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Soil disturbance and stream-adjacent disturbance from tethered logging in Oregon and Washington

Christopher W. Chase[a,*], Maryanne Reiter[b], Jessica A. Homyack[a], Jay E. Jones[c], Eric B. Sucre[b]

[a] Weyerhaeuser Company, 505 North Pearl Street, Centralia, WA 98531, USA
[b] Weyerhaeuser Company, 785 North 42nd Street, Springfield, OR 97478, USA
[c] Weyerhaeuser Company, 220 Occidental Avenue South, Seattle, WA 98104, USA

ABSTRACT

Over the past century, the primary method for harvesting trees on steep slopes in the Pacific Northwest (PNW) was felling with chainsaws and yarding with cable systems, such as towers. Concerns over safety and higher logging costs on steep slopes have caused a shift in felling and/or yarding to ground-based machines tethered to an anchor, generally at the top of the slope. With the recent shift to tethered operations, there has been growing interest in the potential impact of machinery on steep slopes on streams and site productivity. We compared soil disturbance and stream-adjacent disturbance of tethered logging and conventional cable harvest methods on steep slopes in Oregon and Washington, USA. We sampled 30 harvest units that included either conventional ($n = 15$) or combination units with tethered ($n = 15$) harvesting systems to examine soil disturbance within a harvest unit and along stream channels. We compared potential impacts to stream adjacent-disturbance, erosion, and site productivity both between harvesting types within a harvest unit and between conventional versus combination units with tethered operations. We found that combination units with tethered operations had more stream-adjacent disturbance and soil disturbance than conventional cable-harvesting systems, but overall effects were below applicable regulatory thresholds for stream-adjacent disturbance and soil disturbance. Further, at the entire harvest-unit and within-unit scale, tethered operations had similar amounts of soil disturbance as mechanized harvesting systems. We did not find evidence of strong relationships between stream-adjacent disturbance or soil disturbance with either slope or soil depth. Across a wide variation of local site conditions in the PNW, tethered harvesting operations did not have extensive negative impacts on either soil disturbance or stream-adjacent disturbance, but further research could contribute to evolving best management practices and aligning forest practice regulations with current technologies.

1. Introduction

Managed forests in the Pacific Northwest (PNW) of the United States provide wood to meet society's needs for dimensional lumber for building construction and pulp for paper manufacturing. In Oregon and Washington, 80% of the total forest area is classified as timberlands with capability of producing an excess of $1.4\,m^3\,ha^{-1}\,year^{-1}$ (Oswalt et al., 2014) and provides 27.7% of the nation's wood production (Oregon Forest Resources Institute, 2019). State and federal regulations about forest practices have evolved since their inception in the early 1970s. These regulatory systems include measures to minimize soil disturbance to protect forest productivity and reduce water quality impacts from sediment (USDA Forest Service and USDI Bureau of Land Management, 1994; Washington Forest Practices Board, 2001; Oregon Department of Forestry, 2014). One of the factors driving the evolution of forest practice rules has been changes in technology used to harvest and transport trees in the PNW.

Timber harvesting in the PNW has evolved from hand-felling old-growth trees with axes and then cross-cut saws to what is now the common practice of felling smaller second growth timber with chainsaws or mechanical harvesters on flatter terrain. In steep mountainous terrain, timber harvest consisted almost exclusively of hand-falling timber with chainsaws and then fully or partially suspending the logs on cables to yard them to a landing for processing and hauling. Alongside changes in logging technology, transportation of wood has evolved from animals, floating log booms, and railroads to an expansive road network and trucking fleet. Although hand-felling on steep terrain has been used for decades, economic constraints and concerns for worker safety are fostering innovation in alternative, more mechanized methods, including using machines to cut and yard felled trees. Further, mechanized systems are safer than non-mechanized systems with injury rate almost 7 times lower for mechanized systems as compared to hand-felling (Bonauto et al., 2019). However, to operate safely, mechanized systems, such as self-leveling shovels or feller-bunchers have been limited to slopes $< 60\%$ (Belart et al., 2018).

To address concerns over worker safety and improve productivity, innovative efforts have focused on adapting logging machinery for steep slopes. These steep-slope mechanical harvesting and yarding systems are referred to as tethered (term used here), cable-assisted, or winch-assisted operations. They consist of a machine, often a tracked

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* Corresponding author.
E-mail address: christopher.chase@weyerhaeuser.com (C.W. Chase).

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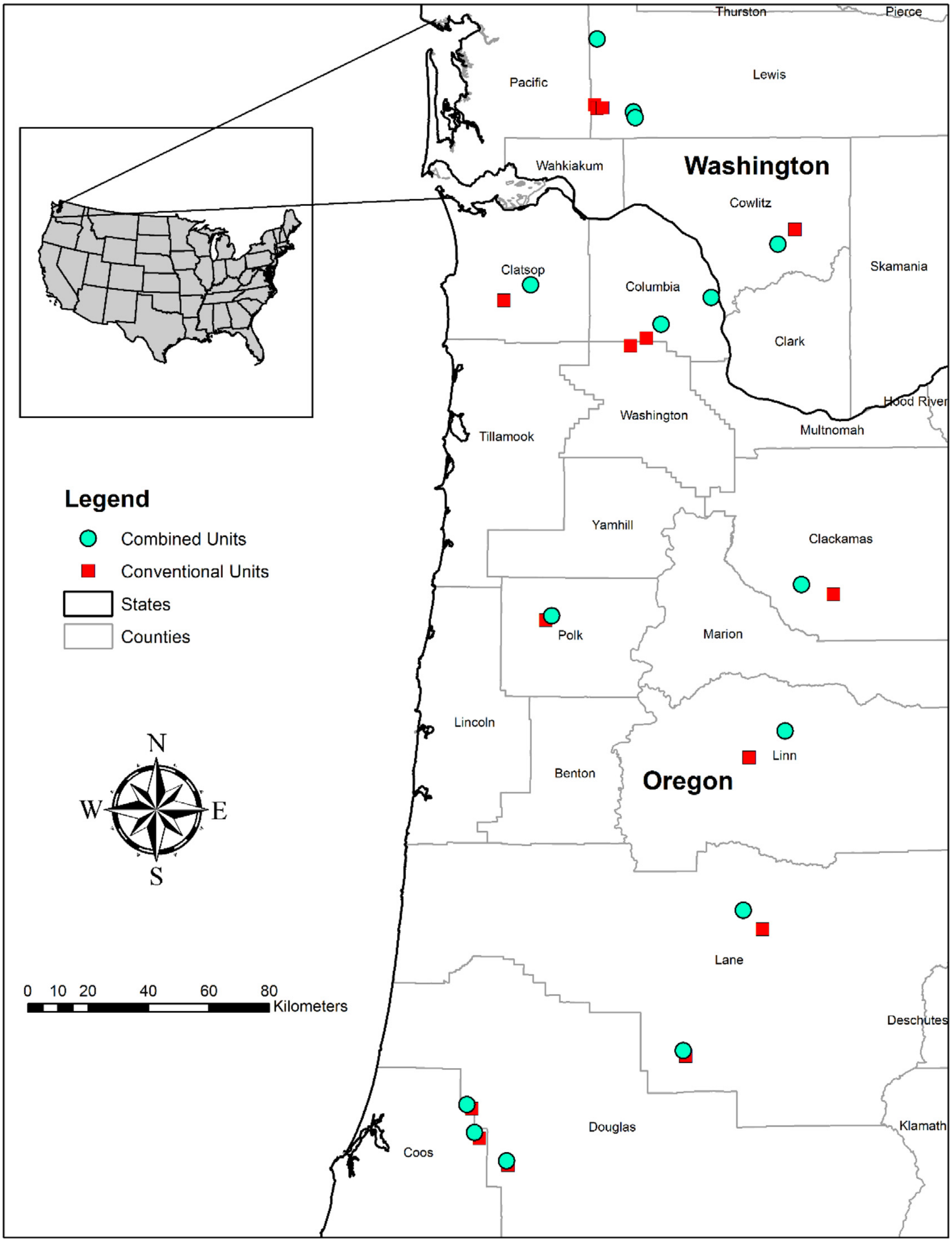

Fig. 1. Location of 30 harvest units (15 units with combined operations and 15 units with conventional steep-slope harvest methods) across Washington and Oregon, USA.

feller-buncher, with a winch and cable attached to an anchor, typically a separate piece of equipment on the road or near the landing at the top of the slope. Although tethered operations have been applied in New Zealand and Europe for more than a decade, they recently have had more widespread adoption in managed forests of the PNW to leverage potential reductions in harvesting costs, increase mechanized harvesting on previously inoperable grounds, increase productivity, and reduce hazard exposure for loggers (Green et al., 2019; Sessions et al., 2016).

Maintaining soil productivity is an integral part of overall forest management (Burger and Kelting, 1999; Grigal, 2000; Fox, 2000; Powers et al., 1990). An important element in protecting soil productivity is minimizing soil compaction. Compaction can also contribute to erosion, which may cause sediment delivery to streams and consequent negative impacts to aquatic ecosystems and downstream resources (Batey, 2009; Gomi et al., 2005; Greacen and Sands, 1980; Litschert and MacDonald, 2009). Protection of water resources from forestry operations is a large focus of state forest practices rules and best management practices (BMPs) in the PNW (Cristan et al., 2016). Both Oregon and Washington regulations limit ground-based machine activity near streams, wetlands and other water features and operations must minimize exposed soil (Washington Forest Practices Board, 2001;

Oregon Department of Forestry, 2014) to prevent sediment delivery. While forest roads and landslides have received considerable attention for their potential sediment delivery to streams (Reid and Dunne, 1984; Luce and Black, 1999; Reiter et al., 2009; Turner et al., 2010; Goetz et al., 2015; Arismendi et al., 2017), there has been less investigation into effects of mechanized forest harvest on soil disturbance and sediment delivery potential (Block et al., 2002; Han et al., 2009), especially on steeper slopes.

Despite the rapid growth of tethered harvesting systems, little is known about the environmental performance of operating these systems on steep slopes (Visser and Stampfer, 2015). Tethered machines working on steep slopes can lose traction under certain conditions, yet when and where track slippage and resulting soil disturbance occurs is complex and affected by environmental factors such as soil properties, moisture and slope gradient and form (Belart et al., 2018; Burger and Kelting, 1999) and machine factors including cable tension, grouser (extenders to increase traction) depths on tracks, and operator experience (Belart et al., 2018). Recent controlled case studies on tethered logging have integrated soil physical properties and machine characteristics to improve understanding of soil disturbance by these harvesting systems at small spatial scales (Zamora-Cristales et al., 2014; Sessions et al., 2016). Contemporary forest management systems are also held to regulatory (e.g., state forest practice acts) and voluntary (third-party sustainability certification systems) standards that relate to minimizing soil disturbance and potential for delivery of sediment to waterbodies. Therefore, as new logging technologies are developed, they must also be evaluated for environmental performance. While research is just beginning to examine effects of tethered logging on soils (Belart et al., 2018; Sessions et al., 2016; Zamora-Cristales, et al., 2014), there has not been an extensive examination of the effects of the technology across the broader PNW landscape. To address gaps in understanding of the environmental effects of tethered logging, we compared soil disturbance and stream-adjacent disturbance of tethered logging to conventional methods of harvesting on steep slopes. Specifically, we quantified soil disturbance (erosion and compaction) and the amount of disturbance adjacent to stream channels across a broad geographic area of Washington and Oregon, USA.

2. Material and methods

2.1. Study area

The study area ranged from the western slopes of the Cascade mountains to the Pacific Ocean coast in Oregon and Washington and was conducted on Weyerhaeuser ownership (Fig. 1). Douglas-fir (*Pseudotsuga menziesii var.menziesii* (Mirb.) Franco), Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and Western redcedar (*Thuja plicata* Donn ex D.Don) are the primary commercial tree species. The topography of the region ranges from gently sloped low elevation hills near the coast to complex steep mountainous terrain > 4000 m above sea level, but most of this study was conducted between 90 and 900 m above sea level. Soils are generally deep with distinct diagnostic horizons and the dominant soil orders include Inceptisols, Andisols, and Ultisols (Soil Survey Staff, 1999). The PNW has a Mediterranean climate defined by its cool wet winters and warm dry summers.

Most forested land in this region is under management of private industry, state (Washington Department of Natural Resources, Oregon Department of Forestry), and federal (United States Forest Service, Bureau of Land Management) organizations. Due to a variety of forest landowners, management strategies are variable from intensively managed plantations to a focus on restoration, recreation, and wildlife habitat.

2.2. Study design

In 2016, we developed our field methods by sampling five post-harvest units in Washington, USA that were logged in part with tethered machinery during the previous wet season (November 1, 2015–March 31, 2016). This timing restriction focused our sampling efforts at locations where the greatest amount of disturbance from tethered machinery was expected due to seasonally wet soils. We used results from 2016 to characterize within and among-harvest unit variation in response metrics, and to estimate sample size requirements. Based on these results we projected that a sample size of 15 conventional and 15 harvest units with tethered operations would provide standard errors for mean estimates of approximately 0.4% for stream-adjacent disturbance and 2% for moderate soil disturbance.

Steep-slope harvest units in the PNW typically deploy more than one cutting and yarding method. For example, felling can occur using both ground equipment and by hand with chainsaws in the same unit. For this study, we characterized the harvest-unit-level operations as either “conventional” or “combined” depending on the predominant harvest method used on steep slopes within the site. Conventional sites were harvested primarily by hand-felling but may have had areas where non-tethered machines were used to log and yard. Conventional cable harvesting was performed with chainsaws to hand-fall trees and yarded with cables from towers. Combined sites included harvesting and/or yarding with tethered feller-bunchers, shovels, or both, but also may have included areas of hand-felling or un-tethered machines. Although units were harvested with different techniques, the steep portions of all the units would have been harvested using cable (conventional) systems prior to the introduction of the tethered technology.

Stand conditions prior to harvest and harvesting techniques used were similar across all units. Managed stands were on their second rotation, averaged approximately 544 trees per ha, 55 m^2 per ha of basal area, 40 cm quadratic mean diameter, and the mean age at harvest was 53 years old. All stands were clearcut harvested between 2016 and 2017. Tracked harvesting equipment was used for ground-based harvesting (including tethered equipment) rather than rubber tires. Conventional cable harvesting included partial suspension of logs during yarding except for when full suspension was required (e.g., over streams).

We used a two-sample design to evaluate the unit-level impact of operations on soil disturbance and stream-adjacent disturbance. We selected 30 units (combined, n = 15; conventional, n = 15) across Oregon and Washington (Fig. 1). Due to operational constraints, harvest operations were not randomly assigned to units, but rather we selected units from the pool of available sites for each method that met our selection criteria. Units selected for combined operations required at least 8.1 ha (20 acres) harvested using tethered systems. For conventional harvesting systems, we only selected steep slope harvest units without tethered systems. The slight differences in unit selection criteria between combined and conventional harvest systems ensured adequate sampling area and reliable control conditions were maintained. We also selected units that had experienced at least one wet (winter) season after logging to facilitate evaluation of stream-adjacent disturbance and erosion potential. Regulations allow harvesting activities to take place adjacent to seasonal streams, as well as temporary stream crossings under certain conditions (Washington Forest Practices Board, 2001; Oregon Department of Forestry, 2014). To quantify stream-adjacent disturbance as a response variable, we selected combined or conventional units with > 1 seasonal stream.

We further designated within-unit areas according to the methods used as “hand cut”, “tethered”, or “other”. Areas of combined units using harvest methods other than tethered logging were termed “combined-other”, while areas of conventional units using harvesting methods besides hand-falling and cable yarding were classified as “conventional-other.” For each selected study unit, we spatially digitized within-unit methods of harvest based on notes from the harvest engineer and verified during the field surveys. The digitized harvest areas were used to delineate subsamples and summarize unit characteristics. Within each unit, we sampled across all harvest methods

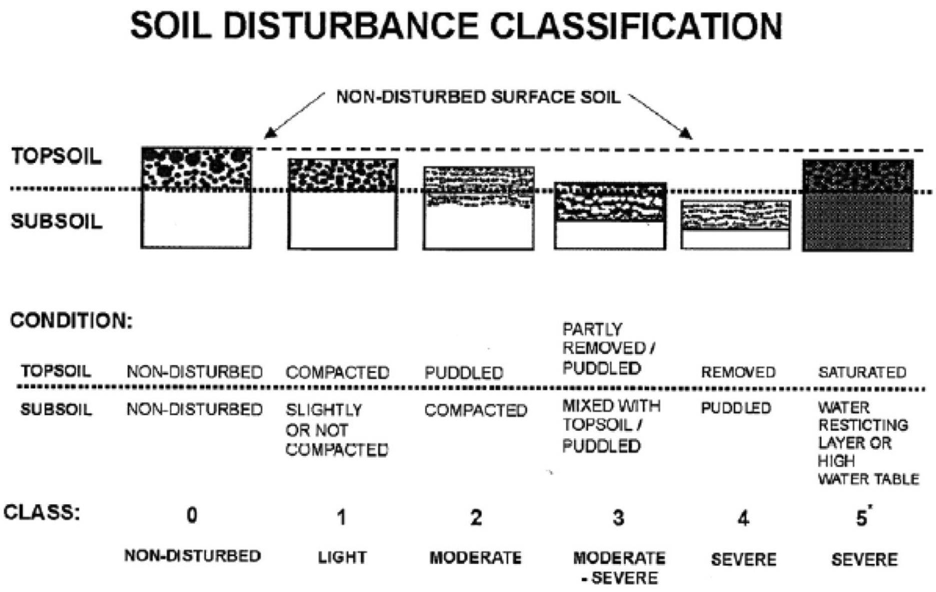

Fig. 2. Diagram of soil disturbance classification system (Heninger et al., 2002).

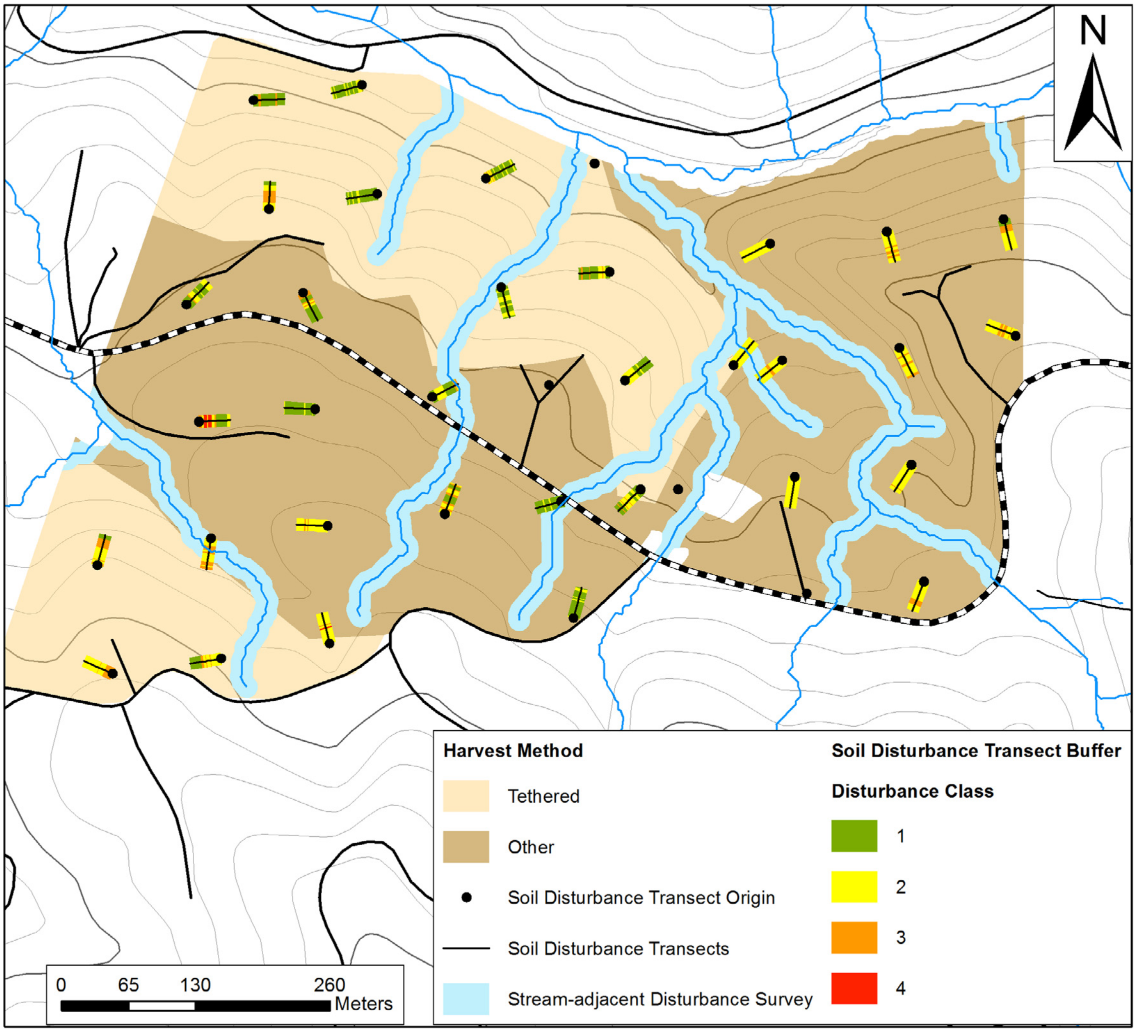

Fig. 3. Example of a combined harvest unit post-digitizing showing the different harvest methods, locations of soil disturbance sampling transects and disturbance classes, and location of stream-adjacent sediment delivery potential survey areas (light blue area along streams). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and slopes, rather than steep-slope only portions. Our aim was to characterize the entire harvest unit, as this is the area of operational and regulatory interest.

2.3. Data collection

We quantified soil disturbance based on visual characteristics as described in the soil disturbance classification of Heninger et al., 2002 (Fig. 2). In this classification, disturbance classes 0 and 1 have generally intact topsoil (A and AB horizons) with some slight compaction from harvesting equipment. Class 2 is characterized by some mixing of topsoil and organic layer (O horizon), some puddling (settling of soil), and compaction. Classes 3 and 4 are defined by partial or complete removal of the A-horizon, respectively. Finally, class 5 often has water puddling at the surface due to excessive compaction as a result of the harvesting activity. Since soil disturbance classes 3, 4, and 5 can lead to long-term reductions in site productivity these classes were deemed excessive disturbance for this study.

In each unit, we quantified soil disturbance on approximately 30 randomly distributed transects proportional to the area in each harvest method. We ensured that > 10 transect origins were assigned to either the tethered or conventional harvest methods to have an adequate sample for those harvest methods. At the origin of each transect, we measured the depth of the topsoil (A horizon), recorded the harvest method by examining evidence of machine tracks on steep slopes, and the method used to cut trees (feller-buncher versus chainsaw) to verify the digitized harvest methods from the harvest engineer's notes.

We randomly oriented a 30.48 (100 ft) meter transect from each transect origin. Along each transect, we recorded length (m) in each soil disturbance classification (Heninger et al., 2002). Occasionally, we encountered harvest unit boundaries, roads, or non-harvested areas as part of the transect. When this occurred, the transect was "mirrored" by stopping along the transect where the obstacle was encountered and continuing 180° until the end of the transect (Gregoire and Monkevich, 1994). We did not sample transects whose origins landed directly on roads or non-harvested areas.

We estimated slope and verified National Resource Conservation Service mapped soil series (Soil Survey Staff, 2018) of each soil disturbance transect from spatially referenced transects to supplement field data. To complete this, we reproduced transects using the 'geosphere' (Hijmans, 2017) and 'rgdal' (Bivand et al., 2019) packages in Program R (R Core Team, 2018). We buffered spatial transects by 6.096 m using the 'rgeos' (Bivand and Rundel, 2018) package in Program R (Fig. 3).

Our pilot project indicated that streams with riparian buffers > 15 m wide had little to no stream-adjacent disturbance based on field observations. Thus, for the current effort we only examined streams and other waterbodies without riparian buffers or with buffers that were < 15.0 m wide where there was higher likelihood of sediment delivery to the stream channel. As a result, we surveyed all small, non-fish seasonal and perennial streams without overstory buffers. Within the 15 m from the stream edge survey area, we plotted the location for each harvest-related disturbance area that had an area of exposed soil greater than 2 m × 2 m. At each disturbance location, we measured the length and width of exposed soil, noted the cutting method (i.e., hand-cut or machine cut), distance to stream channel, and the side-slope gradient leading into the adjacent stream. We qualitatively described soil disturbance type (compaction, gouge, scrape, rut) and potential cause (machine track, yarding scar, landslide, etc.).

2.4. Statistical analyses

We performed two separate analyses on each of the two-response metrics: one to estimate the mean unit-level response for each type of harvest operation (conventional versus combined), and another to estimate the mean response for each within-unit harvest method (conventional-hand cut, conventional-other, combined-tethered, combined-other). We used a quasi-binomial regression model with logit link to analyze the unit-level response. This model contained a two-level factor for harvest method (conventional, combined) as the only covariate. The analysis of the within-unit response used a generalized linear mixed model to account for potential correlation among areas of different harvest methods within a unit. The model used a logit link and binomial distribution, while also accounting for over-dispersion. A four-level categorical harvest method variable was included as the only model fixed effect, and harvest unit was included as a random intercept.

All response variables were aggregated to the unit-level for the first analysis, and to the within-unit harvest method at the area level for the second analysis. For the soil disturbance metric, we used total sampled transect length as the binomial denominator, and the total disturbed transect length as the numerator. Stream-adjacent disturbance was summarized similarly, using survey area and disturbed area as the binomial denominator and numerator, respectively. In addition to the design-based analysis described above, we created graphical displays to explore potential associations between our response variables and both slope and soil depth, and whether such associations varied by harvest method. All analyses were conducted in R using 'glm' and 'glmmPQL' (package MASS, Venables and Ripley, 2002) to fit the models. We used package 'emmeans' (Lenth, 2018) to compute marginal mean estimates for the different harvest methods.

3. Results

The total area sampled for soil disturbance across the different harvest regimes was approximately 994 ha. Units harvested with combined methods consisted of 544 ha (55% of total), of which 200 ha (20%) had tethered equipment and 344 ha (35%) had other methods. Of the remaining 450 ha (45%) harvested using conventional methods, 320 ha (32%) were hand-cut and cable yarded and 130 ha (13%) had other harvest methods (e.g., ground-based, untethered machines). Within units, we sampled approximately 82 ha of stream channels for stream-adjacent disturbance. Combined operations had approximately 49 ha (60% of total) sampled, with 32 ha (39%) of streams harvested using tethered equipment and 18 ha (22%) harvested with other methods. Approximately 32 ha (39%) were sampled across the conventional harvest unit operations, with 25 ha (30%) harvested with cable methods and 8 ha (9%) harvested with other methods.

3.1. Soil disturbance

Across all 30 harvest units, including both conventional and combined operations, 91.5% of the survey area was in soil disturbance class 1 or 2, 8.5% in class 3 or 4, and $< 0.01\%$ in class 5. We avoided sampling unharvested areas (e.g., riparian buffers) so that all soil disturbance transects were deemed a minimum of class 1. Percent disturbed soil for individual harvest units ranged from 0 to 13% on conventional harvest units and from 0.1 to 22% on combined harvest units. At the scale of the harvest unit, we estimated a lower mean percentage of soil disturbance on sites using conventional operations than on sites using combined operations (Table 1).

Within-unit mean soil disturbance percentages (Table 1) for class 3 + 4 were lower for areas using conventional cable harvesting (hand-cut with cable yarding) compared with areas using the other three harvest methods. Average disturbance on harvest areas using the other three methods was broadly similar when accounting for uncertainty in the mean estimates.

We qualitatively examined soil disturbance at the scale of the sampling transect. Our transect-level results show considerable variation across sampling locations. Slopes ranged from 0 to 160%, but most of the area of each harvest unit had slopes between 0 and 60%. In addition, there were slight differences in the distribution of slopes between harvest methods (Fig. 4). Most transects had no class 3 or 4

Table 1
Mean estimates and 95% confidence intervals for each response variable and harvest method.

Study scale	Method	Mean Stream-Adjacent Disturbance (%)	Mean Soil Disturbance (Class 3 + 4) (%)
Harvest unit operations (site-level)	Conventional	0.5 (0.3, 1.0)	3.0 (1.6, 5.5)
	Combined	1.1 (0.8, 1.6)	13.4 (10.2, 17.3)
Within-unit harvest method	Conventional – Hand cut	0.2 (0.1, 0.7)	0.3 (0.1, 1.5)
	Conventional – Other	1.4 (0.6, 3.4)	9.7 (5.9, 15.6)
	Combined – Tethered	1.2 (0.6, 2.2)	12.2 (8.8, 16.8)
	Combined – Other	1.0 (0.6, 1.7)	13.8 (10.2, 18.4)

disturbance (Figs. 5 and 6), and only 1 transect, which was observed in a conventional-cable site, had class 5 disturbance. Mean values of soil disturbance at the transect level do not appear to show strong or clear trends with either slope or soil depth for any of the four harvest method categories (Figs. 5 and 6).

3.2. Stream-adjacent disturbance

Overall stream-adjacent disturbance, among all 30 sites was < 1%. Across our study sites, the percentage of disturbed area ranged from 0 to 1.9% on conventional units and from 0 to 2.6% on combined units. At the scale of the harvest unit (Table 1; Harvest unit operations - site-level analysis), we observed a lower estimated mean percent of stream-adjacent soil disturbance on conventional units (mean estimate = 0.5%; CI: 0.2–1.0%) compared to combined units (mean estimate = 1.1%; CI: 0.8–1.6%). Our analysis at the within-unit scale estimated lower mean values of stream-adjacent disturbed area for conventional – cable harvest (0.2%; Table 1) compared to the other methods. Within harvest units that included combined operations, areas with tethered machinery had similar levels of stream-adjacent disturbance to non-tethered methods (Table 1; 1.0 and 1.2%, respectively). For conventional harvest units with hand-felling and cable yarding there was considerable uncertainty in the conventional – other method estimates due to the smaller sampling area. However, the mean estimate (1.4%) and confidence intervals were comparable with the combined operation methods.

We examined within-unit observations of stream-adjacent percentage disturbed area to understand potential relationships with side-slopes. As with the soil disturbance response, we did not observe strong or clear evidence of an association between stream-adjacent disturbance and stream-adjacent side-slopes (Fig. 7). Although we observed both apparent positive and negative trends for some harvest methods, the uncertainty in these trends is generally greater than the magnitude of the slopes.

Finally, we compared soil disturbance transect and stream survey results graphically to explore possible correlation among these two response measures at the harvest unit level (Fig. 8). The percent of disturbed soil had a weak positive correlation with percent stream-adjacent disturbance ($r = 0.54$, $R^2 = 0.29$).

4. Discussion

In addition to producing an economically sustainable source of wood products, intensively managed forests must meet voluntary and regulatory environmental metrics that protect water quality and habitat for fish and wildlife. Thus, incorporating new harvesting technologies into managed forest landscapes should occur with an understanding of potential effects on environmental sustainability. Here, we evaluated new applications of a steep slope harvesting technology across a broad geographic area in Oregon and Washington. We measured soil disturbance and stream-adjacent disturbance from tethered machinery operating on steep-slopes and compared results to conventional

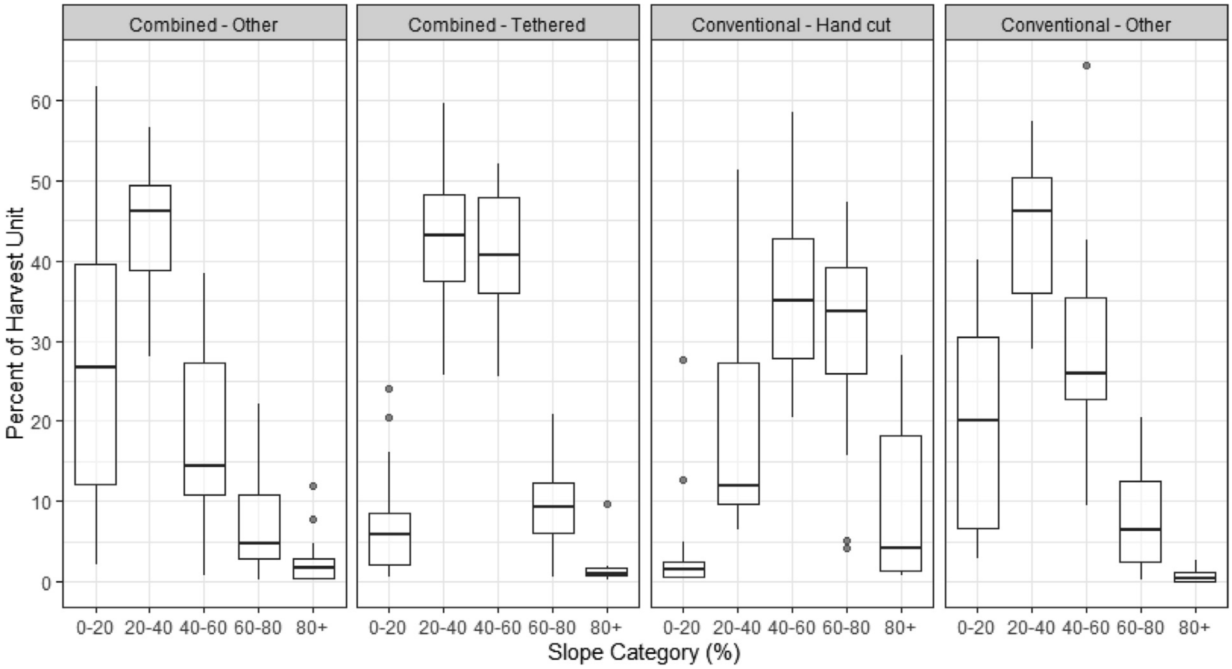

Fig. 4. Percentage of harvest units in 20% slope categories by within-unit harvest method. Conventional – hand cut included felling with chainsaws and yarding with cable systems, conventional – other generally included trees cut with feller bunchers and yarded with mechanical shovels. Combined – tethered harvesting included cutting and/or yarding with tethered equipment and combined – other included any other harvesting technique that did not use tethered equipment in the unit.

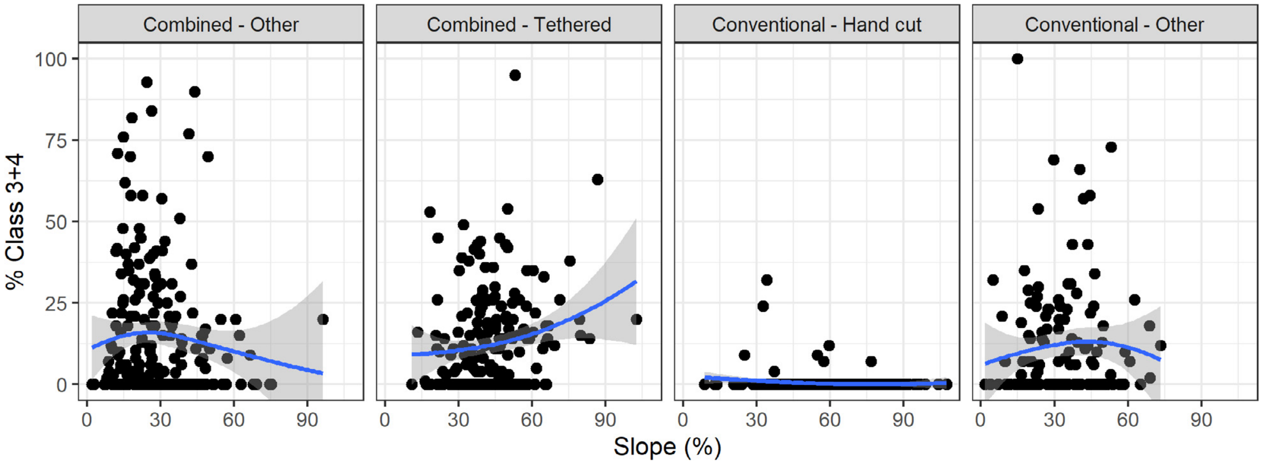

Fig. 5. Percentage of disturbed area for each transect plotted against slope, by within-unit harvest method. Loess curves are fitted to each panel and shaded areas denote approximate 95% confidence intervals.

harvests with hand-felling and cable-yarding. Across our sampling, we observed that conventional cable systems had the lowest amounts of soil disturbance and stream-adjacent disturbance, but tethered operations produced disturbance below levels of environmental or regulatory concerns.

Soil disturbance, regardless of the mechanism, can be identified by the condition and amount of exposed soil, particularly mineral soil (Heninger et al., 2002). Consequently, many forestry BMPs and state forest practice rules in the PNW focus on minimizing the amount of exposed soil when performing harvesting activities. Using those criteria, the amount of disturbed and exposed soil (class 3 and 4) was similar among all harvest methods except for conventional – hand cut. This observation likely occurred because conventional – hand cut was the only harvest method which did not include heavy equipment on the harvested area. We predicted that tethered operations would have less soil disturbance than other harvest types with tracked machinery (i.e., combined – other or conventional – other) because the winch-assist reduces ground pressures (Sessions et al., 2016) and the equipment may traverse across less of the unit area. In contrast to our prediction, we observed that tethered operations had similar amount and intensity of disturbance compared to un-assisted tracked machinery, but that the most intensive soil disturbance (class 5) was very rare.

Neither slope nor soil depth measured at the transect scale showed a strong association with the amount of disturbance across a harvest unit. This was surprising because we anticipated that greater slopes would have more disturbance due to greater track pressure from reduced effective length of track in contact with the ground and higher potential for machine tracks to slip on tethered equipment (Sessions et al., 2016). Spatially recreated transects were not identical to what was sampled on the ground due to GPS error and difficulty walking perfectly straight transects with obstacles and uneven, often steep terrain. Thus, measurement error may have contributed to weak effects. However, weak relationships between amount of disturbance and slope are reported elsewhere in the PNW and the winch-assist may have prevented greater disturbance (Green et al., 2019). Similarly, we anticipated greater topsoil depths to have less disturbance because topsoil can buffer against extensive rutting (Heninger et al., 2002; Fig. 2). Although the trend in depth of topsoil generally agrees with our predictions, the considerable amount of variability prevented strong conclusions. Other research on tethered harvesting identified soil texture and moisture at time of harvest as important predictors of soil disturbance, but were not measured here (Belart et al., 2018). The lack of clear relationships between soil depth, slope, and disturbance suggests that other variables may influence soil disturbance and warrants further research.

Conventional – cable harvest had the lowest amount of stream-adjacent soil disturbance compared to the other harvesting methods. However, all harvest methods, including tethered logging, had very low disturbance, with < 1.5% of the stream-adjacent surveyed areas exhibiting any harvest-related soil disturbance. Thus, tethered operations had disturbance far less than regulatory thresholds in Washington (WAC 222-30-021, 2013) where allowable stream-adjacent exposed soil is limited to < 10% within 10 m (horizontal) of the stream channel

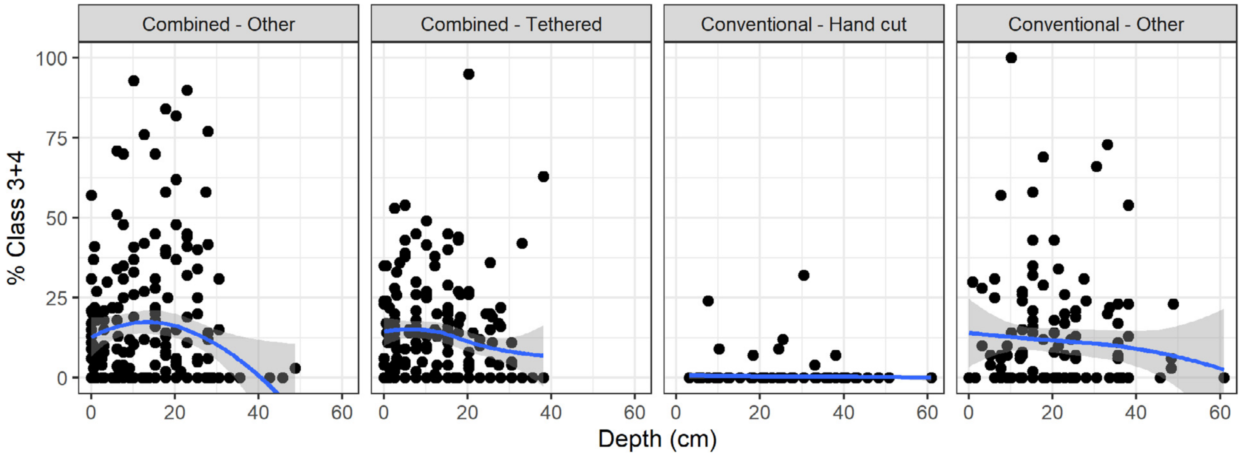

Fig. 6. Transect-level percentage of disturbed area plotted against measured soil depth, by within-unit harvest method. Loess curves are fitted to each panel and shaded areas denote approximate 95% confidence intervals.

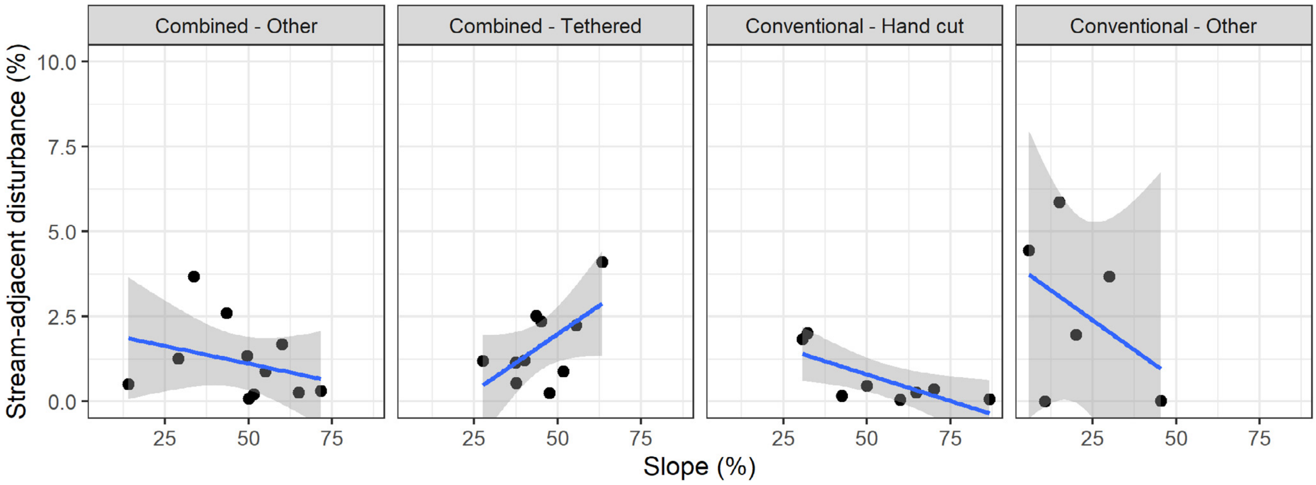

Fig. 7. Stream-adjacent disturbance area as percent of area surveyed by harvest method versus side-slope gradient by harvest operation and within unit harvest method. Solid blue lines display linear trends within a harvest operation type. Shaded areas show 95% pointwise confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

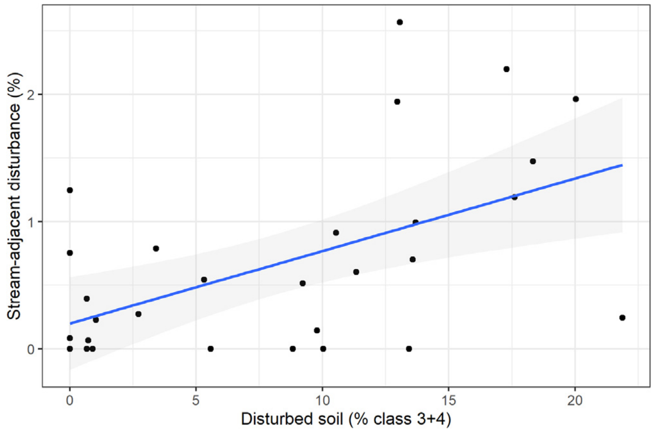

Fig. 8. Comparison of unit-level percentages of soil disturbance and stream-adjacent disturbance across 30 harvest units in Oregon and Washington, USA. A linear regression fit and 95% confidence interval are displayed.

before mitigation is required. The amount of stream-adjacent disturbance we measured also complies with Oregon Administrative Rules to minimize risk of soil delivery to waters of the state (OAR 629-630-0800, 2017). Our investigation of stream-adjacent disturbance indicates that the side slope and harvest-related soil disturbance were only weakly, though positively correlated. The weak correlation may be broadly indicative of variable site conditions and/or operator performance. Additional research is suggested on stream sediment delivery and turbidity including measures of stream-side vegetation and rainfall to have a better understanding of the impact of tethered harvesting on water quality.

Due to the similarity of soil disturbance between the tethered and untethered tracked machinery operating in harvest units, we expect this new logging method will have negligible impacts on soil productivity and erosion. However, numerous site-level factors can contribute to the impact of mechanized harvesting on soil productivity (soil type, climate, rainfall) and erosion (mitigation, slope, slash) (Grigal, 2000). As understanding of the impact of site conditions, equipment operating conditions, operator training and experience and mitigation techniques improves and are incorporated into BMPs, the amount of soil disturbance is expected to decline.

5. Conclusions

Tethered logging in the Pacific Northwest has shown promise of improving safety for woods workers through reduced exposure hours and increasing economic efficiency of steep-slope harvest operations. Through this study, we evaluated soil disturbance and stream-adjacent disturbance across a broad geographic scope to understand the environmental impacts and inform BMPs for tethered operations. Achieving high standards of environmental performance required by state and federal agencies as well as external third-party sustainability certifications (e.g., Sustainable Forestry Initiative) requires understanding and mitigating potential negative effects on water quality and long-term soil productivity. Thus, evaluating the environmental performance of new technologies such as tethered logging is critical to the sustainable production of wood and wood products. Our study indicated that while soil disturbance associated with tethered machines harvesting trees on steep slopes is greater than that caused by conventional steep-slope harvesting practices, disturbance levels are similar to those seen with untethered heavy machinery and meet or exceed regional thresholds for in-unit and stream-adjacent soil disturbance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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