# Soil Disturbance from an Integrated Mechanical Forest Fuel Reduction Operation in Southwest Oregon[1]

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## Abstract

Most mechanical fuel reduction treatments are performed with existing or modified conventional logging equipment. These operations that harvest small, non-merchantable trees are often integrated into commercial thinning prescriptions. Little literature has quantified harvesting system effectiveness or soil disturbance concerns from such operations. This paper reports results of soil disturbance generated from an integrated forest harvesting/mechanical forest fuel reduction operation in southwest Oregon. The study was conducted in a fuel reduction thinning on a 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 timber extraction. Soil characteristics were recorded pre and post treatment using both visual classification and soil strength measurements. The difference between pre and post treatment measurements determined the level of soil disturbance generated from the harvesting machines. Biological significance was based on an a priori soil strength threshold of 3000 kilopascals (kPa). Results indicate that the operation did not contribute to either statistically or biologically significant soil disturbance effects. This investigation will aid forest managers in decision making concerning expected soil disturbance generated from conventional ground-based harvesting systems on gentle terrain when employed in a fuels reduction operation.

*Key words: compaction, fuel reduction, mechanical harvesting, soil strength*

## Introduction

Currently, there is a lack of information concerning mechanical forest fuel reduction systems that are integrated with commercial logging operations. Little literature is available to quantify harvesting system and silvicultural treatment effectiveness as well as residual tree and soil disturbance concerns (McIver et al. 2003). This information deficiency makes it difficult for forest managers to make sound decisions toward employing mechanical fuel reduction treatments. The additional travel required by forest machines to harvest non-merchantable trees in fuel reduction applications can contribute to increased soil disturbance; although, this assumption has not been quantified. Studies are necessary to determine the level of soil disturbance that can be expected from integrated harvesting systems. Regulatory standards established to limit the amount of area disturbed and compacted also lack this information.

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This paper reports the results of soil disturbance generated from an integrated forest harvesting/mechanical forest fuel reduction operation on a 20-acre mixed conifer stand in southwest Oregon. The study attempted to detect changes in soil strength measured in kilopascals (kPa) at depths from 25-400 mm below the soil surface. The specific research questions addressed were as follows: 1) Does the use of an integrated forest harvesting/mechanical fuels reduction operation with conventional ground-based equipment on the 20-acre stand contribute to statistically and/or biologically significant changes in soil strength at various depths below the soil surface?, and 2) Are changes in soil strength related to visual soil disturbance?

### *Biological Significance*

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 inhibits future tree growth. It is unclear as to what level of compaction will consistently be detrimental to future tree growth (Landsberg et al. 2003, Miller and Anderson 2002). This value varies with tree species, soil type, and moisture. The USDA Forest Service has established a criterion based on increases in bulk density and other disturbance variables (USFS 1998). They have regulated harvesting activities to a threshold that must not exceed a 20% increase in bulk density on more than 20% of the area. Other scientists and agencies use soil strength as an indicator of detrimental compaction. It appears to be generally accepted, that for any site type, soil strength values of 3000 kilopascals (kPa) may produce a reduction in tree growth and site productivity (Powers et al. 1998, Powers and Avers 1995). The optimum approach for determining compaction effects on forested stands is to monitor tree growth as a means of “validating” predictions based on increases in soil strength or bulk density (Miller and Anderson 2002). For this study, based on the available literature and conversations with other scientists, we have a priori determined that soil strength values of 3000 kPa or greater will have a biologically meaningful effect on future site productivity.

## Methods

### *Study Site and Prescription*

This study was conducted in a fuel reduction thinning of a 20-acre mixed conifer stand on gentle terrain with average slopes of 12% (min 5%, max 17%) (no replication of study sites or harvesting treatments was used). The study area is located in southwest Oregon approximately 45 miles northeast of Medford and 45 miles southwest of Crater Lake National Park. Tree species consisted predominately of Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and incense-cedar (*Calocedrus decurrens*). The site was chosen by the landowner who was interested in gaining more information on how current mechanical fuel reduction operations affect soil strength characteristics and visual disturbance in mixed conifer forests within his ownership. Terrain, soil, and stand characteristics were considered to approximately represent other areas within the ownership. Soils in the area are well drained and are characterized as Dumont – Coyata gravelly loams (NRCS 1993).

The stand consisted of approximately 680 trees per acre with a quadratic mean diameter of 6.3-in. The unit was thinned with a 20-ft by 20-ft spacing between residual trees. Leave trees were those greater than or equal to 5-inches in diameter at

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17-ft of height (approximately 7.5 inches DBH). These specifications also describe merchantable trees. Small trees greater than 3-in but less than 7.5-in DBH were considered non-merchantable. These trees were harvested and transported to landings to meet forest fuel reduction objectives. No trees less than 3-in DBH were intentionally harvested.

## *Experimental Design and Data Collection*

A tracked, swing-boom feller-buncher and two rubber-tired, grapple skidders were used for felling and timber extraction. Soil strength was measured pre (control) and post (response) harvest using a Rimik CP20 recording soil penetrometer. Visual soil disturbance was also measured pre and post harvest and recorded as one of twelve codes (Table 1). Pre (July) and post (September) harvest measurements were conducted during the 2004 field season to ensure that soil moisture levels were compatible.

**Table 1.** — *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 tire, track, or log passage (imprint < 4 inches deep) | 5 |
| **Deep Disturbance** | |
| Topsoil removed, mineral soil exposed | 6 |
| Erosion feature (rill, gully, etc.) | 7 |
| Rutted, evidence of tire, track, or log passage | |
| 4-8 inches deep | 8 |
| > 8 inches deep | 9 |
| **Clarifiers** | |
| Skid trail | 10 |
| Haul road | 11 |
| Non-soil (stumps, rocks) | 12 |

Within the 20-acre study site, 15 plot centers were identified from a systematic grid of the area (3-chains x 3-chains). This approach was used to establish a representative sample of the entire area. At each of the 15 plot centers, 2 random transect directions were established using a random number generator. Possible azimuths ranged from 20-360° in 20° intervals, yielding 18 possible directions. On each transect, using the point transect method (McMahon 1995), 3 soil strength profiles and 3 visual disturbance observations were recorded at 10, 20, and 30-ft from plot center in a random azimuth direction. The study yielded 87 soil strength profiles pre-treatment and 89 post-treatment or approximately 4.5 per acre. For each profile, the soil penetrometer recorded soil strength (kPa) at depth intervals of 25 mm from 25-400 mm below the soil surface. Each profile contained a total of 16 soil strength 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 units pre-treatment and 89 post-treatment), depth to depth variation (4 units), and visual disturbance class*time variation (5 units). Units of variation reflect the data structure during analysis (see below for the grouped data structures).

## *Data Analysis*

Data analysis for this study was conducted using a completely randomized design with each soil strength 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 the appropriate covariance structure. Akaike's Information Criterion (AIC) (Akaike 1974) 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 (below) to estimate means, differences among means, and their confidence limits. All 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 4 new depth classes: (1) 25-100 mm, (2) 125-200 mm, (3) 225-300 mm, and (4) 325-400 mm. Visual soil disturbance codes were also grouped into broader categories of (1) undisturbed — code 1, (2) shallow disturbance — codes 2-5, (3) deep disturbance — codes 6-9, and (4) skid trail — code 10. Grouped data categories consist of mean soil strength values of each of the initial broader categories. During pre-treatment measurements, only undisturbed (Pre1) and skid trail (Pre10) classifications were observed. Post harvest, observed classifications were undisturbed (Post1), shallow disturbance (Post2), and skid trail (Post10). Therefore, 5 visual soil disturbance codes were used during data analysis: (1) Pre1, (2) Pre10, (3) Post1, (4) Post2, and (5) Post10. ESTIMATE statements were used to generate estimates of pre and post treatment soil strength values at each depth class as well as the difference between these values. In this procedure, the 2 pre-treatment visual disturbance codes were averaged to generate mean soil strength values for all pre-treatment measurements. The same method was used to establish soil strength 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 soil strength, 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:

$\mu$ is the overall mean value of $Y_{ijk}$ (soil strength (kPa))

$V_i$ is the fixed effect of the i^th^ level of visual soil disturbance (i=Pre1, Pre10, Post1, Post2, or Post10)

$\lambda_{ij}$ is the random effect of profile j within visual soil disturbance classification i

$\lambda_{ij} \sim N(0, \sigma^2_t)$ j=1, 2,….,$n_i$, ($n_{Pre1}$=70, $n_{Pre10}$=17, $n_{Post1}$=28, $n_{Post2}$=25, $n_{Post10}$=36)

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$D_k$ is the fixed effect of the $k^{th}$ depth class (k=1, 2, 3, or 4)

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

$\varepsilon_{ijk}$ is the random error term that represents variability among depth classes within profiles, and $\varepsilon_{ij}$~Multivariate Normal($\underline{0}$,Σ) 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 model 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 will determine if there are significant differences in soil strength that can be attributed to the harvesting operation. The visual soil disturbance effect will detect differences in soil strength between disturbance classes and the depth effect will detect differences between depth classes. The visual soil disturbance*depth interaction effect will detect differences in soil strength between disturbance classes at the four depth levels.

## Results

Assumptions of normality were assessed and confirmed through analysis of residual plots. The sample size corrected AIC values (AICc) for each of the covariance models are given in Table 2.

**Table 2. —** *AICc values for each covariance model. TOEP(2) had the minimum AICc value.*

| Model | AICc | Model | AICc |
|---|---|---|---|
| Compound Symmetry | 10095.8 | AR(1) | 10058.2 |
| UN(4) | N/A | TOEP(4) | 10057.9 |
| UN(3) | 10058.9 | TOEP(3) | 10055.9 |
| UN(2) | 10057.7 | **TOEP(2)** | **10053.9** |
| UN(1) | 10094.6 | TOEP(1) | 10093.8 |

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. The structure requires the estimation of 2 parameters. In this model, variance among soil strength values at each depth class was larger than among strength values between depth classes. Correlation among strength values at depth classes 1-2, 2-3, and 3-4 was estimated to be 0.37, whereas strength value correlation among depth classes 1-3, 1-4, and 2-4 was estimated to be 0.

As noted in Table 3 below, the interaction effect between visual disturbance class (VDC) and depth class was not statistically significant ($F_{12,453}$=1.22, p=0.268). This implies that the differences in soil strength values between visual disturbance classes do not depend on depth below the soil surface.

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**Table 3.** — *Table of F statistics for main effects and interactions.*

| Effect | Num DF | Den DF | F Value | Pr > F |
|---|---|---|---|---|
| VDC | 4 | 171 | 0.46 | 0.7685 |
| Depth Class | 3 | 453 | 73.55 | <0.0001 |
| VDC*Depth Class | 12 | 453 | 1.22 | 0.2684 |

The main effect of visual soil disturbance class was not statistically different from zero, indicating that soil strength 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 soil strength changes as depth below the soil surface increases.

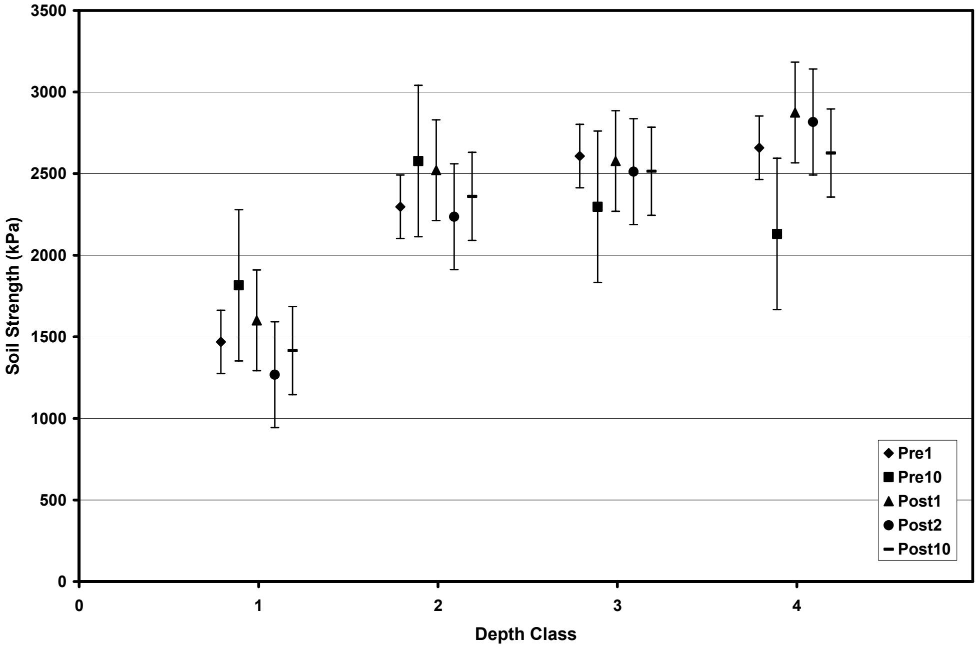

**Figure 1.** — Mean soil strength (kPa) with 95% confidence intervals, for the five visual soil disturbance codes within each depth class.

As indicated in Figure 1, the overlapping of confidence intervals within depth classes for each of the five analyzed visual disturbance classes implies no statistically significant difference between disturbance classes within a depth class. Soil strength values within each disturbance class tend to increase with increasing depth below the soil surface with the exception of pre-treatment skid trail measurements (Pre10). Pre10 observations show an increase in soil strength between depth classes 1 and 2, then decline at depth classes 3 and 4, although this trend is not statistically significant.

Figure 2 shows the estimated mean differences in soil strength values between pre and post treatment conditions at each depth class. Depth classes 1 and 2 show a mean decrease in soil strength following the harvesting treatment, although their confidence intervals include zero indicating no statistically significant difference. Depth classes 3 and 4 each show a mean increase in soil strength following treatment. Although the difference is only statistically different from zero for depth class 4 (t-$\text{value}_{453}$=2.09, p=0.0367, 95% CI=23.39, 732.41).

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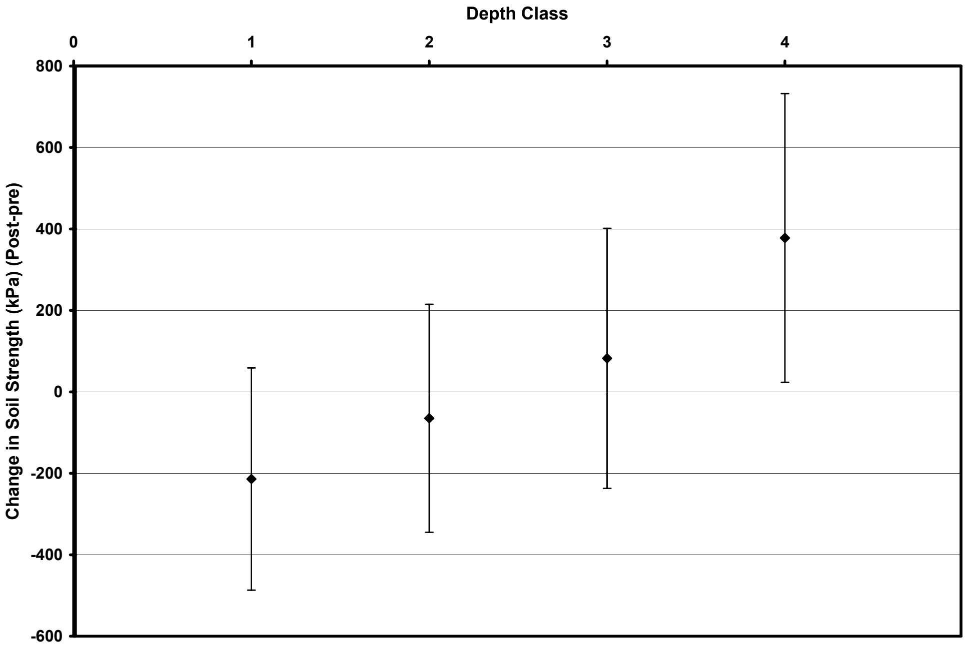

**Figure 2.** — Estimated difference in mean soil strength (kPa) with 95% confidence intervals between pre and post treatment measurements (post-pre) for each depth class (visual soil disturbance not considered). Note: a positive change indicates an increase in soil strength following treatment.

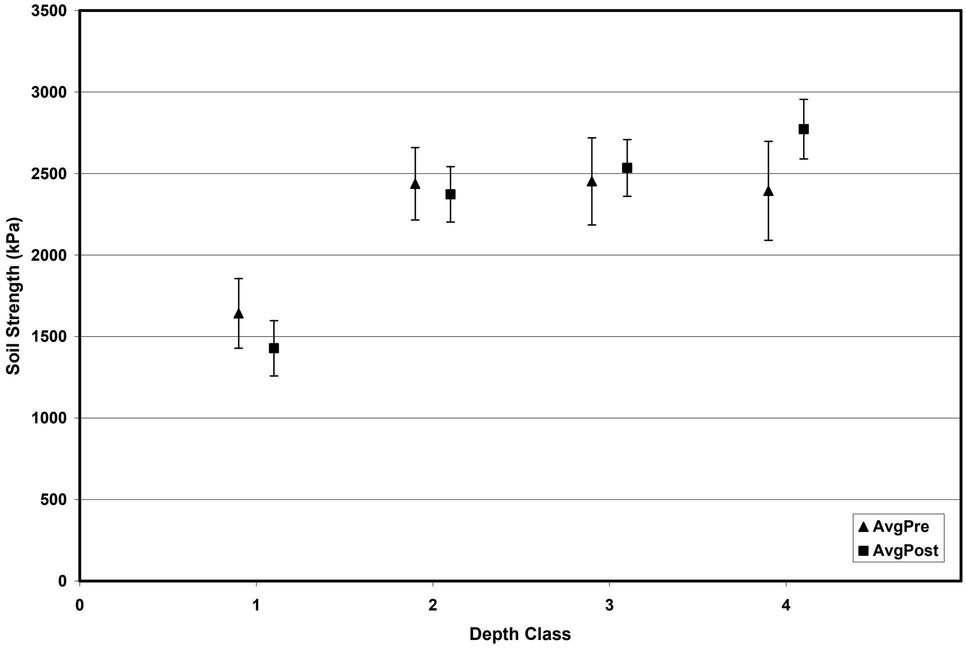

**Figure 3.** — Mean pre and post treatment soil strength estimates and 95% confidence intervals (averaged across visual disturbance classes) at each depth class.

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## *Biological Significance*

Figure 3 shows average pre and post treatment soil strength values along with their 95% confidence intervals. The figure indicates that neither pre nor post treatment soil strength values exceeded the a priori 3000 kPa threshold for biological significance at any depth class. These results imply that the harvesting treatment did not contribute to biologically significant changes in soil strength for any depth class. Assuming that the 3000 kPa value set a priori applies to the 20-acre site, it can be concluded that the harvesting treatment did not result in detrimental soil compaction, reduced site productivity, or a reduction in tree growth.

# Discussion

Based on this analysis, the following conclusions can be drawn in regards to the 2 research questions addressed in the study.

*Question 1: Does the use of an integrated forest harvesting/mechanical fuels reduction operation with conventional ground-based equipment on the 20-acre stand contribute to statistically and/or biologically significant changes in soil strength at various depths below the soil surface?*

Results indicate that the fuels reduction operation did not contribute to either statistically or biologically significant soil disturbance effects. The only statistically significant effect was detected at depth class 4 (325-400 mm 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 often encounters tree roots and/or soil parent material. Often, these obstacles yield erroneously high soil strength values (Miller et al. 2001).

The a priori determined biologically significant soil strength value of 3000 kPa was not exceeded at any depth class. It is difficult to determine how this result applies to differing pre treatment soil strength characteristics. On the 20-acre site, the pre treatment values were below 3000 kPa for each depth class, although depth classes 2, 3, and 4 encompassed 2500 kPa within their 95% confidence intervals. This indicates that soils on the given site were already compacted to near detrimental levels (as specified by the a priori threshold). 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. The ability to increase soil strength with mechanized equipment is largely a function of the existing soil characteristics prior to harvest. Given the high soil strength values pre treatment, it is likely that the soil was already compacted to a level that inhibited further compaction. This may explain the lack of significant effects detected with this study. Had pre treatment conditions been characterized by lower soil strength, the operation may have produced a more measurable and significant effect. Further studies should investigate similar treatments in areas with differing soil conditions (low compaction – high compaction). Such studies may provide more meaningful results that could be used to establish trends in pre vs. post treatment soil strength estimates for differing levels of pre treatment compaction.

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*Question 2: Are changes in soil strength related to visual soil disturbance?*

Visual soil disturbance classifications were not statistically significant for predicting soil strength. Confidence intervals for each of the 5 observed visual disturbance*time codes overlapped within each depth class (Figure 1). This result could be a function of study design. This study was designed to quantify soil strength and visual disturbance for the 20-acre 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 soil strength. 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 reused with subsequent machine entries and may be considered out of production from a tree growth stand point.

## Conclusion

In conclusion, this study was successful in answering the research questions of interest. Interpretation of the results should be used cautiously and applied to similar treatment types, machine configurations, and soil characteristics. As noted earlier, the effects of such a treatment are largely unknown for differing pre treatment soil characteristics. 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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