Soil Compaction and Visual Disturbance Following an Integrated Mechanical Forest Fuel Reduction Operation in Southwest Oregon

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ABSTRACT

Most mechanical forest fuel reduction treatments prescribed to extract biomass are performed with existing or modified conventional logging equipment. Treatments that commonly harvest small, non-merchantable trees are often combined with or integrated into commercial thinning operations. Only a limited amount of literature has quantified harvesting system feasibility or environmental effects from such operations. The extra stand travel required to fell and extract small trees may lead to additional soil disturbance. The objective of this study was to assess soil disturbance from an integrated forest harvesting/mechanical forest fuel reduction operation in southwest Oregon, USA. The study was conducted in a fuel reduction thinning of a densely stocked 8.1-hectare (20-acre) mixed conifer stand on gentle terrain. A tracked, swing-boom feller-buncher and two rubber-tired, grapple skidders were used for felling and extracting both non-merchantable and merchantable trees. Visually classified soil disturbance, along with penetration resistance estimates were recorded pre- and post harvesting. Results indicate that the operation did not contribute to either statistically or biologically significant soil disturbance effects, based on an *a priori* biological reference threshold of 3,000 kPa. A history of multiple harvest entries, low soil moisture, and high initial soil strength conditions contributed to the lack of significant effects. This investigation will aid forest managers in decision making concerning expected soil disturbance effects when prescribing integrated harvesting systems for forest fuel reduction treatments.

Keywords: *forest fuel reduction, biomass, soil disturbance, compaction, soil strength, penetration resistance, integrated harvesting systems, Oregon, United States*

Introduction

Recent catastrophic wildfires, specifically in the western United States, have forced forest managers to take a closer look at active management practices on both public and private lands. Forest management practices such as fire exclusion, suppression, and reduced timber harvesting have allowed many forested stands to become densely overstocked with small-diameter trees (Fitzgerald 2002). These stands are typically characterized by small trees tightly spaced in the understory of mature forests (Mutch et al. 1993). Overabundant small trees increase surface and ladder fuels which both contribute to the spread and intensity of wildfire (Agee et al. 2000). This overstocking can lead to intensive, catastrophic, stand-replacement fires. Not only do overstocking and stand homogeneity increase fire hazard, but they also contribute to decreased vigor and reduced overall forest health and productivity (O'Laughlin and Cook 2003).

To alleviate or reduce fire hazards, several alternatives exist for forest managers. The most common is that of harvesting small trees with mechanical systems (Bolding et al. 2009). Traditional mechanical harvesting systems are designed to fell and extract merchantable-sized trees into products for sale, i.e., pulpwood, sawlogs, etc. Little research has been published on the harvesting of small non-merchantable stems that commonly contribute to wildfire hazards. The knowledge deficiency concerned with harvesting small trees is most pronounced in the areas of system productivity, costs, and soil disturbance effects (McIver et al. 2003). Also, the additional travel required by forest machines to harvest non-merchantable trees in fuel reduction applications may contribute to increased soil disturbance; however, this assumption has not been quantified. Studies are necessary to determine the level of soil disturbance that can be expected from integrated harvesting systems.

Harvesting small stems through mechanical means has been shown to be a viable alternative for reducing forest fuel loads (Fiedler et al. 1999, Bolding and Lanford 2005) and subsequent wildfire hazard (Fulé et al. 2001). But, many problems face forest managers in implementing such treatments. To date, few comprehensive research studies have addressed small wood harvesting in forest fuel reduction applications. Most that have been reported investigated traditional logging operations (Brown and Kellogg 1996) or limited field trials of purpose-

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* Forest Products Society member.
International Journal of Forest Engineering 20(2): 47-56.

built equipment (Coulter et al. 2002). The majority of previous studies have focused on harvesting and extracting merchantable timber with commercial value (e.g., Kellogg et al. 1992). The existing research has been successful in supplementing field experience of forest managers and harvesting contractors, and it has provided an overall better understanding of the capabilities and limitations of timber harvesting systems. Treatments that remove small trees along with conventional merchantable roundwood, however, require more machine travel than conventional commercial thinnings and may lead to adverse soil impacts. It is also important to note that when non-traditional products are removed from the forest, such as limbs, tops, and foliage, machine travel mats are no longer present and can lead to accelerated soil disturbance (Lanford and Stokes 1995).

Soil Disturbance Regulation and Significance

The concern over soil compaction, displacement, visual disturbance, and long-term site productivity has intensified in recent years. Forest stands with long histories of intensive management tend to be characterized by numerous entries of mechanized timber harvesting systems. These entries cause the soil of many stands to become compacted to a level that may inhibit future tree growth. But, it is unclear what level of compaction will consistently be detrimental to future tree growth (Miller and Anderson 2002, Landsberg et al. 2003). What is considered detrimental will vary depending on site conditions (Curran et al. 2007). The value may vary with tree species, soil type, soil texture, depth below the surface, and soil moisture. On public lands, administered by the USDA Forest Service, restrictions have been adopted to regulate the amount of soil disturbance that is acceptable from forest machines (USFS 1998). These restrictions consider a 20-percent increase in soil bulk density on more than 20 percent of the treatment area a detrimental level of soil disturbance. Other scientists and agencies use increases in penetration resistance (PR) as an indicator of detrimental disturbance. A PR value of 3,000 kilopascals (kPa) or 3 megapascals (mPa) has frequently been noted as a possible biological threshold where tree growth is detrimentally reduced (Powers and Avers 1995, Powers et al. 1998). This is a conservative estimate since other studies have shown tree growth to decline rapidly prior to this threshold, further explaining the complexity of the soil strength/tree growth relationship (Sands et al. 1979, Parker et al. 2007). Other approaches to establishing thresholds have been based on moisture content, especially in sensitive soil types (Nugent et al. 2003).

The optimal approach for determining soil disturbance effects on forested stands is to monitor tree growth and product yield (Gomez et al. 2002, Murphy et al. 2004) as a means of validating predictions based on increases in PR or bulk density (Miller and Anderson 2002, Ares et al. 2005) as well as visual disturbance (Aust et al. 1998, Tepp 2002, Murphy and Firth 2004). Froehlich (1979) found that the effects of soil disturbance on tree growth can persist for decades following harvesting while other long-term studies have noted the resiliency of forest soils to forest management and operational manipulation (Powers et al. 2004, Sanchez et al. 2006). Forest productivity response to soil disturbance may not only depend on changes in soil physical properties but also understory competition (Powers et al. 2005), which can be greatly affected by harvesting small trees in fuel reduction operations. Vegetation response (Adams 2005) and consistent reporting protocols (Curran et al. 2005, McFee and Kelly 2005) may be the most important areas in need of research to fill knowledge deficiencies.

Effects of Machine Traffic on Forest Soils

The use of mechanized equipment to fell and extract wood fiber in timber harvesting operations inherently influences soil conditions (Cromack et al. 1978, Greacen and Sands 1980, Froehlich and McNabb 1984). The degree of disturbance has been directly related to future tree growth (Miller et al. 1996, Parker et al. 2007) and economic sustainability of forest management (Murphy et al. 2004). Soil compaction and reduced tree growth resulting from repeated machine travel is often the most referenced negative consequence. Some studies, however, have reported increases in tree growth due to compaction (Heninger et al. 2002). Factors affecting a site's susceptibility for compaction may include machine weight, load weight, drive design (tracked, rubber-tired, or track bands) (Seixas and McDonald 1997), tire width and condition (Aust et al. 1993, Vechinski et al. 1999), operating pattern, travel speed, traffic intensity and frequency, soil organic matter content, amount and placement of surface slash (Wood et al. 2003), soil texture, and soil water content (Gomez et al. 2002, Miwa et al. 2004).

Numerous studies have been conducted to test relative differences in soil disturbance generated from different harvesting systems and equipment configurations. For example, Han et al. (2009) compared whole tree and cut-to-length (CTL) harvesting systems and determined that both systems significantly increased PR at high soil moisture levels. In a central Oregon study, Dodson et al. (2006) found significant differences in soil compaction between harvested and non-harvested sites, but found no difference between harvesting systems. In the southeastern United States, Lanford and Stokes (1995) found conventional ground-based rubber-tired skidder systems to disturb more area and compact more soil than CTL systems using forwarders. These are just a few of the many examples of conventional harvesting impacts studies.

In contrast to the numerous soil disturbance studies related to conventional harvesting, very little information has been published specifically examining forest fuel reduction treatments (Moghaddas and Stephens 2007). These treatments are becoming increasingly popular due to the heightened awareness, frequency, and intensity of wildfire – specifically in the Western United States (Gundale et al. 2005). These treatments have the potential to generate elevated levels of soil disturbance due to unique operational requirements. First, these treatments are usually integrated into a conventional thinning operation that is removing merchantable products. This is often necessary for economic feasibility. Second, many fuel reduction treatments target small trees (ladder fuels) not typically harvested in a conventional thinning. Harvesting additional trees requires more machine travel over a stand area. Extraction patterns may not be substantially different in the case of ground-based harvesting and rubber-tired skidders; however, skidders will likely make more passes over the same or additional trails due to the increased number of stems removed. Past research has shown soil compaction to greatly increase in the first several machine passes (Froehlich 1979), and Gent et al. (1984) determined complete soil compaction to occur after 10 passes. In a CTL harvesting study by Han et al. (2005), PR did not significantly increase after the second pass of a fully loaded forwarder. Felling, using rubber-tired or tracked machines, may be the most significant area of concern due to the increased number of trees harvested requiring more stand travel. Since felling machines, especially drive-to-tree configurations, must either travel to or swing to each tree felled, more total stand area may be impacted. Impact from felling machines is often dispersed throughout the stand and not concentrated on specific trails like extraction. This operating logistic may contribute to increased levels of soil disturbance over a larger area.

Research Questions

This study investigated soil disturbance from an integrated forest harvesting/mechanical forest fuel reduction operation on an 8.1-hectare (20-acre) mixed conifer stand in southwest Oregon. The specific research questions addressed were:

1. Does the use of an integrated forest harvesting/mechanical fuel reduction operation with conventional ground-based equipment contribute to statistically and/or biologically significant changes in PR at various depths below the soil surface?
2. Are changes in PR related to visual soil disturbance?

Methods

Study Site, Prescription, and Harvesting Equipment

This study was conducted in a fuel reduction thinning of an 8.1-hectare (20-acre) mixed conifer stand on gentle terrain with average slopes of 12 percent (min 5%, max 17%). The stand is industrially owned and has, therefore, been managed for timber production over the past several decades which has included several intermediate harvest entries. The study area is located in southwest Oregon, approximately 72 kilometers (45 miles) northeast of Medford and 72 kilometers (45 miles) southwest of Crater Lake National Park in Jackson County. Tree species consisted predominately of incense-cedar (*Calocedrus decurrens*) (19%), Douglas-fir (*Pseudotsuga menziesii*) (18%), and white fir (*Abies concolor*) (11%). Other species within the study site were Pacific madrone (*Arbutus menziesii*), ponderosa pine (*Pinus ponderosa*), Scouler willow (*Salix scouleriana*), sugar pine (*Pinus lambertiana*), Oregon white oak (*Quercus garryana*), Pacific yew (*Taxus brevifolia*), vine maple (*Acer circinatum*), and hazel (*Corylus* spp.). The site was chosen by an industrial landowner who was interested in gaining more information on mechanical fuel reduction operations that are integrated with commercial thinning. Terrain, soil, and stand characteristics were similar to other areas within the ownership. Soils in the area are well drained and are characterized as Dumont (50%) – Coyata (30%) gravelly loams. The Dumont soil is very deep and well drained. The surface of both soils is typically covered with a layer of needles, leaves, and twigs approximately 3.8 cm (1.5 in) thick. The Dumont surface layer is a dark reddish-brown gravelly loam about 23 cm (9 in) thick. In some areas the surface layer is cobbly or stony. Permeability is moderately slow in the Dumont soil with an available water capacity of approximately 23 cm (9 in). The Coyata soil is moderately deep and well drained. The surface layer is a dark reddish-brown gravelly loam approximately 28 cm (11 in) thick that may be cobbly or stony. Permeability is moderate and the available water capacity is about 5 cm (2 in). The main limitations affecting timber production are erosion, compaction, seedling mortality, and plant competition (NRCS 1993).

The stand consisted of approximately 1,715 trees per hectare (694 trees per acre) with a quadratic mean diameter of 16.2 cm (6.4 in). Detailed pre- and post-treatment stand characteristics are shown in **Tables 1 and 2**. The site was thinned from below with a 6.1-m (20-ft) by 6.1-m (20-ft) spacing between residual trees. Merchantable leave trees were those greater than or equal to 12.7-cm (5-in) in diameter at 5.2-m (17-ft) of height (approximately 17.8-cm [7-in] DBH). Small trees greater than 7.6-cm (3-in) but less than 17.8-cm [7-in] DBH were considered non-merchantable within local merchantability standards. In addition to merchantable stems, these trees were harvested and transported to landings to meet forest fuel reduction objectives. The resulting landing slash and extracted small, non-merchantable trees were then processed by an in-woods chipper and tub grinder into fuel chips. Merchantable log lengths were loaded separately and transported to processing facilities. No trees smaller than 7.6-cm (3-in) DBH were intentionally harvested. This constraint was imposed by the landowner and harvesting contractor for operational feasibility.

A logging contractor with approximately 25 years of experience implementing ground-based harvesting treatments was

Table 1. ~ *Pre-treatment stand exam statistics.*[a]

	Mean	SD	CV	SE	95% CI	%SE
			(%)			
Trees per hectare (per acre)	1,715 (694)	662.64 (268.16)	39	171.10 (69.24)	1,347.96 to 2,081.86 (545.50 to 842.50)	10
Basal area (m^2/ha) (ft^2/ac)	33.14 (144.37)	9.74 (42.44)	29	2.52 (10.96)	27.75 to 38.54 (120.87 to 167.87)	8
QMD (cm) (in)	16.33 (6.43)	4.19 (1.65)	26	1.07 (0.42)	13.99 to 18.64 (5.51 to 7.34)	6

[a] SD = standard deviation; CV = coefficient of variation; SE = standard error; CI = confidence interval; and QMD = quadratic mean diameter.

Table 2. ~ *Stand density and biomass statistics.*

	Pre-harvest[a]	Harvested[a]	Residual[a]
Trees per hectare (per acre)			
Non-merchantable[b]	1324 (536)	561 (227)	763 (309)
Merchantable[c]	390 (158)	161 (65)	230 (93)
Total	1715 (694)	724 (293)	990 (401)
Green tonnes per hectare (per acre)			
Non-merchantable[b]	128.1 (51.9)	53.5 (21.7)	74.6 (30.2)
Small tree	28.6 (11.5)	14.6 (5.9)	13.9 (5.6)
Merchantable tree (limbs and tops)[d]	99.5 (40.3)	39.0 (15.8)	60.7 (24.6)
Merchantable[c]	212.1 (85.9)	83.8 (33.9)	128.2 (51.9)
Total	340.2 (137.7)	137.3 (55.6)	202.7 (82.1)

[a] Number of observations = 15.
[b] Trees < 17.8-cm (7-in) DBH.
[c] Trees ≥ 17.8-cm (7-in) DBH.
[d] Biomass above a 15.2-cm (6-in) top (diameter outside bark).

selected. The contractor also had extensive experience with thinning prescriptions, similar to the one used in this study, in which non-merchantable material is removed for forest fuel reduction objectives. Harvesting equipment details and specifications used during the study were:[1]

Feller-buncher (**Fig. 1**) – The TigerCat L830 with a 5400 series single post felling saw is a tracked swing-to-tree excavator with 61-cm (24-in) wide single grouser tracks and a 280 horsepower Cummins diesel engine. The felling head has a maximum 56-cm (22-in) DBH felling capacity and can accumulate approximately eight to ten 15.2-cm (6-in) DBH trees. The machine weighs 32,659 kg (72,000 lb) has an 8.4 m (27.5 ft) boom reach, a self-leveling cab, and zero tail-swing.

Rubber-tired skidders (**Fig. 2**) – Two rubber-tired grapple skidders were used during the study. The Caterpillar 518C is a single-arch grapple skidder with 154 horsepower, 71L by 66-cm (28L by 26-in) tires, weighs 12,576 kg (27,725 lb), and has a wheel base of 326.1 cm (128.4 in). The John Deere 548E has a single-arch grapple with 121 horsepower, 71L by 66-cm (28L by 26-in) tires, weighs 10,342 kg (22,801 lb), and has a wheel base of 292 cm (115 in).

Experimental Design and Data Collection

Within the study site, 15 plot centers were identified on a systematic grid of the area (3 chains by 3 chains). This approach was used to establish a representative sample of the entire harvest unit. At each of the 15 plot centers, a 0.04-hectare (0.1-acre) fixed radius plot (11.35 m) (37.25 ft) and six random transect directions were established using a random number generator. Possible transect azimuths ranged from 20° to 360° in 20° intervals, yielding 18 possible directions. At each of the 15 points, the following data were collected, before and after harvesting, using the approach outlined in **Figure 3** (detailed shrub and down woody fuel methodology and results are outlined by Bolding (2006)):

Figure 1. ~ *TigerCat L830 tracked, swing-to-tree feller-buncher with a 5400 series 22-inch DBH capacity felling head felling small trees.*

Figure 2. ~ *Caterpillar 518C rubber-tired, grapple skidder bringing small trees to the landing.*

1. Soil characteristics (two 9.1-m [30-ft] transects),
    a. visual disturbance,
    b. penetration resistance (PR),
    c. moisture,
2. Standing tree information (11.35-m [37.25-ft] radius plot),
3. Understory shrub percent cover (two 15.2-m [50-ft] transects), and
4. Down woody fuel composition (two 15.2-m [50-ft] transects).

Soil surface disturbance, PR, and soil moisture were recorded before and after treatment. Response was the difference between pre- and post-treatment measurements and determined the level of soil disturbance generated from the harvest-

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[1] The use of brand or model names is for reader convenience only and does not represent an endorsement by the authors, Virginia Tech, or Oregon State University.

Table 3. ~ *Visual soil disturbance codes used during data collection. Adapted from McMahon (1995).*

Disturbance type	Code
Undisturbed	
No evidence of machine or log passage, litter and understory intact	1
Shallow disturbance	
Litter still in place, evidence of minor disruption	2
Litter removed, topsoil exposed	3
Litter and topsoil mixed	4
Evidence of track, or log passage (imprint < 10.2-cm (4-in) deep)	5
Deep disturbance	
Topsoil removed, mineral soil exposed	6
Erosion feature (rill, gully, etc.)	7
Rutted, evidence of track, or log passage	
10.2 to 20.4 cm (4 to 8 in) deep	8
> 20.4-cm (8-in) deep	9
Clarifiers	
Skid trail	10
Haul road	11
Non-soil (stumps, rocks)	12

ing machines. The study attempted to detect changes in PR measured in kilopascals (kPa) at depths from 25 to 400 mm (1 to 16 in) below the soil surface.

PR was measured before (control) and after harvest using a Rimik CP20 recording soil penetrometer. Visual soil disturbance was also estimated before and after harvesting and recorded as one of 12 codes (**Table 3**). Pre- (July) and post-harvest (September) measurements were conducted during the 2004 field season to ensure that soil moisture levels were compatible. In addition, soil cores (30.5-cm [12-in] below the surface) were collected with a tube-type soil sampler at each of the 15 plot locations pre- and post-treatment, weighed, and oven-dried (110°C for 24 hours) to determine soil moisture content.

On two of the six transects per plot, using the point transect method (McMahon 1995), three PR profiles and three visual disturbance observations were recorded at 10, 20, and 30 feet from the plot center in a random azimuth direction (**Figs. 3 and 4**). The study yielded 87 PR profiles before treatment and 89 after treatment or approximately 10.8 profiles per hectare (4.5 per acre). For each profile, the soil penetrometer recorded PR (kPa) at depth intervals of 25 mm (1 in) from 25 to 400 mm (1 to 16 in) below the soil surface. Each profile contained a total of 16 PR measurements. The above methods and plot locations were used both prior to any harvesting activity and after harvesting concluded. Transect directions were located randomly for both pre- and post-treatment measurements; therefore, sampling points were not in the same location, in most cases. Sources of variation within the data include profile to profile variation (87 profiles pre-treatment and 89 post-treatment), depth to depth variation (four depth classes), and visual disturbance class variation (two classes pre-treatment and three post-treatment).

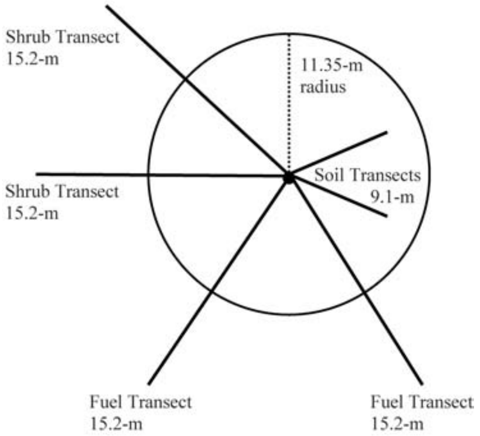

Figure 3. ~ *Example sampling diagram used during pre- and post-treatment data collection. Note: drawing not to scale.*

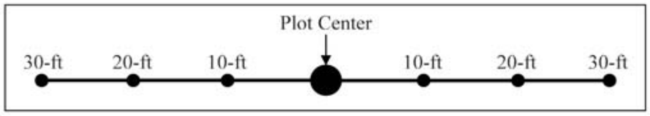

Figure 4. ~ *Example plot center location with 2 transects showing penetration resistance (PR) and visual disturbance measurement locations. Note: drawing not to scale.*

Data Analysis

Soil disturbance data analysis was conducted using a completely randomized design with each PR profile as the replicate experimental unit (repeated subject), and each of the depth classes (repeated factors) as repeatedly measured units within each profile. A repeated measures analysis of variance (ANOVA) procedure was performed with SAS v9.1 statistical software (SAS Institute 2002). The CLASS, MODEL, RANDOM, and REPEATED statements were used within the PROC MIXED procedure. A macro was used to determine an appropriate covariance structure since PR measurements within a profile were correlated with depth below the surface. Akaike's Information Criterion (AIC) values for each of 10 proposed structures were ranked and the lowest value determined the appropriate structure for the data in this investigation. The chosen structure was then used in the final model to estimate means, differences among means, and their 95 percent confidence limits. All of the statistical tests were conducted at the $\alpha = 0.05$ significance level. To minimize the number of repeated measures per replicate, the 16 depth intervals were grouped into four new depth classes:

1. 25 to 100 mm (1 to 4 in),
2. 125 to 200 mm (5 to 8 in),
3. 225 to 300 mm (9 to 12 in), and
4. 325 to 400 mm (13 to 16 in).

The following depth covariance structures were analyzed:

1. compound symmetry,

2. autoregressive,
3. toeplitz 1 to 4, and
4. unstructured 1 to 4.

To facilitate analysis, visual soil disturbance codes were also grouped into broader categories of:

1. undisturbed = code 1,
2. shallow disturbance = codes 2 through 5,
3. deep disturbance = codes 6 through 9, and
4. skid trail = code 10.

Grouped data categories consist of mean PR values of each of the initial broader categories. During pre-treatment measurements, only undisturbed (Pre UNDISTURBED) and skid trail (Pre SKID TRAIL) classifications were observed. Post-harvest, observed classifications were undisturbed (Post UNDISTURBED), shallow disturbance (Post SHALLOW), and skid trail (Post SKID TRAIL). Therefore, the following five visual soil disturbance codes were used during data analysis:

1. Pre UNDISTURBED,
2. Pre SKID TRAIL,
3. Post UNDISTURBED,
4. Post SHALLOW, and
5. Post SKID TRAIL.

ESTIMATE statements were used to generate estimates of pre- and post-treatment PR values at each depth class as well as the difference between these values. In this procedure, the two pre-treatment visual disturbance codes were averaged to generate mean PR values for all pre-treatment measurements. The same method was used to establish PR means for all post-treatment measurements. The DIFF option was used to obtain estimates of differences between least square means for all pairwise comparisons. The following ANOVA model was used to describe the relationship between PR, depth below the soil surface, and visual disturbance observations both pre- and post-harvesting.

$$Y_{ijk} = \mu + V_i + \lambda_{ij} + D_k + VD_{jk} + \varepsilon_{ijk}$$

where:

Y_{ijk} = PR at the k^{th} depth in the i^{th} visual disturbance class

μ = the overall mean value of Y_{ijk} (PR (kPa))

V_i = the fixed effect of the i^{th} level of visual soil disturbance (i = Pre UNDISTURBED, Pre SKID TRAIL, Post UNDISTURBED, Post SHALLOW, or Post SKID TRAIL)

λ_{ij} = the random effect of profile j within visual soil disturbance classification i
$\lambda_{ij} \sim N(0, \sigma^2_t)$ $j = 1, 2, \ldots, n_i$, ($n_{\text{Pre UNDISTURBED}} = 70$, $n_{\text{Pre SKID TRAIL}} = 17$, $n_{\text{Post UNDISTURBED}} = 28$, $n_{\text{Post SHALLOW}} = 25$, $n_{\text{Post SKID TRAIL}} = 36$)

D_k = the fixed effect of the k^{th} depth class (k = 100, 200, 300, or 400)

VD_{jk} = the interaction effect of the i^{th} level of visual soil disturbance and the k^{th} depth class

ε_{ijk} = the random error term that represents variability among depth classes within profiles, and $\varepsilon_{ijk} \sim$ multivariate normal $(0, \Sigma)$ and $\Sigma =$

$$\begin{bmatrix} \sigma^2 & \sigma_1^2 & 0 & 0 \\ \sigma_1^2 & \sigma^2 & \sigma_1^2 & 0 \\ 0 & \sigma_1^2 & \sigma^2 & \sigma_1^2 \\ 0 & 0 & \sigma_1^2 & \sigma^2 \end{bmatrix}$$ represents a Toeplitz (2) covariance structure among depth classes within a profile.

The mathematical model above assumes that measurements recorded on different profiles are independent, observations within a profile are dependent and correlated, and that all errors are normally distributed. This analysis attempted to detect significant differences in PR that could be attributed to the harvesting operation. The visual soil disturbance effect attempted to detect differences in PR between disturbance classes and the depth effect detected differences between depth classes. The visual disturbance class*depth interaction effect detected differences in PR between the five disturbance classes at each of the four depth levels.

Results and Discussion

The 87 pre-treatment visual soil disturbance measurements consisted of 70 undisturbed (Pre UNDISTURBED) (80%) and 17 existing skid trails (Pre SKID TRAIL) (20%). Following the fuel reduction treatment, the 89 visual disturbance measurements were classified as 28 undisturbed (Post UNDISTURBED) (31%), 25 shallow disturbance (Post SHALLOW) (29%), and 36 skid trail (Post SKID TRAIL) (40%). Based on these results, skid trail area was doubled from 20 to 40 percent and 49 percent of the total area experienced some form of additional soil disturbance due to the fuel reduction treatment. But, no deep disturbance observations were recorded.

After oven-drying and weighing soil samples, average moisture contents were determined to be 14.95 percent for pre-treatment samples and 16.26 percent for post-treatment samples. One way ANOVA determined no significant difference between the means (F = 2.14; $p = 0.1549$). This finding indicates similar very dry soil sampling conditions for both pre- and post-treatment measurements.

To appropriately characterize the data, assumptions of normality were assessed and confirmed through analysis of residual plots. The sample size corrected AIC values (AICc) for each covariance model are given in **Table 4**. The TOEP (2) structure was selected due to its minimum AICc value and was used in the final mathematical model to estimate means, differences among means, and their confidence limits. In this model, variance among PR values within each depth class was larger than among PR values between depth classes. This is partially due to establishing four new 100 mm depth classes from the original 16 recorded by the penetrometer. As noted in the correlation

Table 4. ~ *AICc values for each covariance model.*

Model	AICc	Model	AICc
Compound symmetry	10095.8	Autoregressive (1)	10058.2
Unstructured (4)	N/A	Toeplitz (4)	10057.9
Unstructured (3)	10058.9	Toeplitz (3)	10055.9
Unstructured (2)	10057.7	**Toeplitz (2)**	**10053.9**
Unstructured (1)	10094.6	Toeplitz (1)	10093.8

Table 5. ~ *F-statistics for main effects and interactions.*

Effect	Num DF[a]	Den DF[b]	F-value	Pr > F
VDC[c]	4	171	0.46	0.7685
Depth class	3	453	73.55	< 0.0001
VDC*Depth class	12	453	1.22	0.2684

[a] Numerator degrees of freedom.
[b] Denominator degrees of freedom.
[c] Visual disturbance class.

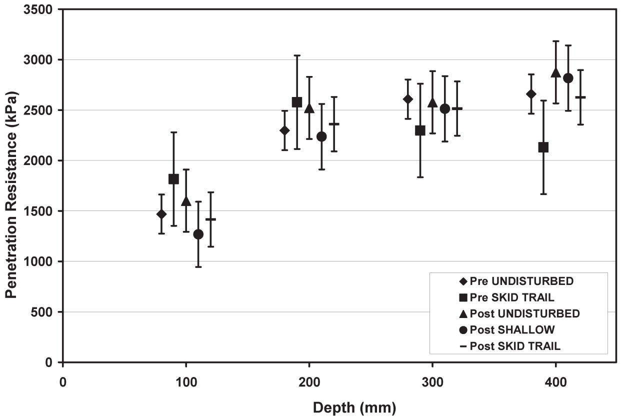

Figure 5. ~ *Mean penetration resistance (PR) (kPa) with 95% confidence intervals, for the five visual soil disturbance codes within each depth class.*

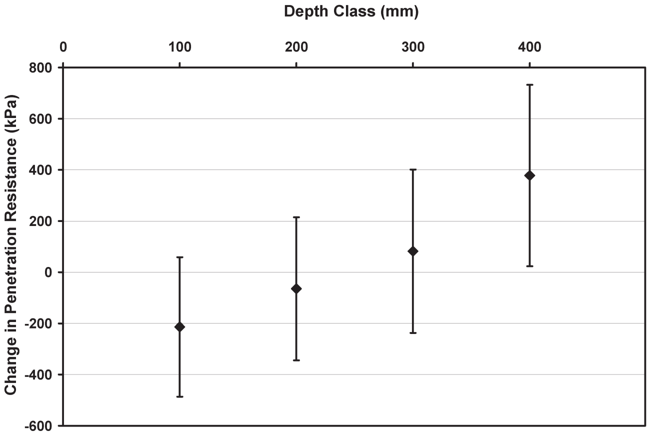

Figure 6. ~ *Estimated difference in mean penetration resistance (PR) (kPa) with 95% confidence intervals between pre- and post-treatment measurements (post-pre) for each depth class (visual soil disturbance not considered). Note: a positive change indicates an increase in PR following treatment.*

matrix below, correlation among PR values at adjacent depth classes 100 to 200, 200 to 300, and 300 to 400 was estimated to be 0.37. Correlation among PR values at non-adjacent depth classes 100 to 300, 100 to 400, and 200 to 400 was estimated to be 0 indicating that 100 mm adjacent depth classes may be the minimum for establishing meaningful relationships of PR and depth.

$$\begin{bmatrix} 1.00 & 0.37 & 0.00 & 0.00 \\ 0.37 & 1.00 & 0.37 & 0.00 \\ 0.00 & 0.37 & 1.00 & 0.37 \\ 0.00 & 0.00 & 0.37 & 1.00 \end{bmatrix}$$

The interaction effect between visual disturbance class (VDC) and depth class was not statistically significant ($F_{12,453} = 1.22$; $p = 0.268$) (**Table 5**). This implies that the differences in PR values between visual disturbance classes do not depend on depth below the soil surface.

The main effect of visual soil disturbance class was not statistically different from zero, indicating that PR does not depend on visual disturbance classification. As expected, the main effect of depth class was statistically significant ($F_{3,453} = 73.55$; $p < 0.0001$). This result implies that PR changes as depth below the soil surface increases.

The similarity between confidence intervals within depth classes for each of the five analyzed visual disturbance classes implies virtually no statistically significant difference between disturbance classes within a depth class (**Fig. 5**). PR values within each disturbance class tend to increase with increasing depth below the soil surface with the exception of pre-treatment skid trail measurements (Pre SKID TRAIL). Pre SKID TRAIL observations show an increase in PR between depth classes 100 and 200, then a decline at depth classes 300 and 400, although this trend is not statistically significant.

Figure 6 shows the estimated mean differences in PR values between pre- and post-treatment conditions at each depth class. Depth classes 100 and 200 show a mean decrease in PR following the harvesting treatment, although their confidence intervals include zero indicating no statistically significant difference. This result may be due to some soil stirring by machines near the surface. Depth classes 300 and 400 each show a mean increase in PR following treatment, although the difference is only statistically different from zero for depth class 400 ($\text{t-value}_{453} = 2.09$; $p = 0.0367$; 95% CI = 23.39, 732.41).

Soil Disturbance Biological Significance

For this study, based on the available literature and site characteristics, we have *a priori* determined that PR values of 3,000 kPa or greater may have a biologically meaningful effect on future site productivity. This threshold value is presented for data reference only and does not represent an absolute level where reduced site productivity occurs as it may occur well before this threshold. **Figure 7** shows average pre- and post-treatment PR

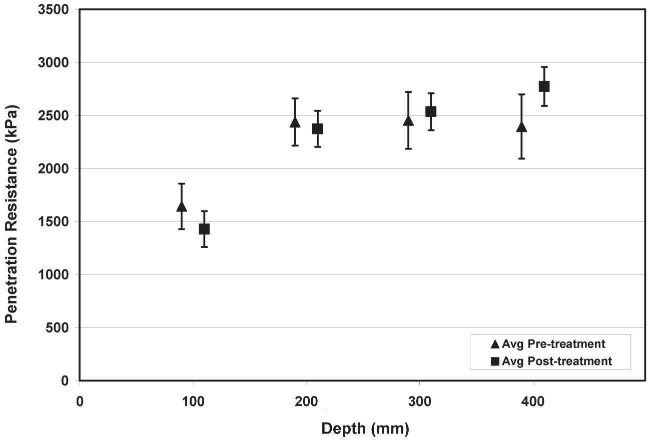

Figure 7. ~ *Mean pre- and post-treatment penetration resistance (PR) estimates and 95% confidence intervals (averaged across visual disturbance classes) at each depth class.*

values along with their 95 percent confidence intervals. The figure indicates that neither pre- nor post-treatment PR values exceeded the *a priori* 3,000 kPa threshold for biological significance at any depth class. Assuming that the threshold applies to the 8.1-hectare (20-acre) study site, these results imply that the harvesting treatment did not contribute to biologically significant changes in PR for any depth class. It is important to note, however, that the threshold level for biological significance varies from site to site and the 3,000 kPa level is presented here for reader convience and comparison purposes only. Other studies, depending on soil types and tree species, have found tree growth to decline well in advance of 3,000 kPa (Sands et al. 1979, Parker et al. 2007). Without measuring vegetation response to the harvesting treatment, valid conclusions cannot be drawn as to the actual relationship between PR and future growth potential.

Summary and Conclusions

Results indicate that the fuel reduction operation did not contribute to either statistically or biologically significant soil disturbance effects, assuming 3,000 kPa applies to the study site as a biological threshold. The only statistically significant effect was detected at depth class 400 (325 to 400 mm [13 to 16 in] below the soil surface). Since no deep disturbance was detected with the visual disturbance codes, this result could be due to measurement error and is unlikely the result of the harvesting operation. At increasing depth below the soil surface, the soil penetrometer typically encounters large rocks, tree roots, and soil parent material. Often, these obstacles yield erroneously high PR values (Miller et al. 2001).

The *a priori* determined biologically significant PR value of 3,000 kPa was not exceeded at any depth class. It is difficult to determine how this result applies to differing pre-treatment PR characteristics. Pre-treatment PR values were below 3,000 kPa for each depth class, although depth classes 200, 300, and 400 encompassed 2,500 kPa within their 95 percent confidence intervals. This indicates that soils on the given site were already compacted to near or beyond detrimental levels (as specified by the *a priori* threshold and past studies (Sands et al. 1979, Parker et al. 2007)). This could be a function of either past entries by mechanized harvesting operations or the inherent properties of the specific soil type characteristic to the area. It is important to note that the ability to increase PR with mechanized equipment is largely a function of the existing soil characteristics prior to harvest. Given the high PR and low soil moisture values pre-treatment, it is likely that the soil was already compacted to a level that inhibited further compaction. These factors may explain the lack of significant effects detected with this study since dry soils and high PR affect both soil penetration resistance and compaction potential. Further studies should investigate similar treatments in areas with differing soil conditions, i.e., low compaction – high compaction and low moisture – high moisture. Such studies may provide results that could be used to establish trends in pre- versus post-treatment PR estimates for differing levels of pre-treatment compaction.

Visual soil disturbance classifications were not statistically significant for predicting PR. Confidence interval ranges for the five observed visual disturbance*time codes were similar within each depth class (**Fig. 5**). This result could be a function of study design. This study was designed to quantify PR and visual disturbance for the stand as a whole. Had skid trails and feller-buncher corridors been observed separately from undisturbed areas between residual trees, for example, visual disturbance classifications may have proved more important for predicting PR. Although, for the forest manager, concerns regarding site productivity and tree growth are best addressed by assessing soil disturbance over the entire area since skid trails are often re-used with subsequent machine entries and may be considered out of production from a tree growth stand point.

Interpretation of these results should be used cautiously and applied to similar stand and treatment types, machine configurations, and soil characteristics. As noted earlier, the effects of such a fuel reduction treatment are largely unknown for differing pre-treatment soil characteristics and moisture contents. Forest managers should carefully investigate soil conditions and the potential effects of the prescribed management action before implementation of any forest fuel reduction operation. These factors will have a significant effect on soil disturbance generated from ground-based harvesting systems. Further, it is recommended that to optimally quantify the effects of soil disturbance on site productivity, long-term studies of tree growth should be established. This quantification will serve as validation of results from studies such as this and could possibly allow for further inference to be drawn. Such an approach will allow forest managers to make informed decisions regarding possible impacts from integrated fuel reduction treatments and aid regulatory agencies in policy formulation.

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