**Lower 95% CI**	**Upper 95% CI**	**Estimate**	**T-stat**	**P-Value**	**df**	**Lower 95% CI**	**Upper 95% CI**	**Estimate**	**T-stat**	**P-Value**	**df**	**Lower 95% CI**	**Upper 95% CI**
A	**10**	3.28	2.64	0.02	17.00	0.66	5.90	4.72	2.15	0.05	17.00	0.10	9.35	0.39	0.69	0.50	17.00	-0.79	1.57
	20	5.33	3.79	0.00	17.00	2.36	8.30	11.28	6.38	0.00	17.00	7.55	15.01	-0.22	-0.27	0.79	17.00	-1.99	1.55
	30	5.28	3.17	0.01	17.00	1.77	8.79	12.56	6.35	0.00	17.00	8.39	16.72	0.11	0.11	0.92	17.00	-2.11	2.33
	40	4.94	2.42	0.03	17.00	0.64	9.25	11.50	5.09	0.00	17.00	6.73	16.27	-1.00	-0.76	0.46	17.00	-3.77	1.77
	50	7.17	2.79	0.01	17.00	1.76	12.58	10.39	4.97	0.00	17.00	5.98	14.80	1.94	0.66	0.52	17.00	-4.26	8.15
B	**10**	-0.72	-1.05	0.31	17.00	-2.18	0.73	0.56	0.71	0.49	17.00	-1.09	2.20	-0.39	-0.31	0.76	17.00	-3.00	2.23
	20	2.17	1.62	0.12	17.00	-0.66	5.00	3.50	3.50	0.00	17.00	1.39	5.61	1.00	0.85	0.41	17.00	-1.48	3.48
	30	1.50	1.07	0.30	17.00	-1.45	4.45	4.72	4.33	0.00	17.00	2.42	7.02	-0.22	-0.14	0.89	17.00	-3.49	3.04
	40	0.67	0.38	0.71	17.00	-3.01	4.34	2.67	1.11	0.28	17.00	-2.39	7.73	0.22	0.14	0.89	17.00	-3.05	3.50
	50	-4.89	-1.51	0.15	17.00	-11.73	1.95	6.39	2.46	0.02	17.00	0.91	11.87	-2.06	-0.72	0.48	17.00	-8.07	3.95
C	**10**	-0.94	-2.17	0.05	15.00	-1.86	-0.02	-0.19	-0.42	0.68	15.00	-1.15	0.77	0.06	0.12	0.91	15.00	-1.08	1.20
	20	0.31	0.65	0.53	15.00	-0.71	1.34	-0.44	-0.44	0.67	15.00	-2.56	1.68	-0.19	-0.46	0.65	15.00	-1.06	0.69
	30	0.19	0.34	0.74	15.00	-1.00	1.37	-1.00	-0.74	0.47	15.00	-3.90	1.90	-0.50	-0.62	0.55	15.00	-2.23	1.23
	40	-1.13	-1.32	0.21	15.00	-2.94	0.69	-0.63	-0.35	0.73	15.00	-4.42	3.17	0.06	0.06	0.95	15.00	-2.12	2.24
	50	-2.00	-0.74	0.47	15.00	-7.79	3.79	0.88	0.44	0.66	15.00	-3.34	5.09	0.00	0.00	1.00	15.00	-5.11	5.11
D	**10**	0.17	0.15	0.89	5.00	-2.68	3.02	0.67	0.50	0.64	5.00	-2.76	4.09	0.00	0.00	1.00	5.00	-1.48	1.48
	20	-0.50	-0.56	0.60	5.00	-2.78	1.78	1.67	0.38	0.72	5.00	-9.65	12.98	-0.67	-0.24	0.82	5.00	-7.84	6.50
	30	2.00	1.73	0.14	5.00	-0.97	4.97	3.33	0.82	0.45	5.00	-7.09	13.76	-1.67	-0.40	0.70	5.00	-12.34	9.01
	40	-0.33	-0.11	0.91	5.00	-7.83	7.17	8.17	1.93	0.11	5.00	-2.71	19.04	1.83	0.91	0.41	5.00	-3.37	7.03
	50	2.67	0.58	0.59	5.00	-9.24	14.57	7.67	1.89	0.12	5.00	-2.78	18.11	-0.33	-0.17	0.87	5.00	-5.33	4.66

Table 18: Paired T-test Bulk Density Results

	Left						Center						Right					
Corridor	**Estimate**	**T-stat**	**P-Value**	**df**	**Lower 95% CI**	**Upper 95% CI**	**Estimate**	**T-stat**	**P-Value**	**df**	**Lower 95% CI**	**Upper 95% CI**	**Estimate**	**T-stat**	**P-Value**	**df**	**Lower 95% CI**	**Upper 95% CI**
A	-0.04	-0.89	0.38	16	-0.14	0.06	-0.04	-1.48	0.16	17	-0.11	0.02	-0.02	-0.71	0.49	17	-0.10	0.05
B	-0.08	-2.20	0.04	17	-0.16	0.00	-0.02	-0.45	0.66	17	-0.11	0.07	-0.05	-1.44	0.17	17	-0.11	0.02
C	-0.12	-6.03	<.001	15	-0.16	-0.08	-0.10	-4.79	<.001	15	-0.14	-0.06	-0.09	-3.45	<.001	15	-0.15	-0.04
D	0.06	0.90	0.41	5	-0.12	0.24	0.01	0.10	0.92	5	-0.13	0.14	-0.02	-0.25	0.81	5	-0.20	0.16

Discussion

The results found in this study are largely site dependent and must be viewed through an appropriate scope for reasonable application and interpretation. Compaction metrics and their associated results can vary widely between sites based not only on their soil composition, but also including and not limited to soil moisture, machine passes, operator experience, and machine configuration (Coder, 2016; Green, 2019; Sessions et al., 2017; McNabb et al., 2001). The design of this study through side by side harvest corridors and harvest systems allowed for minimization of condition differences for soil and operators, opposed to comparing harvest corridors and harvest systems operating in distant and different locations. Although there are some limitations, the study design helps facilitate comparison of the soil effects contributed to by harvest corridor and harvest system applied.

Limitations of the study were known through initial planning due to harvest operation requirements, as well as becoming further evident through operational progress and further data analysis. Initial interest was present in observing the impact of felling method and extraction method per corridor, yet soil measurements following tree felling was not possible due to obstruction from fallen trees. This results in harvest impacts being observed as a combination of felling and extraction method. Furthermore, results in this study display effects of corridor conditions and harvest system impact, as corridor conditions confound harvest system impacts that were of original interest. This confounding of corridor to harvest system pairing became further apparent as operational corridor boundaries were exceeded in certain corridor areas. Due to these crossings of corridor boundaries, inequalities of harvested volume, and machine presence brought additional limitations of comparison into our study. Additional operational limitations due to machine malfunctions and inadequate payload lift in cable logging added another layer of limitation to the study. Through the limitations present in operations, planned areas of our study site were not fully extracted, therefore further limiting our usable observations of paired pre-harvest and post-harvest data. With a limited data set, statistical power was also decreased of conclusions to be drawn or estimated of harvest systems within the study. In addition, the method of prediction at a fixed level of production doesn't allow quite as direct of an observation of machine pass impact. Results from this study analyze harvest system impact given a set amount of harvest volume or production, rather than a comparison of impact given a set amounts of machine passes.

Analyzing within corridor changes (Figure 10 & 11), a mixture of results was found for combined effects of corridor and harvest system per corridor. Corridor A exhibited significant soil densification throughout the soil profile past 10cm with post-harvest conditions following pre-harvest conditions. Corridor B resulted in a post-harvest mixture of soil responses with significant soil densification between 20cm and 30cm from the pre-harvest state. Alternatively, Corridor C shows a general case of loosening, but only a statistically significant amount at the surface in post-harvest following pre-harvest condition. With utilization of a tethered feller-buncher for cutting and a tethered skidder for extraction in Corridor A, it seems to be the harvest system that has the greatest potential for the greatest number of machine passes across the harvest corridor. As found by many researchers, machine passes even in the early stages of minimal passes can be very impactful to forest soils (Ares et al., 2005; Cambi et al., 2015).

Comparatively, the shovel logging method following tethered feller-buncher felling has less machine passes due to the operational technique facilitating less machine movement along the corridor compared to skidder use as seen in Figure 4 and Table 9. The lesser amount of significant soil densification in Corridor B may be attributed to the lesser number of machine passes due to the shovel logging technique as exposed by the results of the machine pass GPS tracks (Figure 4). Regression analysis results in Table 14 further indicate the impact of machine passes through the variable of cycles, showing significance only in Corridor A. Corridor B, C and D indicated this variable as insignificant, giving insight to the lesser impact observed from these systems. Corridor B as previously mentioned exhibits lesser machine passes overall due to the technique of shovel logging, but the cable systems of Corridor C and D also have inherent qualities of machine passes. Although the variable of cycle accounts for machine passes during outhaul and inhaul, cable systems only contact the soil with payload during the inhaul phase of their extraction cycle.

Corridor C utilized the traditional steep slope methods of hand falling and cable logging extraction. In the case of Corridor C, no machines were on the slope and the only significant soil change observed was the top 0-6cm of the soil profile. Compared to mechanized cutting by feller-buncher, motor manual hand falling typically lends less control of the tree being cut to the forest worker. Mechanically felled trees by feller-buncher are typically grasped by the machine, cut, then deliberately placed into a position or pile. Alternatively, hand falling techniques typically send felled trees downhill with no machine grasping assistance or deliberate handling. Due to the absence of worker control of the tree following it’s felling, trees sliding downhill on steep harvest areas is common. The falling and subsequent sliding of felled timber may lend inference to the significant loosening that occurred in Corridor C, coupled with the absence of machines traversing the corridor.

Differences of impacts between harvest corridor and harvest system pairs are apparent as seen in Figure 5. Although differences are apparent in the associated plots, their comparative differences lend additional information to interpret. Bulk density measurements were found to be insignificantly different from each other, yet did demonstrate a lower bulk density value (.31 g/cm^3) in Corridor A utilizing grapple skidder extraction, as opposed to bulk densities found in Corridor B with shovel logging extraction (.37 g/cm^3) and Corridor C cable logging extraction (.32 g/cm^3), as well as Corridor D with grapple carriage cable logging extraction (.48 g/cm^3).

Bulk density observations as seen in Figure 5 and 13, show decreased bulk density values following harvest operations in the 0-6cm depth of the soil profile. Resulting bulk density values across harvest corridor and harvest system treatments ranged from .31 g/cm^3 to .48 g/cm^3. In accordance with the fine sandy loam soil texture present on the site, the threshold of root growth limiting compaction of 1.65 g/cm^3 (Daddow & Washington, 1983) is far from being met, highlighted by a loosening of top soil from 0-6 cm in depth. Varied findings have been presented in the past with ground-based harvest systems either compacting, not effecting, or loosening topsoil in harvest sites (Sakai et al., 2008; Jansson & Johansson, 1998) in sandy and silt loam forest soils. Although bulk density results have been historically variable, there have been documented differences between bulk density measurements compared between tracked and wheeled machinery on the same site (Sakai et al., 2008; Jansson & Johansson, 1998). Sakai et al. (2008) observed bulk densities values for low pressure tires at .68 g/cm^3 compared to tracks

1.06 g/cm^3 on an identically loaded forwarder. Jansson and Johansson (1998) observed the same trend between 2 equal mass machines with the rubber tire forwarder reducing bulk density while the steel tracked harvester increased bulk density.

Penetrometer resistance utilized measurements throughout the soil profile from 10 to 50 cm in depth in order to characterize profile impacts across different harvest corridors and harvest system treatments. Penetrometer measurement results are important as understanding of soil response to vehicular loading has developed greatly in the last two decades, highlighting different load types and their impacts to the soil profile (Duiker, 2005). Knowledge has developed that topsoil (0-12”) compaction is impacted by contact pressure, while the upper part of the subsoil (12-20”) is a combination of contact pressure and axle load, with lower subsoil (20”+) effects due to axle load (Duiker, 2005). These findings can aid in drawing conclusions between the observed values of the harvest corridors and harvest systems utilized in this study.

Penetrometer resistance amongst the corridors and systems utilized in Corridor A, B, and C demonstrate unique comparative trends as shown in Figure 14, with Corridor A penetrometer resistance measurements being greater than Corridor B, C, and D at depths of 10-50 cm. These results align with findings from Duiker (2005), indicating that greater contact pressures present from rubber-tired machinery versus steel tracked machinery (Jansson & Johansson, 1998) may facilitate soil compaction in upper horizons, while higher axle loads regardless of contact pressures manifest themselves at deeper depths in the soil. Although different harvest corridor and machine treatments exhibited increased penetrometer resistance, none of the measurements entered or exceeded the generally accepted critical 20.4 Kg/cm^2 (2000 Kpa) to 30.6 Kg/cm^2 (3000 Kpa) root growth threshold (Ares et al. 2005).

The results from this study currently represent combined effects of harvest corridor soil composition and harvest system implemented. With knowledge of other studies characterizing impacts contributed by axle loads and machine-to-soil contact characteristics, there is room for further exploration of the data. Soil responses to harvest systems are due to the contact relations that occur between machinery and their payload with the soil. Some methods facilitate transportation through dragging, while others provide full or partial suspension to the payload during extraction. Additionally, different extraction methods rely on different contact treads such as rubber tires or steel tracks in contact with soil aside from cable logging systems. In the case of Corridor A utilizing a tethered skidder, there are rubber tires with metal chains wrapped around the tires. Corridor B utilizes a tethered logging shovel, equipped with metal tracks that are in contact with the soil. Corridor A and B utilized tethered felling, representing another contact relation of steel track to soil on the harvest corridor. Corridor C and D utilize cable logging methods with no machine presence on the slope during extraction, only with machine contact of the steel tracked feller-buncher during felling of Corridor D, while Corridor C was subject to human foot traffic during felling. Shovel logging has been recognized as the least impactful whole tree ground based harvesting method (Egan et al., 2002), while rubber-tired skidders have long been scrutinized for their soil impacts (Greacen & Sands, 1980). Due to Corridor A and Corridor B having the same felling treatments with a tethered feller-buncher, analysis of extraction methods can be brought to light. Corridor A is characterized by a lower bulk density in comparison to Corridor B, aligning with findings from Jansson & Johansson (1998) and Egan (2002), supporting traditional untethered soil impact trends of rubber-tired skidder impacts producing lower resulting bulk densities than shovel logging impacts. Although in this case, study results are unique due to overall decrease in bulk density from both harvest systems. This overall decrease is likely due to the deep ash over loam soil composition of the site being low in bulk density by nature. Although an overall decrease was observed with Corridor A and B, rubber-tired equipment showed the traditional larger decrease trend of bulk-density in comparison to steel track shovel logging equipment.

Early predictions of soil compaction in harvest operations were largely based on measurements of machine ground pressure or soil susceptibility ratings (Boyer, 1979; Howard, 1981), but have been found to not accurately characterize soil compaction (Froehlich et al., 1980) or impacts from dynamic soil loading present under logging operations (Lysne, 1983). Harvest systems not only have unique machine-to-soil contact characteristics, but each have unique patterns associated with their payload extraction. As mentioned, payload extraction varies fully from dragging across the ground to complete suspension, and furthermore by volume per machine cycle in extraction operations. Between the ground-based systems utilized in Corridor A and Corridor B, each of the machines transport their payload in a different configuration mechanically, and in spatial distribution on the harvest site as seen in Figure 4.

From a mechanical standpoint, grapple skidders utilize a large grapple on the rear of the machine to lift the ends of multiple logs for transportation. Grapple skidder payload is often limited by the total machine weight and grade of slope to be traveled, as payload weight is leveraged against machine weight in a fulcrum across the rear axle. Due to this fulcrum effect, skidders exhibit a large proportion of their loaded ground pressure across the rear tire contact patches with the ground. Alternatively, logging shovels have a very large footprint with long track frames. Shovel logging typically occurs through the grasping and swinging of payload while the machine tracks remain stationary. These physical differences help to contrast the machine to soil contact relationships as they repeatedly interact with the site through multiple machine passes.

Machine pass frequency during extraction also differs between grapple skidding and shovel logging methods. Similar to grapple skidding needing to travel directly to the intended payload, it makes a complete cycle to the landing once the payload is grappled. This results in a large number of trips up the corridor transporting each cycle of payload. In contrast, shovel logging methods utilize a gradual swinging of payload towards the landing, lessening the need for repeated machine passes between payload in the corridor and the destination of the landing. Coupling the previous description of machine to soil interaction with the skidders small but intense footprint compared to the shovel, and spatial distribution of the extraction in Corridor A with more machine passes than Corridor B, helps explain the larger magnitude of impact seen in Corridor A (Figure 14).

Conclusion

Tethered timber harvesting equipment is becoming increasingly common and therefore broader in application to different landscapes and forest types. As a progression has occurred from European countries to various others and the United States, improvements will continue to propel this technology. This study aimed to explore the comparisons of soil impacts between steep slope logging methods utilizing traditional cable logging and emerging tethered ground-based equipment. Results suggest that many previously observed characterizations of soil impact from these harvest systems are consistent with earlier ground-based operations now placed onto steep slopes in tethered fashion. This is illustrated with greater soil impacts from grapple skidder extraction in contrast to shovel logging or cable logging, although none in this study were found to reach or enter a point of detriment according to the previous studies (Daddow & Washington, 1983; Ares et al. 2005).

Further development of tethered logging system research is essential in understanding the advanced forces in effect opposed to traditional ground-based configurations. As outlined by Sessions et al. (2017), tether use has the ability to actively engage greater lengths of track frame or alternatively machine wheelbase, improving gradeability as well as payload. With increases of payload and introduction of additional force into the system via tether tension, tethered harvesting systems may exhibit less track and wheel slippage, yet increase overall soil loads.

Although soil compaction comparison trends may reflect previous findings on flat ground between harvest system combinations, peak soil loads on slopes may be entering new thresholds.

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