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Measuring the Response of Conifer Seedlings to Soil Compaction Stress

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Abstract

A test of seedling growth response to several levels of soil compaction showed that root penetration depth was best correlated with soil compaction. Shoot biomass, root biomass, root elongation, and seedling height were not well correlated with compaction. The results reveal that most measurements of growth do not give a good indication of seedling response to stresses induced by compaction. In fact, selecting a growth measurement to determine seedling response may require a separate test. There were good partial correlations between mean seedling height and all other measures of growth, but relationships must be developed for each growth response. When the relationships are known, mean seedling height can be used to predict the mean value of any of the other growth variables.

Introduction

Urban forests are often subjected to hostile environments that discourage tree growth. A number of stress factors were recently reviewed by Himelick (1976), who found soil conditions to be important. Urban soils may be disturbed and compacted to densities well above normal and impose severe stresses on urban vegetation (Patterson 1976). Despite these stresses, tree seedlings can be established and grow on compact urban soils (Zisa et al. 1980). Although the seedlings grew, there were differences in growth, and little is known about growth pattern response to stresses induced by soil compaction.

Measuring tree response to environmental factors, including soil-induced stress, is a necessary step in understanding growth patterns. Traditional measures of tree response have been establishment success and height growth, as used by Little and Trew (1979).

Top growth and volume increment are important variables when maximum wood volume is the management objective. Wood volume is not a usual management objective in urban forests. Rather, other amenity values are primary, and values such as esthetics are subjective and not readily quantifiable. Because traditional measures of growth emphasize volume, they are not appropriate for urban seedlings. Other criteria must be used to evaluate tree vigor.

Seedling response to different soil properties could be measured by a number of variables. The traditional measure is height growth. Forms of below-ground growth and biomass also are important measures of growth response. All of these variables have been used in the past, but none has been determined as the "best" measure of response to stress. Pham and others (1978) showed that fertility and soil moisture interact and produce unusual growth responses, such as accelerated top growth and restricted root growth. This suggests that top growth may not be a good measure of seedling response to soil factors.

The objective of this study was to determine the effects of soil compaction on seedling growth, and to identify the growth variable most responsive to soil compaction level. A secondary objective was to determine if the nondestructive measure of response, shoot height, was a good indicator of soil compaction levels. Also, we wanted to determine if height can be used to predict other growth variables.

Methods

Soil Type

Two soils were used in the study. The soils were chosen because they are common in the urban areas and because a difference in clay and silt content suggested the soils might have different characteristics when compacted. One soil, a silt loam, was taken from an area classified as a poorly drained variant of the Nixon soil series. The other soil series, Lakewood, has a coarser texture and was classified as a sandy loam. The physical and chemical properties of the two soils were described by Zisa and others (1980).

Soil Compaction Level

The soils were sieved to remove coarse fragments and then transferred to 6.35-cm inside-diameter cast acrylic transparent tubes. The soils were packed under static pressure into each tube in 1-cm increments until a soil column 15 cm long was constructed. Soil was packed to a bulk density of 1.2, 1.4, 1.6, or 1.8 g/cm^{-3}. A total of 48 tubes of soil were constructed from each soil type. A perforated plate was attached to the bottom of each tube to allow for drainage and to retain the soil column.

Except for screening, we did not alter the soil before it was compacted into the tubes. Neither fertilizer or lime was added, because earlier research on these two soils showed that heavy fertilization accelerated top growth and restricted root growth in maple (Pham et al. 1978).

Tree Species

Several species of the genera *Picea* and *Pinus* are the most frequently planted urban conifers in the Northeast (Gerhold et al. 1975). Since pine and spruce are commonly planted, we used stratified seed of pitch pine (*Pinus rigida* Mill.), Austrian pine (*Pinus nigra* Arnold), and Norway spruce (*Picea abies* (L.) Karst) for the experiment. Seeds were soaked in water and treated with a fungicide to control disease. Twenty seeds of each species were sowed in each soil type and bulk density combination. Four replicates of each treatment combination were constructed.

Growing Conditions

The containers with sowed seed were transferred to a greenhouse bench; the study design was a randomized complete block. Soil water potential was maintained near − 1/3 bar for the duration of the study. We used water, not a nutrient solution, to moisten the soil to avoid the problem of zones of nutrient solution encouraging abnormal development. For example, Minore and others (1969) suggested that nutrient accumulation in a gap between a container wall and a soil column accelerated root development next to the container wall. To prevent microbial growth at the interior of the wall, we covered the outside of the tube with foil. Artificial lighting was used to maintain a 14-hour photoperiod. Air temperatures during the period varied between 16° and 34°C; the relative humidity ranged from 26 to 98 percent.

Thirty days after germination, the seedlings were thinned to one per tube. The selected residual seedling was centrally located on the soil columns. At this time, we also removed the foil covering to be sure the seedling root was penetrating the soil, not the boundary between the tube wall and the soil.

After thinning, the seedlings were allowed to grow for an additional 90 days. Watering was continued to maintain soil water potential near − 1/3 bar, and the soil tubes were examined periodically to ensure that roots were growing in the soil. After 90 days, a few seedling roots had penetrated the entire length of the soil column, and the experiment was terminated.

Growth Variables

The seedlings were then removed from the tube by washing the soil from the roots, starting from the bottom of the tube. Measurements of growth variables were then made on the harvested seedlings.

We measured root penetration depth by noting the depth of soil left when a root was first encountered as the soil was washed away from the bottom of the tube. After the soil was removed, we immediately measured the shoot height and the extended length of the root. Each seedling was separated into top and root portions. Each portion was dried in a forced draft oven at 80°C for 48 hours and then weighed.

Analysis of Growth Data

We used analysis of variance to test the effects and interactions of growth factors. Each factor was analyzed separately. There were statistically significant differences in the effects of soil type, soil compaction level, and tree species on each of the growth variables (Table 1). The interactions for shoot growth were not significant but there were significant interactions for all root growth variables. All simple effects, two-way interactions, and the three-way interactions were significant for root weight. The significant three-way effects show that mean root weight for each soil type, soil density, and tree species combination must be kept separate. Other work showed growth reduced as soil compaction level increased, but interpretations were confounded by interactions and there were no significant differences in establishment or growth until the highest bulk density was reached (Zisa et al. 1980).

In this experiment, the primary objective was to identify the growth response most related to soil compaction level. Information from the analysis of variance was used to determine how much of the variance in growth response was due to soil compaction level. The variance due to soil compaction is measured by the intraclass correlation coefficient. Shoot height, root length, and shoot weight variations were very poorly related to compaction level (Table 2). Root weight was weakly correlated with compaction. Root penetration depth was well correlated with soil compaction level, with a intraclass correlation exceeding 0.94 (Table 2). The analysis showed that the root penetration growth response was more related to stresses due to compaction than to any other response we measured. Details of the analysis are in the Appendix.

Shoot height is a nondestructive measure of growth response and was investigated for use as an indirect measure of seedling response. In this experiment, shoot height was poorly correlated with soil compaction level for individual seedlings. Shoot height of individual seedlings also was poorly related to seedling root penetration depth. Consequently, height could not be used to predict performance of an individual seedling.

Table 1.—Analysis of variance of seedling growth variables

Source of variation	Degrees of freedom	Growth variable				
		Shoot height	Root length	Shoot weight	Root weight	Root penetration depth
		Mean squares				
Replicate	3	0.14	15.14	1052.10	129.30	1.37
Soil type (T)	1	5.27**	11.62	8319.79**	69111.93**	403.85**
Soil density (D)	3	5.11**	155.84**	4487.21**	30222.48**	732.72**
Tree species (S)	2	8.33**	718.35**	92456.27**	86937.11**	8.48**
T × D	3	.23	305.32**	750.12	16688.43**	119.82**
T × S	2	.75	73.54	1822.72	20645.17**	1.48
D × S	6	.34	71.17**	1727.78	6907.42**	1.20
T × D × S	6	.70	44.79	2022.74	6071.40**	1.08
Individual plant	69	.49	17.25	801.03	1115.32	1.68

**Significant at the 0.01 level.

Table 2.—Variance components and intraclass correlation for growth variables

Component	Growth variable				
	Shoot height	Root length	Shoot weight	Root weight	Root penetration depth
$S^2_D(Y)$	0.1925	5.816	153.591	1212.798	30.460
$S^2_e(Y)$	.4938	17.251	801.031	1115.328	1.667
$S^2_T(Y)$	.6863	23.067	954.623	2328.117	32.127
$R^2(Y)$	.281	.252	.161	.521	.948

Table 3.—Average value of growth variables of conifer seedlings at four levels of soil compaction

Soil density level	Average soil density	Growth response				
		Shoot height	Root length	Shoot weight	Root weight	Root penetration depth
	g/cm^{-3}	*cm*	*cm*	*mg*	*mg*	*cm*
1	1.2	5.42	18.50	97.65	138.12	14.50
2	1.4	4.62	13.64	92.12	87.66	8.85
3	1.6	4.84	14.18	88.88	79.15	4.77
4	1.8	4.33	12.77	66.52	53.40	1.73
	mean	4.80	14.78	86.29	89.58	7.46

We also analyzed the mean height growth of our seedling population, two pines and a spruce, versus the mean each of the other measures of growth response (Table 3). We found that although shoot height does not predict other growth variables on individual trees, the mean shoot growth response of a population of trees is related to other growth responses.

The regression equations for predicting a mean growth response for our species and soils from average height and the coefficients of determination (R^2) are:

Variable	*Equation*	*R^2 (among means)*
Mean root length	$\bar{y} = 14.78 + 5.99(h^* - 4.80)$	1.09
Mean shoot weight	$\bar{y} = 86.29 + 25.05(h^* - 4.80)$	0.89
Mean root weight	$\bar{y} = 89.58 + 81.25(h^* - 4.80)$	1.03
Mean root depth	$\bar{y} = 7.46 + 11.62(h^* - 4.80)$	0.93

where h^* is average seedling height.

The linear relationships between the mean of each of the growth variables and mean shoot height are strong. Two of the estimated correlations exceed 1.0, which may be questioned. However, these values are estimates and sample correlations among means as based on the estimated values of the variance and covariance components can exceed 1.0. Details of this analysis are in the Appendix.

Discussion

The analysis of variance showed that soil type, soil compaction level, and species were significant factors affecting seedling growth response. Partitioning the variance among the various main effects and interactions suggested that soil compaction levels had the greatest impact on root penetration depth since more of the variance was explained by this model (Table 1).

Removing the effect of species and soil type confirmed the suggestion that root penetration depth is highly correlated with soil compaction stress. The correlation values (Table 2) showed that average root penetration depth was highly related to average soil compaction level. None of the other responses in growth variables were well related to soil compaction stress. Soil compaction effects did not account for much of the variation in seedling height.

Depth of root penetration is not a traditional measure of seedling response to stress. For example, in a study of western conifer seedling germination and establishment, Noble and others (1979) found that height, root elongation, and biomass were not significantly related to stresses imposed by different soil moisture levels during the first 20 weeks of growth. Although the study of seedling response to water stress is not directly related to this work, it is significant that traditional measures of seedling response were not well correlated with stress during a growing period of similar length. In tests with loblolly pine, Foil and Ralston (1967) also found poor correlations between root weight and root length with soil bulk density, though the growth period was a full season.

The results of this study and interpretation of some reported results suggest that seedling response to soil compaction stress is poorly indexed by most common measures of growth. In this study, root penetration of the soil was the "best" measure of seedling response. There is no evidence that these measurements would be the best to use in future studies of soil compaction stress, though other types of measurement did not perform as expected. It may be necessary to conduct a pilot or companion test to determine the proper growth measurement that should be used.

Because measuring seedling height is nondestructive, we estimated the regression equation between mean seedling height and the mean of each of the other growth variables. The relationship with root penetration depth is of greatest interest, because predicting this variable from a nondestructive measurement will indicate how well the seedlings are performing on compacted soils. These equations showed strong relationships among the mean of the growth variables. The correlations among the means suggest that mean height growth might be used to predict the mean response in seedling studies, but only if equations are developed between the variables. Developing the relationships also would require a separate experiment.

The equations were derived for the mean response of our population of trees. For example, if we duplicated the experiment with the same species, and had height measurements from a large number of seedlings grown on a compacted soil, we could obtain good estimates of the mean of each of the other growth variables by using the prediction equations.

If we had only a few seedling height measurements from trees grown on soil with a known compaction level, the best estimate of the several growth variables would be the mean growth response at that compaction level (Table 3).

Acknowledgment

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Zisa, Robert P.; Halverson, Howard G.; Stout, Benjamin B. **Establishment and early growth of urban conifers on compact soils.** 1980; USDA For. Serv. Res. Pap. NE-451. 8 p.

Appendix

Analysis of Growth Response

The analysis is based on the variances and covariances of the growth variables. The soil compaction level mean square for shoot height is $MS_D = 5.11$ and the mean square for individuals (error) is $MS_e = 0.49$ (Table 1). For a model with all fixed treatment effects, the expected value of MS_D is $\sigma_e^2 + 24\sigma_D^2$ and the expected value of MS_e is σ_e^2 (Table 4). Equating the mean squares to their expected values and solving for the estimators (S^2) of σ^2 as:

$$S_D^2 = \frac{MS_D - MS_e}{24}$$

and

$$S_e^2 = MS_e$$

The estimates of σ_D^2 and σ_e^2 for shoot height (H) based on the variance table are:

$$S_D^2(H) = 0.19$$

$$S_e^2(H) = 0.49$$

Similarly, the variance of the response at the four soil compaction levels for each of the other growth variables (Y) is estimated by:

$$S_D^2(Y) = \frac{MS_D(Y) - MS_e(Y)}{24}$$

and error by:

$$S_e^2(Y) = MS_e(Y)$$

In a future experiment in which soil compaction level is the only factor, it is expected that the total variation in the measurement of the i^th^ growth variable will be:

$$S_T^2(Y) = S_D^2(Y) + S_e^2(Y)$$

The amount of variation accounted for by the soil compaction effects is measured by the intraclass correlation coefficient

$$R^2(Y) = S_D^2(Y) \,/\, S_T^2(Y)$$

The values of the variances and $R^2(Y)$ are given in Table 2 and show that root penetration depth variations are closely related to soil compaction level.

Table 4.—Expected mean squares for a model with all fixed treatment effects

Source of variation	Degrees of freedom	Expected mean square
Soil type (T)	1	$\sigma_e^2 + 48\,\sigma_T^2$
Soil density (D)	3	$\sigma_e^2 + 24\,\sigma_D^2$
Tree species (S)	2	$\sigma_e^2 + 32\,\sigma_S^2$
T × D	3	$\sigma_e^2 + 12\,\sigma_{TD}^2$
T × S	2	$\sigma_e^2 + 16\,\sigma_{TS}^2$
D × S	6	$\sigma_e^2 + 8\,\sigma_{DS}^2$
T × D × S	6	$\sigma_e^2 + 4\,\sigma_{TDS}^2$
Individual plant	69	σ_e^2

Table 5.—Covariance components between shoot height (H) and growth variable (Y)

Covariance component	Growth variable (Y)			
	Shoot weight	Root weight	Root length	Root penetration depth
$S_D(H, Y)$	4.823	15.785	1.154	2.236
$S_e(H, Y)$	7.770	− 1.898	− .186	0.137
$S_T(H, Y)$	12.593	13.887	.968	2.373

Correlations Among Growth Responses

Covariances were used in this experiment to develop realistic estimates of correlation coefficients between mean shoot height and the mean response in other variables.

The estimate of the covariation between mean seedling height (H) and the mean of growth variables (Y) is

$$S_D(H, Y) = \frac{MS_D(H, Y) - MS_e(H, Y)}{24}$$

The covariation due to individual tree effects is

$$S_e(H, Y) = MS_e(H, Y)$$

The total covariance between top growth and growth variable (Y) is estimated by (Table 5)

$$S_T(H, Y) = S_D(H, Y) + S_e(H, Y)$$

The regression of the mean of growth variable (Y) on the mean shoot height in a new sample ($\bar{h}^*$) is estimated by

$$\bar{y}^* = \bar{\bar{y}} + b_D(H, Y)(\bar{h}^* - \bar{\bar{h}})$$

where $\bar{y}^*$ = predicted mean growth response
$\bar{\bar{y}}$ = estimated grand mean of growth response (Y)
$\bar{h}^*$ = mean shoot height of new sample
$\bar{\bar{h}}$ = estimated grand mean shoot height

and $b_D(H, Y) = S_D(H, Y) / S_D^2(H)$

and, the correlation among the means is given by

$$R_D^2(H, Y) = \frac{S_D^2(H, Y)}{[S_D^2(H)\, S_D^2(Y)]^{1/2}}$$

Halverson, Howard G.; Zisa, Robert P. **Measuring the response of conifer seedlings to soil compaction stress.** Broomall, PA: Northeast. For. Exp. Stn.; 1982; USDA For. Serv. Res. Pap. NE-509. 6 p.

Evaluation of several growth responses showed that root penetration depth was best related to soil compaction stress. Conventional measures such as seedling height were not well related to soil compaction level, but seedling height can be used to predict root penetration. Selecting the proper growth variable is an important step in any seedling study.

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Keywords: urban trees, growth form, soil properties

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