



# Impacts of Tethered Logging Equipment on Soil Compaction, Moisture and Seedling Growth

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## Abstract

Traditional hand-felling on steep slopes in the Pacific Northwest (USA) minimizes soil disturbance but is labor intensive and hazardous. Tether-assist machine harvest offers a safer alternative, yet its soil impacts are less understood. This study compared soil impacts (bulk density (Db), sediment production, penetration resistance) and soil resilience (volumetric water content (VWC), seedling growth) between hand-felled and tethered machine-felled areas on > 30% slopes with Ultisol soils (silty clay loams) in Southwest Oregon. Pre- and post-yarding soil measurements were taken in both harvest areas, with tracked and untracked zones assessed for resilience in the tethered system. Both methods showed a general decrease in near-surface Db that persisted through to the post-yarding phase. A general increase in subsurface penetration resistance occurred across treatments, with varying significance. No sediment production was observed over two years. Tracked soils exhibited higher VWC, especially during dry months with high vapor pressure deficit, and greater Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedling biomass than untracked soils. These results suggest, for the two-year observation period, that tether-assist harvest on these soils does not more negatively impact soil compared to the current steep slope harvest standard of hand-felling. The higher plant biomass and VWC in tracked zones suggest machine traffic collapses macropores, increasing water retention, which may allow for more plant available water during dry seasons. This study contributes to the growing understanding of tethered versus traditional harvesting on steep terrain and suggests that tethered machine-felling could be a safer and viable alternative to hand-felling on steep (> 30% slopes) terrain with Ultisol soils in dry conditions.

**Keywords** Tether assist · Soil disturbance · Soil resilience · Cable logging · Steep terrain

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Extended author information available on the last page of the article

## Abbreviations

Db	Soil bulk density
VWC	Volumetric water content
PAW	Plant Available Water
LTSP	Long-Term Soil Productivity

## Introduction

Managing forests in the steep and rugged terrain of the Pacific Northwest (USA) presents unique challenges. Ground-based logging in these areas has largely been limited to slopes less than 35% due to safety concerns, the economic viability of the operation, and the risk of environmental damage. Decades of fire suppression have further complicated management by disrupting natural disturbance regimes, leading to increased stem density and the accumulation of hazardous ladder fuels, even on steeper terrain (Zald and Dunn 2018). Despite the growing need to address fuel loading and achieve forest restoration on these slopes (Haugo et al. 2019; Johnston et al. 2018), significant concerns regarding the environmental and operational impacts of steeper slope harvesting persist.

Traditionally, steep slope timber harvests were conducted with hand felling to minimize ecosystem impacts from soil disturbance. However, hand-felling is labor intensive and carries a higher risk of worker injury. Tether-assist machine harvest systems have emerged as a potentially safer alternative (Garland et al. 2019), offering the possibility of efficient timber harvest and fuel-reduction thinning in the Pacific Northwest's steep, fire-susceptible forests, but their ecosystem impacts across various soil types remain understudied.

Soil compaction, displacement, and rutting are common and generally undesirable consequences of heavy machinery traffic over forest soils (Cambi et al. 2015; Powers et al. 2005). Heavy machinery, such as harvesters, skidders, and forwarders, are known to compact soils, leading to increased bulk density and decreased soil porosity, infiltration capacity, and hydraulic conductivity across harvested areas. This alteration of soil properties can subsequently increase hillslope runoff and erosion (Mohr et al. 2013; Sidle et al. 2006). For example, Oyarzun and Peña (1995) observed 1.8- to 3.9-times greater runoff and 1.9- to 5.8-times greater sediment concentrations from harvested plots compared to undisturbed Monterey pine (*Pinus radiata* D. Don) forest plots in the first two years after forest harvesting.

The potential negative impacts of soil disturbance during timber harvesting on soil productivity are a significant concern (Clayton et al. 1987; Grigal 2000; Picchio et al. 2020; Zabowski et al. 1994). However, the relationship between soil disturbance and productivity can be complex and influenced by site-specific ecological factors. For example, Gomez et al. (2002) reported on four years of ponderosa pine (*Pinus ponderosa* Douglas ex Lawson) growth on three California sites of the North American Long-Term Soil Productivity (LTSP) research network. They found that on compacted sandy loam soils, ponderosa pine had increased height growth as compared to non-compacted soils. Compacted loamy soils had similar growth to non-compacted soil, while compacted clay soils resulted in less tree height growth.

Soil water release curves for these soils indicated that in the clayey soils, plant available water (PAW) (soil water held between permanent wilting point and field capacity) was decreased whereas PAW was increased in the sandy soils (Gomez et al. 2002).

To minimize soil impacts and maintain the sustainability of timber resources, various harvest methodologies and mitigation techniques have been developed and implemented (Grigal 2000; Page-Dumroese et al. 2021; Picchio et al. 2020; Labelle et al. 2022). For example, a harvester machine used in the cut-to-length system places slash mats from harvest debris to reduce soil compaction, rut formation, and displacement (Han et al. 2006; Labelle et al. 2019; Poltorak et al. 2018). Trafficability mapping and machine modification designed to improve machine ground pressure distribution and traction are known methods to mitigate traffic-induced soil impacts (Kankare et al. 2019; Labelle et al. 2022).

A recent development involves the increasing adoption of tethered ground-based logging equipment for steep slope regions (Chase et al. 2019; Green et al. 2020). Since the introduction of cable-assist or tether-assist technology in Europe in the early 2000s, only a limited number of studies have investigated its effects on soil disturbance (Holzfeind et al. 2020), including some research in the western USA (Fagundes 2022; Green et al. 2020). For example, Wratschko (2006) found that on gently sloped terrain (22% to 36%), rut depth from forwarder extraction increased with slope gradient; however, tether assistance significantly reduced rut depth ( $9.3 \pm 4.2$  cm) compared to operations without tether assistance ( $19.3 \pm 7.9$  cm). This study also showed that tether assistance reduced wheel slip by approximately 30%, while soil penetration resistance remained similar before and after machine traffic, regardless of tether assistance. Similarly, a recent qualitative soil disturbance evaluation in Canada (Strimbu and Boswell 2018), using the methodology of Page-Dumroese et al. (2009), found 6% greater soil disturbance with a conventional skidder system compared to a tether-assisted skidder. Furthermore, Strimbu and Boswell (2018) reported that a tether-assisted harvesting required 36% less total built road length.

While the aforementioned studies, using qualitative assessments on soil disturbance in tethered operations (Fagundes 2022; Green et al. 2020; Strimbu and Boswell 2018), highlight the benefit of tether assistance in reducing disturbance, they offer limited insight into the impacts on deeper mineral soil horizons and erosion potential. Green et al. (2020) provided a more quantitative comparison of harvester and forwarder operations with and without tether assistance, finding a general (though not statistically significant) increase in soil penetration resistance in the untethered system after both harvesting and forwarding. In contrast, tether assistance resulted in decreased bulk density of surface mineral soil after harvester operations. Tether-assisted forwarding also led to lesser soil compaction compared to untethered forwarding. Further, a study in Brazil quantified soil property changes caused by a tethered forwarder operating on slopes ranging from 51 to 78% (Garren et al. 2019). This research revealed a significant increase in soil bulk density on gentle slopes but no significant increase on the steeper slopes where the tether system was more actively engaged in load support. These results further confirm the effectiveness of tether assistance in reducing concentrated ground pressures, and the

authors concluded that both bulk density and rut depth levels compared favorably with ground-based operations on gentle slopes.

The LTSP program (Powers et al. 2005) demonstrated that the impacts of timber harvest practices are strongly influenced by regional soil characteristics. Given the significant geospatial variations in soil properties, such as texture, mineralogy, native fertility, and undisturbed porosity, a generalized approach to assessing the applicability of tethered systems for steep slope harvesting is inappropriate. At a minimum, assessments should focus on regionally defined areas with similar inherent soil properties, and inferences regarding the impacts on the soil should not be extrapolated beyond these regions without site-specific ground validation. The Pacific Northwest has a variety of soil regions, including highly weathered soils derived from basalt rock and uplifted marine sediments, as well as late Holocene volcanic ash derived soils (Thorson et al. 2022). Each of these systems present different baseline soil productivity and varying susceptibilities to disturbance.

Soil resilience is defined as “the ability of soil to resist or recover from an anthropogenic or natural perturbation” (Lal 1997). To maintain soil and site productivity after harvest operations, organic and mineral soils must be on a trajectory towards recovery to pre-harvest disturbance levels. The speed of that recovery will depend on soil type, climatic regime, harvest intensity, trafficking amount, and other site factors. Determining the rate or response to disturbance can be assessed by measuring soil parameters such as bulk density, erodibility, penetration resilience and changes in water holding capacity, as well as monitor plant response.

To address the knowledge gaps regarding the impacts of tethered machine felling on steep slope soils in the Pacific Northwest, we conducted a field case study within a clearcut harvest unit on silty clay loam soils located in southwest Oregon, USA. The primary objectives of this research were to:

- 1) Quantify and characterize the immediate impacts on steep slope soils resulting from hand-felling and tethered machinery traffic in the study unit.
- 2) Evaluate post-logging soil resilience by quantifying erosion, sediment transport, changes in soil moisture regimes, and seedling growth over time.

We hypothesized that impacts of tether-assist machine-felling would not be significantly different than traditional hand-felling.

## Methods

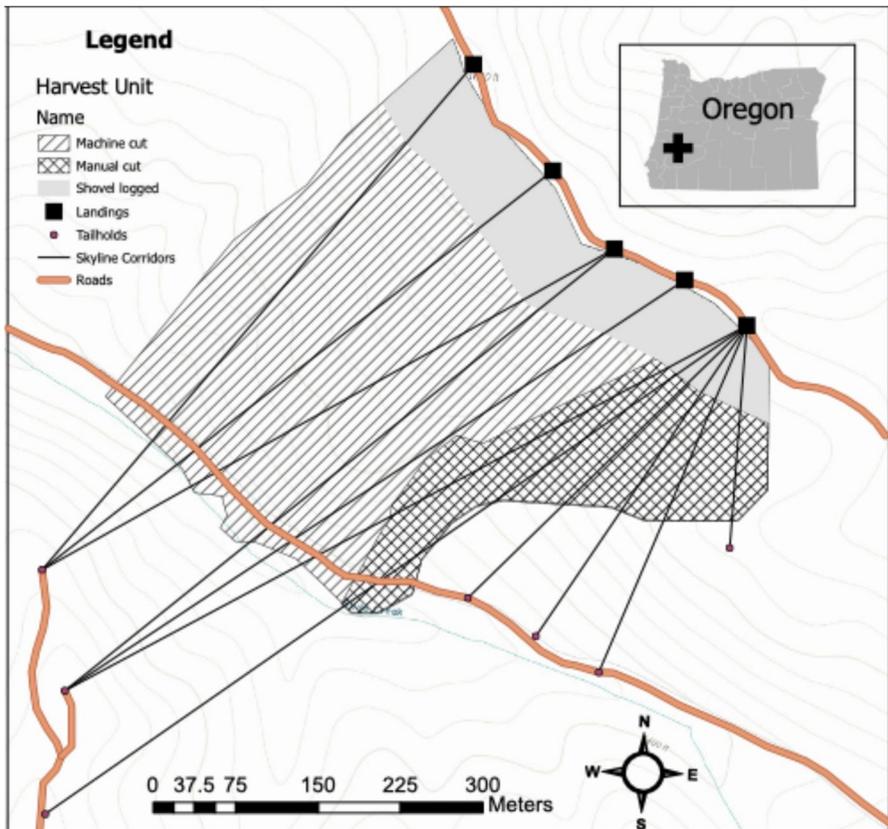
This study included two phases of implementation over three years. Phase 1 was associated with the time frame around the harvest activities. Phase 2 is the extended period after harvest (27 months), during which we assessed longer-term impacts of harvest activities on soil resilience.

## Site Description

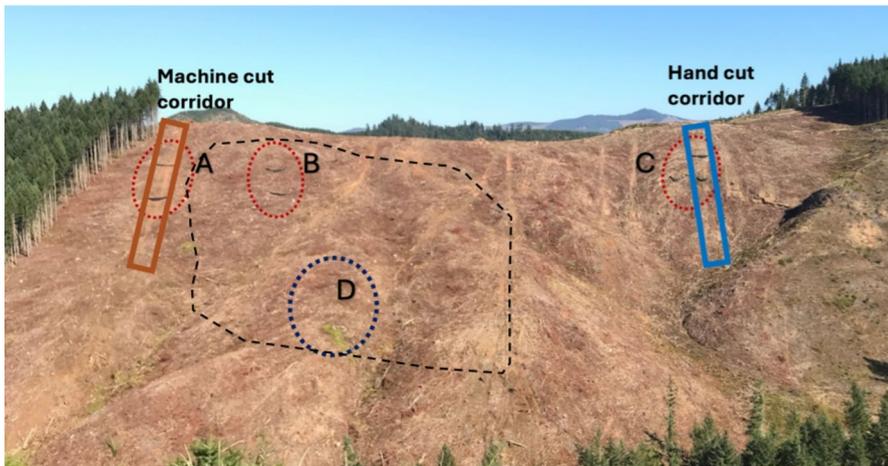
The 17-ha study harvest unit, located near Sutherlin, OR (Fig. 1) (43.30628° N, 123.09587°W) is situated on private forestlands owned by Lone Rock Resources. Elevations within the unit range from 380 to 520 m AMSL.

Across the entire unit, hillslope complexity is relatively low, with an average slope of 35% and a southwest aspect. The area has a climate characterized by cool, wet winters and warm, dry summers, with a mean annual precipitation of 880 mm and a mean annual temperature of 11.6 °C (PRISM Group 2014).

The majority of the study area is mapped as Nekia-Jory complex, 30–60% slopes with about 3.2 ha mapped as Jory silty clay loam, 20–30% slopes (Fig. 2) (NRCS Order 2 soil survey) (Soil Survey Staff (Soil n.d.)). The 3.2 ha area included Jory soils with slopes in our target range. Jory soils are clayey, mixed, mesic Xeric Palehumults, and Nekia are clayey, mixed, mesic Xeric Haplohumults. These are deep



**Fig. 1** The 17-ha study harvest unit located near Sutherlin, Oregon. The unit includes 10 ha that were machine felled (hatched), 4 ha that were hand felled (cross-hatched), and 3 ha in a buffer strip along the road on top of the ridge (solid gray)



**Fig. 2** The photo of the study harvest unit after logging was completed. The solid boxes in orange and blue show the locations of machine and hand felled corridors, respectively, established for soil sampling. The orange dotted ovals show the silt fence locations installed after logging for machine felled + skyline corridor area (A), machine corridor only (B), and hand felled + skyline corridor area (C). The blue dotted oval (D) shows the approximate locations of four soil moisture monitoring stations for machine track and non-track soil moisture comparisons. The black dashed line indicates the approximate soil map unit boundary (Soil Survey Staff, (Soil n.d)). The soil inside the boundary is mapped as Jory silty clay loam, 20–30% slope. Area outside the boundary is mapped as Nekia-Jory complex, 30–60% slopes

and moderately deep soils formed in residuum and colluvium of volcanic origin. Near-surface textures are silty clay to silty clay loam and transition to clay at a depth around 40 cm. Forest operations on Nekia soil types are generally rated ‘severe’ for potential impacts such as rutting and erosion whereas Jory is generally rated ‘moderate’ for impacts; slope and soil strength are the risk variables for both soils (Soil Survey Staff (Soil n.d.)). Our field observations during soil sampling indicated that this specific study area exhibited very low rock content, as is expected in the Nekia and Jory soils. Our operations areas were focused on landscape positions associated more with the deeper Jory soils.

## Harvest Methods

The harvest unit was clearcut between late March and early April 2018 using a whole-tree harvesting system. The unit was split into three sections (Fig. 1). A 3-ha strip of the unit on the gentler upper slope was harvested with a shovel logger before our experiment for safety reasons, to provide easy access and view for the swing yarder, and allow for roadside decking, eliminating the need for any landing construction. Therefore, this area of the unit was excluded from our study. Both machine- and hand-felled areas shared similar stand characteristics, with an average ground slope of 35%, an average d.b.h. of 41 cm, and a pre-harvest density of 374 trees/ha (average volume of 1.27 m<sup>3</sup> per tree). In the 10-ha machine-felled area, trees

were cut using a tethered shovel logger (TigerCat LS855D) with a directional felling head, anchored to an upslope Caterpillar 330D equipped with a remote-controlled, synchronized winch system (Summit Winch Assist). The 4-ha hand-felled area was cut manually with chainsaws. Both areas were subsequently yarded as whole trees using the same Thunderbird TSY255 swing yarder, ACME 528 motorized slack-pulling carriage, and logging crew.

### Phase 1: Soil Disturbance Data Collection and Analysis

Two designated skyline corridors were selected and marked for soil sampling and measurement prior to logging: one in the machine-felled area (230 m) and the other in the hand-felled area (200 m) (Fig. 2). Slopes for the two corridors ranged between 30 and 35%. A total of 22 slope sample locations were established per corridor, with a 9.1-m spacing. Access to mineral soil at sampling locations dictated post-felling data collection. In the machine-felled corridor, the felling machine made log piles outside the corridor, making sampling locations accessible. Consequently, soil was sampled pre felling, post felling and post yarding. In the hand-felled corridor, individual cut trees prevented access to the mineral soil at sampling locations between felling and yarding periods, therefore soil was only sampled pre felling and post yarding.

Although previous studies indicate that the surface organic horizon can reduce soil impact, particularly when reinforced with slash mats in cut-to-length harvesting (Sirén, et al. 2019; Labelle et al. 2022), the whole-tree system used in this study does not generate slash mats on machine corridors. Given the uniformity of the stand, we assumed that the pre-harvest surface organic layer was consistent across both the machine- and hand-felled areas. Organic horizons in *Nekia* and *Jory* soils, when present, are thin, typically 0–3 cm, and consist of hemic materials. Therefore, the specific buffering effects of the organic layer were not quantified as a variable. This assumption of a uniform organic horizon was consistent with our field observations.

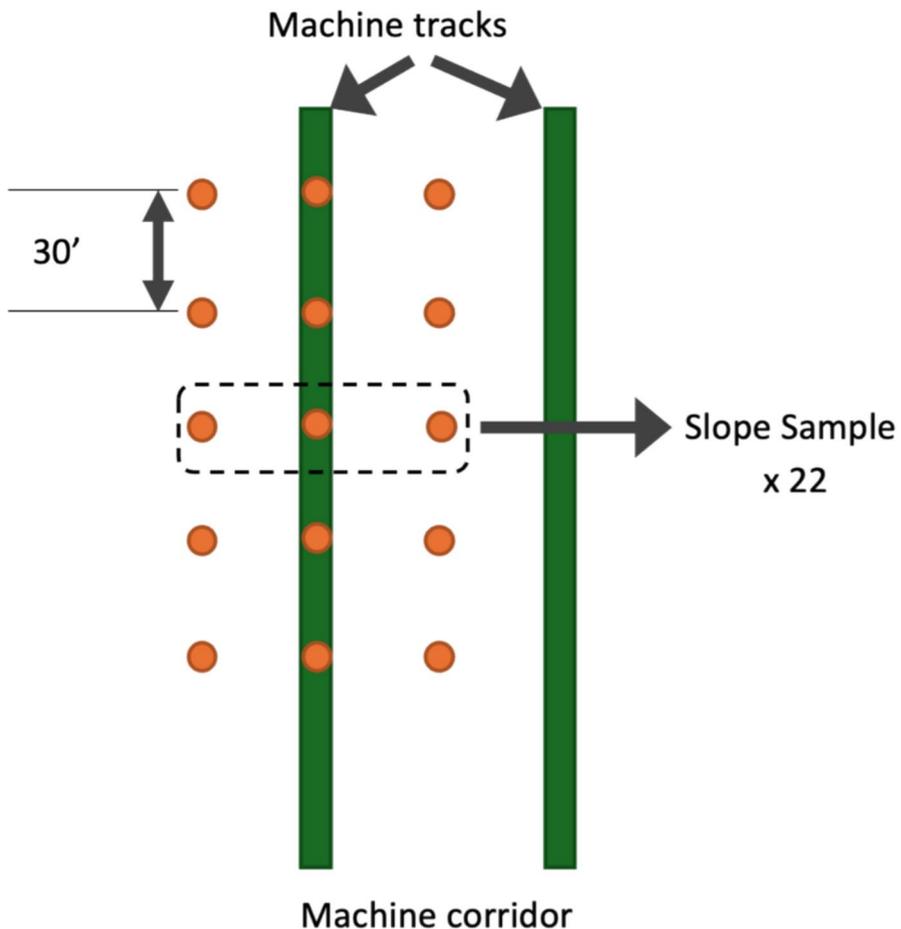
### Bulk Density and Volumetric Water Content

Bulk Density (Db) samples were collected for the mineral soil depth 0–10 cm at multiple stages of the harvest period (i.e., pre felling, post felling and post yarding). To collect samples, all surface organic matter was removed prior to sampling the mineral soil. A 130-cm<sup>3</sup> cylindrical soil core (height=6 cm; inner diameter=5.3 cm) was then gently hammered into the mineral soil until the top of the core was level with the soil surface. The sampling core was then excavated and carefully extracted. The sample was placed in a plastic collection bag for laboratory evaluation of moisture content and dry Db (Soil Survey Staff 2014).

Db samples were taken at each sample location for machine- and hand-felled treatments prior to timber felling. In the machine-felled area, samples were collected after felling and after yarding. Machine tracks were identified near each sample location. The tethered felling machine made one down and one up pass

in the selected tracks. Db samples were taken from machine tracks, between tracks and 1-m outside of tracks (Fig. 3).

In the hand-felled area, pre-treatment Db samples were collected from along the projected linear yarding corridor for the cable yarding. Post-yarding, it was apparent that the yarding corridor was not linear due to microtopography that impacted the drag line; therefore, seven original sampling locations were outside the corridor and not impacted by tree drag, but may have been impacted by hand-felling activities. We collected and processed post-yarding samples at the seven outside-yarding-corridor sites. We then sampled at seven new locations within the observed drag line close to the original sample site in order to have adequate in corridor samples post-yarding.



**Fig. 3** Soil sample and measurement locations along tethered feller-buncher corridor. Bulk density (Db) soil samples, penetration resistance, and moisture content were measured at each sample location

All field collected Db samples were weighed moist and then oven-dried to calculate Db and volumetric water content (VWC). VWC was calculated as:

$$VWC = \frac{M_t - M_s}{M_s} \times \frac{D_b}{D_w}$$

where  $M_t$  is total moist sample mass,  $M_s$  is mass of oven-dried solids, and  $D_w$  is density of water. VWC was also measured at each sampling location using a handheld dielectric moisture probe (ML3 Thetaprobe). Values of lab and handheld VWC were compared to assess the accuracy of the dielectric probe, as these probes were used in collecting longer term in-situ VWC.

### Penetration Resistance

Assessing traffic impact on soil properties and subsequent plant growth is challenging (Powers et al. 1999). Bulk density has been a preferred indicator, yet, as Powers et al. noted (1999), plant growth is reliant on oxygen, water, and root penetration, which is influenced by soil strength. Soil strength is assessed rapidly and easily via penetration resistance. Early studies between plant root growth and penetration resistance demonstrated that penetration resistance at a specific Db is decreased as VWC increases (e.g. Taylor et al. 1966). Additionally, in finer textured soils, similar to those of this study, root growth decline began at  $\sim 3 \text{ kg cm}^{-2}$ , with root growth being stopped at  $\sim 250 \text{ kg cm}^{-2}$  (Taylor et al. 1966). More recent studies on timber stock, including Douglas-fir, demonstrated similar root growth limitations (Gebauer et al. 2012). Powers et al. (1999) proposed initiation of limiting plant growth impact at a penetration resistance of  $\sim 20.4 \text{ kg cm}^{-2}$ . In silty clay and clay soils, the critical value for penetration resistance for forest species detrimental growth impact is proposed to be around  $33 \text{ kg cm}^{-2}$  (Gebauer et al. 2012). For our analyses, we compare our results to the more conservative  $20 \text{ kg cm}^{-2}$ .

A total of 95 mm of rain was recorded at the cooperative weather station for the time between pre- and post-timber felling data collection. Additional rainfall of 97.5 mm was recorded between post-felling and post-yarding. Soil moisture content impacts penetration resistance (Henderson et al. 1988; Lowery and Morrison 2002), but less so in finer textured soils (Taylor et al. 1966), such as the soils in this study. Precipitation, as well as evapotranspiration, can limit the interpretation of the penetration resistance data between sample periods. Rather than comparing penetration between sampling periods, we focus on comparing penetrometer resistance for each sample date period and comparing against the  $20 \text{ kg cm}^2$  limiting threshold.

Penetration resistance measurements were recorded at each sample location at mineral soil depths of 10, 20, 30, 40, and 50 cm to observe horizontal and vertical zone of influence (compaction) with depth as a result of machine traffic. Measurements were taken using a Humboldt Manufacturing HS-4210 dual-rod digital static cone penetrometer, which has a  $60^\circ$  head ( $1.5 \text{ cm}^2$  surface area) and a dual-rod design (Lowery and Morrison 2002). In the unexpected occurrence of root or coarse fragment, the penetration sample was shifted by approximately 15 cm until the required depth was achievable. We applied depth increment markings on the rod to

aid in accurate depth-from-surface measurements. We did not adjust depth measurements to account for surface topography variations (e.g. ruts) that may have occurred during harvest operations. Our observations of the tracks at sample locations suggested minimal rutting. In both machine and hand felled areas, pre-felling penetration resistance readings were taken. Penetration resistance readings post felling and post yarding followed the same location sampling as the Db strategy described above.

## Data Analysis

Phase 1 pre-treatment Db data were compared between the machine- and hand-felled corridors using an unpaired, unequal variance t-test. To assess changes within each corridor due to logging activities, pre-treatment Db and VWC data were separately compared to post-timber felling and post-yarding data using paired t-tests assuming equal variance with the null hypothesis of no difference between pre- and post-logging data at a 0.05 level of significance. Comparisons of penetration resistance data were also performed separately for each soil depth using a paired t-test assuming equal variance.

## Phase 2: Soil Resilience Data Collection

Post-harvest soil resilience was evaluated through periodic monitoring of soil erosion, sediment transport, soil moisture changes and vegetation recovery over 27 months between July 2018 through November 2020.

### Soil Erosion and Sediment Transport

We identified three distinguishable areas in terms of disturbance source within the study area: machine + skyline corridor, machine corridor only, and hand felled + skyline corridor. Seven silt fences (Robichaud and Brown 2002) were installed in July 2018 to quantify sediment transported from shallow surface runoff. The locations of these silt fences included two erosion fences with 40 m spacing in the machine cut + skyline corridor area, two fences in the machine corridor only area, and three fences in the hand felled + skyline corridor area (Figs. 2 and S1). Sediment, if present, was to be collected and weighed for quantification. Silt fences were monitored at least twice per year until November 2020. The study site in general was also evaluated during sampling days for evidence of rill formation.

### Soil Moisture

We measured in-situ VWC in the soil profile for 20 months post-harvest to monitor potential long-term impacts of harvest operations. Four sample locations were selected where machine tracks were clearly visible on the ground, representing two machine passes (down and up) (Fig. 2). At each sample location, two sample points

were identified: in the machine track and in a control in an undisturbed, outside-track area where grass cover was intact. The undisturbed, outside-track area was identified within 3 m from the machine track parallel to the ground slope. We installed dielectric soil moisture probes (Meter ECH<sub>2</sub>O 5TM, Pullman, WA) with factory settings (accuracy  $\pm 3\%$  VWC) at every 10 cm of depth from 10 to 50 cm (Fig. S2). In total, there were four monitored profiles under tracked soil and four profiles in undisturbed soils. These profiles were within the B and C planting areas discussed below. VWC data were recorded at 15-min intervals and wirelessly transmitted through Meter Em60G data loggers for cloud storage.

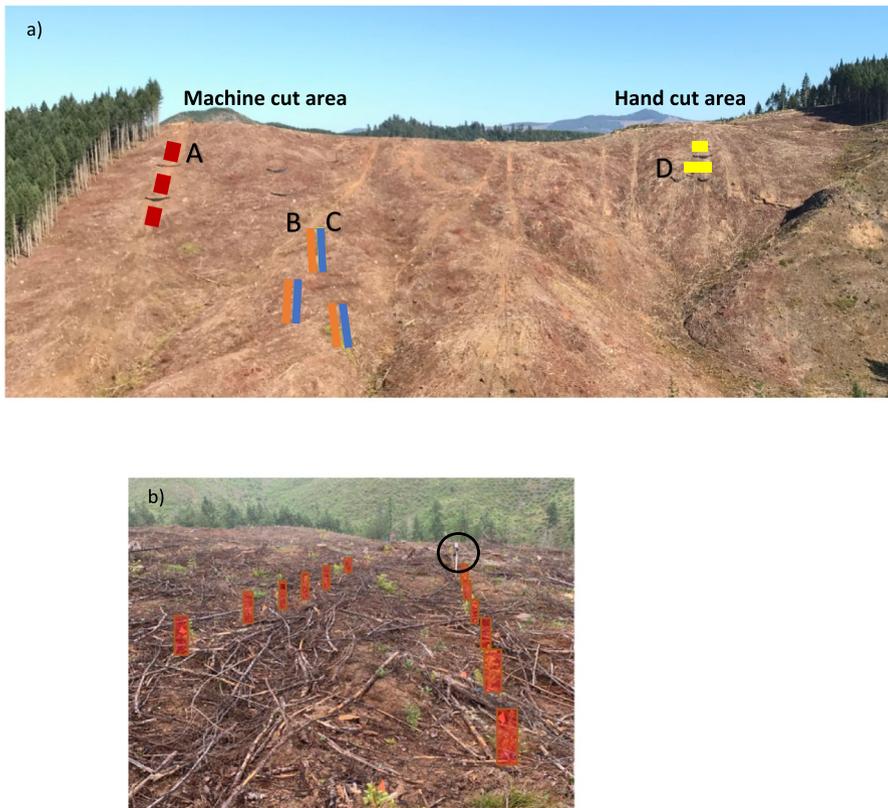
## Seedling Growth

Reviewing several months of in-situ VWC in late 2018, differences became apparent between tracked and untracked areas. Recognizing a unique opportunity, during site replanting, we opted to include an unplanned plant growth study. Industrial site replanting occurred in March 2019 using Douglas-fir seedlings. The improved seed originated from a cooperative seed orchard (Lebanon, OR) sourced from the Southern Oregon Coast Range program (150 to 460 m AMSL). The seeds were initially sown into styro block container using a peatmoss-based medium at IFA Nurseries (Klamath Falls, OR) in 2017. In August of 2017, they were transplanted into a bare-root field at IFA Nurseries (Elkton, OR), where they grew until lifted in February 2019. The seedlings were kept in cold storage until planting in March 2019.

To investigate potential impact of disturbance condition on seedling growth, and to investigate the potential influence of the observed differing VMC, we established four locations for each of the four different disturbance source areas where seedlings were planted for destructive sampling (Fig. 4):

- Skyline corridor in the machine-felled area, consisting of three 4 × 10 seedling blocks (upper, middle and lower skyline corridor)
- Machine corridor only areas, three 1 × 16 seedling blocks
- Non-machine (adjacent to machine corridor, 5 m away from machine track), three 1 × 16 seedling blocks
- Hand-felled skyline corridor, one 5 × 4 and one 10 × 7 seedling blocks.

Seedlings were planted at 1.5 m spacing in all blocks. Twenty seedlings were randomly selected before planting to measure initial metrics including: stem length (root collar to terminal bud; mean = 64.40 cm), root collar diameter (mean = 10.73 mm), root volume (mean = 61.25 cm<sup>3</sup>), root dry mass (mean = 18.94 g), shoot dry mass (mean = 30.49 g). For monitoring purposes, 2–8 seedlings were randomly collected from each block twice a year (i.e., pre-growing season and post-growing season) over a 20-month period for growth measurements. Excavated seedlings were measured for diameter at the base, stem length, current year leader growth, root mass, root volume, and above ground mass and volume. Root and above ground biomass volumes were determined using the water displacement method (Harrington et al. 1994). Seedlings were planted on March 12, 2019, and seedling samples were



**Fig. 4** a) The location of seedling growth experiment plots in four disturbance areas: (A) machine felled+ skyline corridor area, (B) machine-only corridor, (C) non-machine, and (D) hand felled+ skyline corridor area. b) Seedlings planted in Block B (machine track, right) and Block C (non-machine track, left) as pairs; a datalogger for soil moisture can be seen in a black circle at the end of the B run

collected four times on June 6, 2019, November 19, 2019, June 3, 2020, and November 16, 2020.

### Data Analysis

Volumetric water content (VWC) was analyzed using descriptive statistics. To compare VWC between track and outside of track areas, data were aggregated into daily averages. Additionally, a 7-day rolling average was calculated as the arithmetic mean of VWC values over a consecutive 7-day moving window to smooth short-term fluctuations. The difference in moisture content ( $\Delta$ VWC) was then calculated by subtracting the outside of track average from the track average to visually compare distinct hydrological trends. For seedling growth, metrics were compared between machine- and hand-felled areas (A and D in Fig. 4a) and between track and non-track areas (C and D in Fig. 4a) using two-sample t-tests. Data for each growth

metric were tested for homogeneity of variance using F-test, and t-tests assuming either equal or unequal variances were applied accordingly.

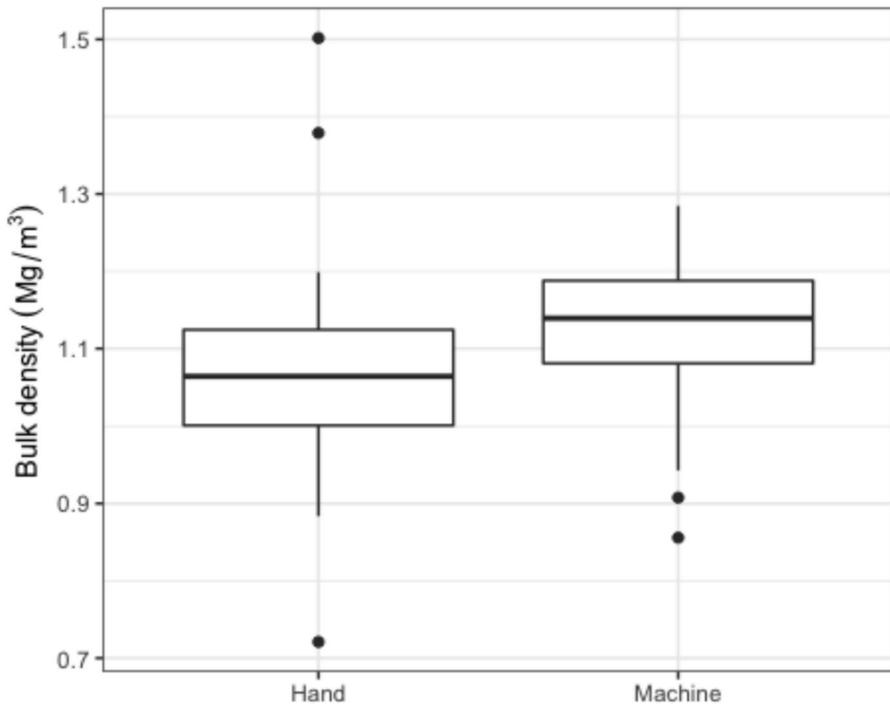
## Results

### Phase 1: Soil Disturbance—Treatment Comparisons

#### Surface soil bulk density (Db)

Pre-treatment Dbs in the 0–10 cm mineral soil for the machine-felled and hand-felled areas were similar and not significantly different ( $p = 0.32$ ), although variance was greater in the machine-felled area (Fig. 5).

In the hand-felled area, pre and post yarding Db samples within the yarding corridor had no significant difference (Table 1). The yarding corridor was not linear and post-yarding sampling provided seven outside-of-corridor samples from original pre-treatment sampling sites. These post-treatment samples did show a significant decrease in Db compared to the pre-treatment (Table 1).



**Fig. 5** Boxplots showing pre-treatment soil bulk density (Db) measurements in the hand and machine felled corridors. An unpaired, unequal variance t-test indicated no significant difference between pre-treatment Db's

**Table 1** Average ( $\pm$ SD) soil Db (Mg/m<sup>3</sup>) in the hand- and machine-felled corridors. For the machine-felled corridor, post-treatment sample locations are in the machine track, between machine tracks, and outside machine tracks

Hand-felled corridor		Machine-felled corridor						
Pre-treatment (n=22)	Post-yrarding inside corridor (n=21)	Post-yrarding outside corridor (n=7)	Pre-treatment (n=25)		Post-yrarding			
			In track (n=19)	Between (n=19)	In track (n=21)	Between (n=18)	Outside (n=16)	
1.08 $\pm$ 0.16	0.96 $\pm$ 0.24	0.85 $\pm$ 0.14*	1.12 $\pm$ 0.11	0.92 $\pm$ 0.18*	0.88 $\pm$ 0.16*	1.08 $\pm$ 0.16	0.91 $\pm$ 0.16*	0.94 $\pm$ 0.16*

\*Significant difference compared to pre-treatment (p < 0.05)

For the machine-felled area, all locations after the tethered machine traffic (i.e., In track, between tracks, and outside track) saw a significant decrease post felling in surface soil Db (Table 1). Also, a decrease persisted between tracks and outside track after yarding. No increase in soil density was found in any location groups compared to pre-treatment after felling and yarding.

No significant differences were identified in near-surface VWC across the treatments or sample locations in this phase of the study. Average difference in VWC between the lab-based versus hand-held meter VWC was never above 10%, and the total average difference was less than 5%. Our conclusion is that the moisture probe readings, which we use for full soil profile analysis, provide acceptable interpretations of VWC for these soil types.

### Soil Penetration Resistance

In the machine-felled area, post-felling mean penetration resistance was significantly greater in the tracks compared to outside the tracks at depths of 20 cm to 40 cm (Table 2). Although track resistance was also greater than between tracks at these depths, the difference did not reach statistical significance ( $p > 0.05$ ). These data suggest that even two passes of the felling machine can cause subsurface compaction, as indicated by the increased penetration resistance extending into the rooting zone.

Post-yarding penetration resistance in the machine-felled area along tracks, between tracks, and outside tracks had diminished, and no differences, slight or significant, were detected (Table 2). In the hand-felled area, comparing soils in the yarding disturbance to soils outside the drag line (i.e., undisturbed), penetration resistance with depth had no statistical difference (Table 3). The average penetration resistance in both machine and hand-felled areas remained well below the 20 kg  $\text{cm}^{-2}$  threshold.

**Table 2** Average ( $\pm$ SD) soil penetration resistance (kg  $\text{cm}^{-2}$ ) for the post-felling and post-yarding sample periods, measured at each soil depth in the machine-felled corridor. Sample locations are in the machine track, between machine tracks, and outside machine tracks. Comparisons are not made between values of post felling and post yarding

Soil Depth	Post Felling			Post Yarding		
	In track (n=22)	Between (n=21)	Outside (n=22)	In track (n=22)	Between (n=22)	Outside (n=22)
10 cm	4.91 $\pm$ 3.21	5.05 $\pm$ 2.27	3.77 $\pm$ 2.71	3.72 $\pm$ 2.35	2.82 $\pm$ 1.94	3.64 $\pm$ 2.56
20 cm	10.00 $\pm$ 7.20	6.90 $\pm$ 3.14	5.45 $\pm$ 2.65* <sup>§</sup>	6.32 $\pm$ 2.88	5.45 $\pm$ 2.04	5.50 $\pm$ 2.58
30 cm	9.95 $\pm$ 5.39	7.57 $\pm$ 4.15	7.09 $\pm$ 4.66*	7.41 $\pm$ 2.11	7.32 $\pm$ 3.05	8.14 $\pm$ 3.38
40 cm	10.45 $\pm$ 5.07	7.71 $\pm$ 3.51	8.00 $\pm$ 3.66*	8.91 $\pm$ 2.72	8.18 $\pm$ 3.02	9.45 $\pm$ 5.03
50 cm	13.41 $\pm$ 9.32	8.71 $\pm$ 4.89*	9.09 $\pm$ 4.36	10.73 $\pm$ 4.75	9.55 $\pm$ 3.86	10.86 $\pm$ 3.04

\*Significant difference compared to in track ( $p < 0.05$ )

§Significant difference compared to between tracks ( $p < 0.05$ )

**Table 3** Average ( $\pm$ SD) soil penetration resistance ( $\text{kg cm}^{-2}$ ) for the post-yarding sample period, measured at each soil depth for the original and undisturbed locations in the hand-felled corridor. There was no significant difference in post-yarding measurement between original and undisturbed outside-of-corridor locations ( $p > 0.05$ )

Soil Depth	Original sample location (n=22)	Undisturbed location (n=7)
10 cm	4.45 $\pm$ 2.26	3.57 $\pm$ 1.27
20 cm	6.50 $\pm$ 2.94	7.71 $\pm$ 3.45
30 cm	7.41 $\pm$ 3.10	8.57 $\pm$ 3.99
40 cm	8.55 $\pm$ 3.56	10.71 $\pm$ 4.23
50 cm	11.27 $\pm$ 5.03	8.86 $\pm$ 3.08

**Table 4** Average daily difference in volumetric water content ( $\Delta\text{VWC}$  in  $\text{m}^3 \text{m}^{-3}$ ) between track and outside of track areas by sample location and soil depth. The relative difference (%) is calculated as  $\Delta\text{VWC}$  divided by the outside of track value. Positive values indicate higher VWC in the track areas

Location	10 cm	20 cm	30 cm	40 cm	50 cm
1	0.074 (36%)	0.031 (13%)	0.035 (15%)	0.037 (14%)	0.015 (5%)
2	0.044 (16%)	0.043 (17%)	0.017 (6%)	0.013 (4%)	0.034 (12%)
3	0.117 (46%)	0.194 (75%)	0.238 (87%)	0.178 (53%)	0.108 (28%)
4	0.030 (11%)	0.004 (1%)	0.032 (10%)	0.035 (10%)	0.075 (20%)

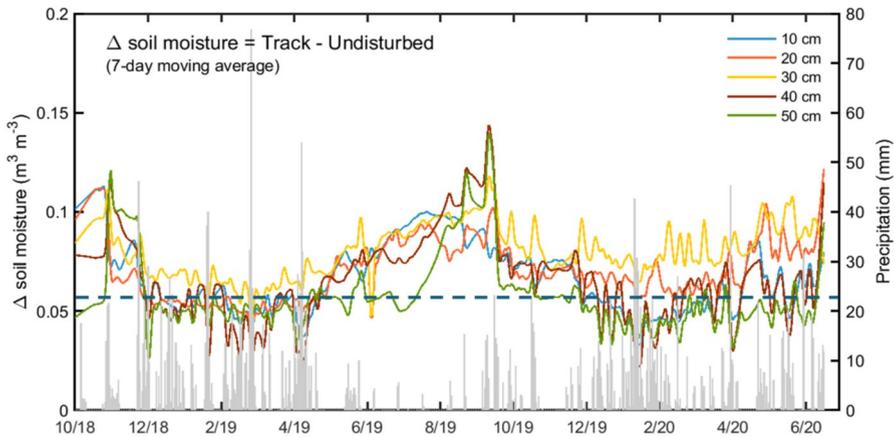
## Phase 2: Soil Resilience Analysis

### Soil Erosion

During the two-year post-harvest deployment of silt fences, no measurable silt was found in the silt fences, nor was soil erosion observed within the soil sample collection corridors. No rills were evident elsewhere as the site was transversed for other sample collections over the study period. This result was consistent with the low soil impacts of tether-assist harvesting found in the harvest unit, i.e., no significant increase in surface soil Db in the machine-felled area.

### Soil Moisture

Volumetric water content (VWC) was continuously monitored at 15-min intervals for 20 months at five depths in four paired locations (machine track vs. adjacent undisturbed area outside of the track). Analysis revealed that soils within the machine tracks consistently maintained higher moisture content at all measured depths compared to the undisturbed locations (Table 4). The magnitude of this relative increase

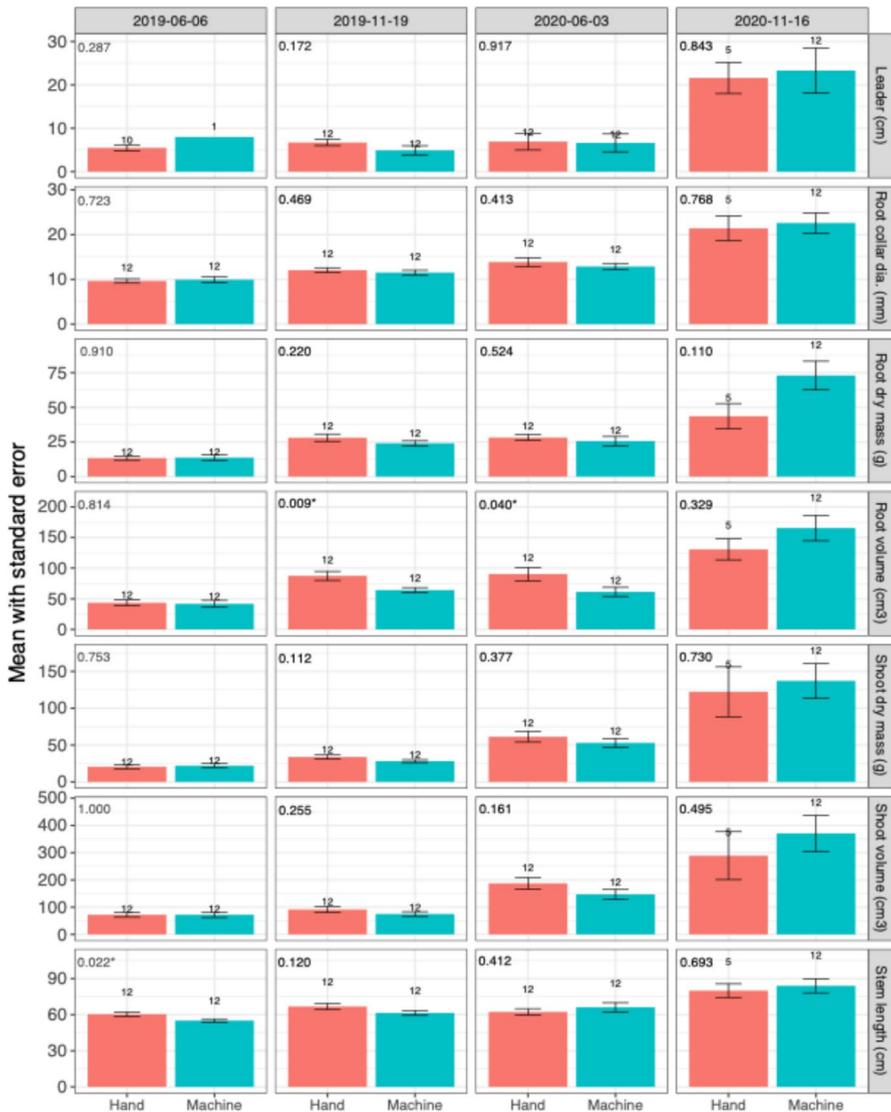


**Fig. 6** Soil moisture content difference between track and non-track locations as a series of 7-day average of all sites and depths. Precipitation is shown in gray bars. The dashed line at  $0.06 \text{ m}^3 \text{ m}^{-3}$  represents the combined  $\pm$  accuracy of the moisture probe

varied by location and depth, ranging from 1 to 87%, with the difference being most pronounced during the dry season. When aggregated across all sample locations and soil depths, the mean VWC for the entire study period was  $0.335 \text{ m}^3 \text{ m}^{-3}$  in the tracks and  $0.287 \text{ m}^3 \text{ m}^{-3}$  outside the tracks, representing a mean difference of  $0.068 \text{ m}^3 \text{ m}^{-3}$  (24%). While this moisture gap remained relatively stable during the wet season (November–April) at a 20% difference, it expanded to 29% during the dry season (May–October). The most pronounced difference occurred during peak dryness in August, where tracked areas maintained a VWC of  $0.318 \text{ m}^3 \text{ m}^{-3}$ , which was 41% greater than the  $0.226 \text{ m}^3 \text{ m}^{-3}$  observed outside the tracks. The 7-day rolling average of  $\Delta \text{VWC}$  (Fig. 6) highlights that moisture retention was most evident at the 30–50 cm depths during the peak dry months (i.e., August and September), which correspond to the soil horizons where significantly greater soil penetration resistance was observed under the machine tracks.

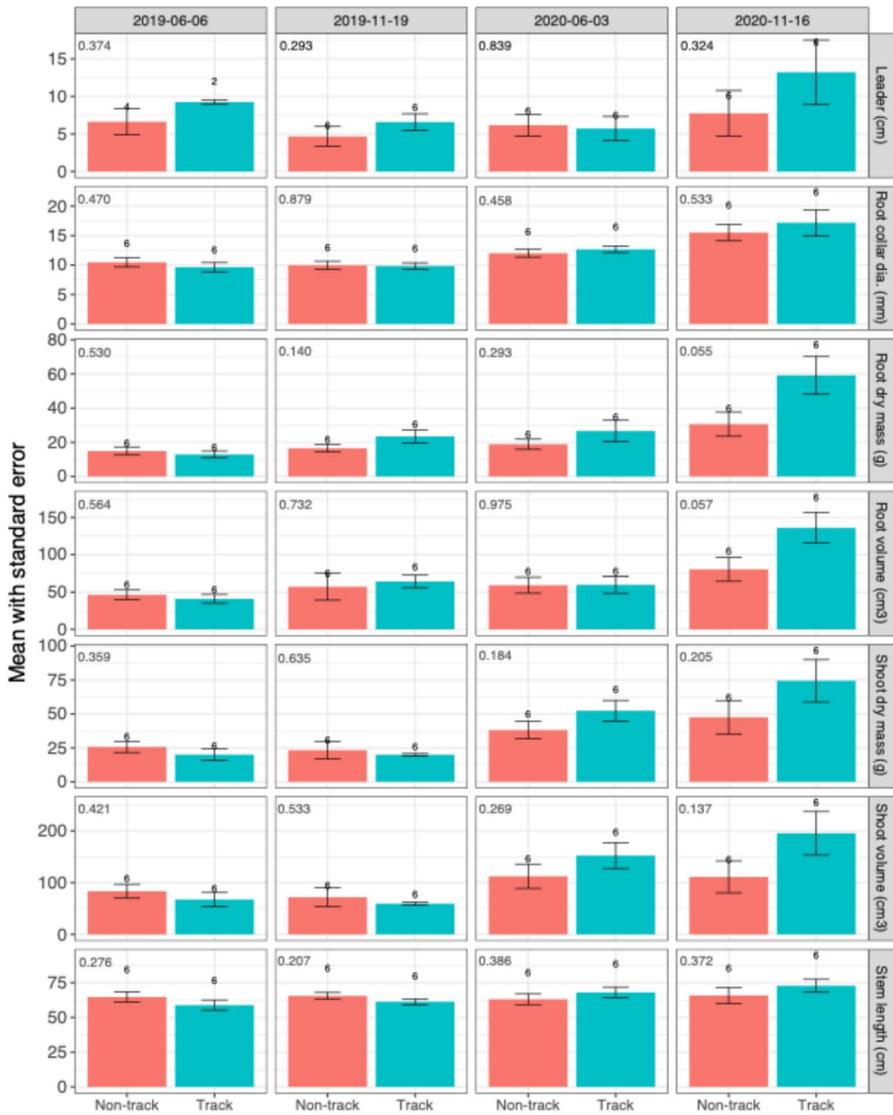
## Seedling Growth

We compared seven growth metrics for seedlings planted in the machine and hand-felled areas (Fig. 7). Statistical analysis using two-sample t-tests indicated no significant differences in the growth metrics between the machine and hand-felled areas throughout the majority of the sampling period ( $p > 0.05$ ) except root volume measured in November 2019 and June 2020 where hand-felled area showed greater root volume compared to machine-felled area. Despite this greater root dry mass in early periods in hand-felled area, by the final sampling period, mean values for all growth metrics were greater in the machine-felled area, though this trend did not reach statistical significance.



**Fig. 7** Average seedling characteristics 20 months after outplanting in the hand- and machine-felled areas (experimental blocks A and D in Fig. 4a). Sample size ( $n$ ) is indicated above the error bar. P-values from two-sample t-tests are shown in the upper left corner of each panel

The greatest differences in seedling growth were observed when comparing track to non-track areas (Fig. 8). By the final sampling period, growth metrics for seedlings planted in the tracks were substantially greater than those in off-track locations. Specifically, total dry biomass (root+shoot) was approximately 71% greater in the track seedlings. Despite these large differences in mean values, the t-tests indicated



**Fig. 8** Average seedling characteristics 20 months after outplanting in the track and non-track areas (experimental blocks B and C in Fig. 4a). Sample size (n) is indicated above the error bar. P-values from two-sample t-tests are shown in the upper left corner of each panel

no statistically significant difference ( $p > 0.05$ ). This outcome is likely attributable to low statistical power resulting from the small sample size ( $n = 6$ ). Nevertheless, the magnitude of the difference suggests a biologically relevant growth advantage for seedlings established within the machine tracks.

## Discussion

### Surface Soil Response and Erosion Potential

Harvest operations, by tethered machine or hand-felling followed by cable yarding, decreased Db in the 0–10 cm zone. Surface Dbs for native forested soils of the western Cascade Range are typically below  $1 \text{ g cm}^{-3}$ , especially where organic horizons are intact and soils are undisturbed (Froelich and McNabb 1983). Miller et al. (1996) on similarly textured soils in the Washington Coast Range measured Db of  $\sim 0.30 \text{ g cm}^{-3}$  in the 0–10 cm depth pre harvest operations. Our pre-treatment Db values (Table 1) fall within in the reported ranges. Results suggest that surface soils had an overall decrease between 10 and 20% in Db, regardless of machine or hand felled or location (inside, between, or outside of track). This is contrary to some regional studies on similar soils where surface Db increased by 30–40% (Ares et al. 2005; Miller et al. 1996). However, those other studies were on untethered harvest systems. Green et al. (2020) demonstrated reduced Db in a tethered system also in Oregon.

We hypothesize that the reduction in Db is related to the typical agitation of the surface soil in a harvest system, but with a reduced machine ground pressure. This can displace surface soil, and incorporate organic material, thereby increasing pore space and decreasing Db. This physical loosening of the surface soil has direct implications for sediment transport. While sediment production via erosion is often anticipated in steep, machine and log trafficked corridors, our study observed no sediment movement. This lack of erosion in our system can likely be attributed to the limited machine traffic and tree drags within the designated corridors, which did not cause the significant disturbance or surface sealing typically associated with increased runoff. Our findings of decreased Db in the surface soils indicate increased near-surface pore volume, and the high levels of organic debris within the corridors likely stabilized the soil surface, allowing water infiltration rather than runoff. Post-harvest regrowth of grasses and forbs appear to have stabilized the trafficked areas, suggesting that erosion is unlikely moving forward.

### Subsurface Compaction and Hydrological Implications

Penetration resistance is shown to increase with increasing Db and decrease with increasing VWC (Lowery and Morrison 2002; Taylor et al. 1966; Vepraskas 1984).

Resistance with depth is often used to infer compaction: greater resistance equates to higher Db as a result of compaction, although, variations in VWC between sampling can affect that assertion. As suggested by Powers et al. (1999), penetration resistance is a valuable indicator of plant rooting success, with plant root growth being negatively impacted at resistances  $>20 \text{ kg cm}^{-2}$ . Several studies have also related tree root growth with Db (Heilman 1981; Wasterlund 1985), finding, in general, that increased Db decreased plant root growth. Heilman (1981)'s work, in particular, is relevant to this study as he investigated Douglas-fir on similar soils in western Washington (Salkum series; fine, kaolinitic, mesic Xeric Palehumults).

Given the demonstrated relationships between penetration resistance and root growth, root growth and Db, and Db and penetration resistance, we feel confident that our resistance measurements can be interpreted for both relative changes in Db as well as impacts on plant root growth and overall plant growth, regardless of soil moisture content at the time of sampling.

Penetration resistance with depth was significantly greater under the tracked area compared to outside the track following felling (Table 2). The soils between the tracks also showed a noticeably lesser resistance than the tracked, but were not statistically different. These findings indicate that the tether-assist felling is associated with an increase in Db with depth in the track area of the study site soils. The post-yarding soil penetration resistance measurements at each depth are very similar across locations in the machine-felled area (Table 2). The statistically significant resistance increase under the tracks post-felling is not apparent in the post yarding data. In the hand-felled area, there was no apparent difference in resistance between the yarding drag line and the undisturbed area (Table 3). Other than the disturbance of the near surface soils, felling and yarding did not appear to have an impact with depth on the hand-felled harvest unit. The average penetration resistance across all sample periods or locations at any depth remained well below the  $20 \text{ kg cm}^{-2}$  threshold for root growth (Gebauer et al. 2012; Powers et al. 1999). We conclude that in the silty clay loam soils of our study site, plant root growth is not negatively impacted by the tether-assist system.

The 20-month continuously measured VWC, when compared for the sample period, suggests that the tracked area exhibited a greater VWC compared to adjacent outside track locations. VWC was consistently higher in the tracked areas across all measured soil depths (Fig. 6). When we relate this information with the penetration resistance, we speculate that the subsoils in the tracked locations experienced a decrease in pore size compared to the outside track locations. Ares et al. (2005) in west-central Washington reported similar results, where Db increased approximately 27%, leading to a 10–13% decrease in pore space, including a 60% decrease in macropores at 10–20 cm depth. They reported a corresponding increase in PAW. Gomez et al. (2002) also reported PAW increases and enhanced tree growth after intentional compaction for some soil types. In our study, we did not measure soil water potential, and therefore we cannot conclude that PAW increased for the tracked soils; however, we believe this to be a possibility given the performance of the seedling responses. We posit that the compaction-induced smaller pores in the track locations yield a greater matric potential (Bird et al. 2005), allowing them to retain water against gravitational and evapotranspiration forces, thereby yielding higher PAW as the summer progresses.

## Seedling Response

Within the machine-felled treatments, seedlings in tracked areas exhibited greater increases in leader length, stem diameter, and root and shoot mass compared to seedlings outside of the track. Similarly, the Ares et al. (2005) non-tethered study on similarly textured (compared to Jory series) found that after three years, above-ground

tree-volume index ((basal diameter)<sup>2</sup> x height) was higher in trafficked areas. Our displacement-measured stem volume for seedlings in tracked areas (Fig. 8) was approximately 60% greater than those in out-of-track areas after 20 months. Crawford et al. (2021) summarized how harvesting disturbance could impact plant growth and found mixed results; however, improved seedling growth after disturbance is not uncommon, regardless of soil texture type. Generally, the controlling variable would be degree of compaction that could lead to reduced root penetration and reduced pore space and thereby reduced plant available water capacity. We speculate that in our study a collapse of macro pores but retention of small pores led to a greater matric potential giving the seedlings in the tracked blocks a moisture advantage especially during the drier growing season months. In the Mediterranean climate of the Pacific Northwest, adequate late-summer moisture is a critical determinant of seedling success (Hobbs 1992).

## Conclusions

The immediate and longer-term (up to 32 months post-harvest) soil impacts following tether-assisted steep slope harvesting showed no significant difference in the evaluated soil metrics, including Db, penetration resistance, erosion, water holding capacity, and seedling growth, when the tether-assisted system was compared to the traditional hand-felling system coupled with cable logging. However, within the machine-felled area, the following trends were observed: We observed no soil erosion in the areas equipped with silt fencing, a decrease rather than an increase in surface soil Db, penetration resistance with depth that is well below negative rooting-impact levels, and enhanced seedling growth in tracked soils, which also showed increased AWC with depth. This evaluation of these resilience metrics suggests that the soils of these steep-sloped systems are resilient when harvested using tethered-assisted felling followed by cable logging under similar soil and work conditions as the study area. Compared to conventional hand-felling methods on steep slopes, which have been used as an acceptable logging method, our study found no observable significant net negative consequence for the soil conditions with a tether-assist system. These results are similar to those of Chase et al. (2019) when comparing soil disturbance and stream-adjacent disturbance of conventional, combined, and tether-assisted harvesting operations in Oregon and Washington.

Research on soil impacts on steep-slope tether assist operations is nascent. As with all site-specific research, the results presented here are limited in their extrapolation to areas of vastly different soil types and environmental conditions. Our landscape had relatively low complexity with regard to topography and soils. Soils in similar stages of pedological development, were rock-free in the study area, and topographic complexity was low. Further investigation is warranted to explore the nuances and broader applicability of our observations across a wide range of soil and ecological conditions.

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**Data Availability** All data can be made available upon reasonable request to the corresponding author.

## Declarations

**Competing interests** The authors have no competing interests to declare that are relevant to the content of this article.

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