GROWTH-LIMITING SOIL BULK DENSITIES
AS INFLUENCED BY SOIL TEXTURE

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Table of Contents

List of Tables

List of Figures

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1.0 Introduction

An important forest management concern is the possibility of reduced vegetative productivity due to soil compaction. Various research studies have shown the detrimental effects of soil compaction on the establishment and growth of forest and range plants (Lull 1959, Foil and Ralston 1967, Hatchell et al. 1970, Wilshire et al. 1978, Froehlich 1979, Greacen and Sands 1980, Wert and Thomas 1981). The effects of soil compaction on plant growth are a complex interaction between many soil and plant properties, but for many situations there appears to be an upper limit or threshold soil bulk density value where resistance to root penetration is so high that plant root growth is essentially stopped (O'Connell 1975). Restricted root penetration and elongation reduces the volume of soil that can be exploited by a plant for essential nutrients and water, which can cause a reduction in total growth. This threshold bulk density will be referred to as "growth-limiting" bulk density (GLBD).

GLBD is influenced by many soil properties but for most cases, soil texture appears to be the most important property determining the GLBD of a soil (Veihmeyer and Hendrickson 1948, Schuurman 1965, O'Connell 1975). The main reason why soil texture strongly influences GLBD is its effect on soil pore size and mechanical resistance.

The purpose of this paper is to (1) discuss the relationship between soil texture and GLBD, (2) provide forest soil scientists with a tool for estimating the GLBD of many different kinds of soils, and (3) illustrate how GLBD may be used to guide management practices so that vegetative growth is not significantly reduced by soil compaction.

2.0 Relationship of Soil Texture to Growth-Limiting Bulk Density

Roots grow in soil through large soil pores and by moving soil particles aside when the roots penetrate pores that are smaller than the root tips. When a soil is compacted to its GLBD value, most soil pore diameters are substantially smaller than the diameters of growing roots. In this situation, root growth is essentially stopped because the roots cannot exert enough pressure to overcome the mechanical resistance and move soil particles (Wiersum 1957, Aubertin and Kardos 1965).

A soil's GLBD is strongly influenced by soil texture because this property has a major effect on the average pore size and mechanical resistance of a compacted soil. A soil with a large amount of fine particles (silt and clay) will have smaller pore diameters and a higher penetration resistance at a lower bulk density than a soil with a large amount of coarse particles. Zisa et al. (1980) reported a silt loam soil had 19 percent macropore space and a measured penetration resistance of 2.5 bars at a bulk density of 1.4 g/cm^3. A coarser sandy loam had 28.9 percent macropore space and a penetration resistance of 1.2 bars at the same bulk density. Because of this relationship, coarse-textured soils will usually have higher GLBD than fine-textured soils. For example, Veihmeyer and Hendrickson (1948) reported that sunflower root growth was stopped at a GLBD of 1.75 g/cm^3 for sandy soils and 1.46 to 1.63 g/cm^3 for clayey soils. Schuurman (1965) and O'Connell (1975) reported similar relationships between soil texture and GLBD.

3.0 Analysis Methods and Results

An extensive literature search was done to review the relationship between plant root growth and soil compaction over a wide range of soil textures. This literature emphasized that there are primarily two general soil parameters--soil strength and soil bulk density--used to evaluate the effects of soil compaction on plant root growth.

Soil strength is defined as "the ability or capacity of a particular soil in a particular condition to resist or endure an applied force" (Gill and Vanden Berg 1967) and is usually measured by a penetrometer. Measurement of soil strength is an attempt to determine the actual soil physical forces the roots are encountering. However, soil strength measurements are highly dependent on both soil moisture and bulk density at the time of measurement (O'Connell 1975, Mulqueen et al. 1977). The type of penetrometer and method of measuring soil strength as a function of penetrometer resistance can also produce highly variable results (Greacen and Sands 1980).

Soil bulk density can be measured by various methods, such as clod, sand cone, core, or auger-hole (O'Connell 1975). Although each method has its disadvantages, observed soil bulk density values appear to be less dependent on soil moisture and measuring techniques than are soil strength values. For these reasons, soil bulk density was selected as the appropriate parameter for evaluating the relationship of soil texture to compaction and plant root growth.

In order to establish a relationship between soil texture and GLBD, published research data were used that included soil mechanical analysis (percent sand, silt, and clay) and GLBD measurements of either a single point or a narrow range for each soil. This information is listed in Table 1 and plotted on a textural triangle in Figure 1. Much of the literature about bulk density and plant growth could not be used because a soil mechanical analysis was not available or experimental bulk densities were not high enough to effectively stop plant root growth.

As illustrated in Figure 1, available data about GLBD are not uniformly distributed over the entire soil textural triangle. In order to estimate the GLBD values for all possible soil textures, an empirical relationship was developed that correlated published GLBD for all the soils listed in Table 1 with computed average pore radii. Average pore radius was calculated for each soil using a modified version of the soil bulk density model developed by Gupta and Larson (1979) to simulate the packing of soil particles into defined geometric arrangements based on the particle size distribution (texture) of a soil. Through regression analysis of 21 soil textures (Table 1), calculated average pore radii were found to be linearly correlated (r^2 = 0.70, with standard error of 0.09 g/cm^3) with their given GLBD values (Figure 2) by the equation:

$$GLBD = 1.34 + 3.02\ (PR)$$

where

GLBD = Growth-limiting bulk density (g/cm^3),

and

PR = Calculated average pore radii (mm).

Average pore radii for 80 different soil textures uniformly distributed over the textural triangle were calculated using the previously mentioned bulk density model. GLBD's were then computed for all 80 soil textures with the above regression equation and plotted on a USDA soil textural triangle in order to locate the growth-limiting isodensity lines in Figure 3. These isodensity lines represent equal GLBD values and are used to estimate the GLBD of a soil.

Table 1.--Soil and plant data related to growth-limiting bulk densfty values

SOIL TYPE	PLANT	SAND (%)	SILT (%)	CLAY (%)	MOISTURE (Bars)	LIMITING BULK DENSITY	COMMENTS	REFERENCE
1) Colo Clay	Corn	27	31	42	0.10	1.30	Severe reduction (79%) in root elongation	Phillfps and Kirkham 1962a, b
2) Loam	Pea	71	I7	12	0.30	1.70	Severe reduction (69%) in length of all roots	Barley et al. 1965
3) Miles Loamy Fine Sand	Cotton	83	8	9	0.33	1.82	No root penetration, 19 bars penetrometer resistance	Taylor et al. 1966
4) Naron Fine Sandy Loam	Cotton	79	11	10	0.33	1.79	No root penetration, 20 bars penetrometer resistance	Taylor et al. 1966
5) Quinlan Very Fine Sandy Loam	Cotton	73	20	7	0.33	I.77	No root penetration, 25 bars penetrometer resistance	Taylor et al. 1966
6) Columbia Loam	Cotton	44	37	19	0.33	1.55	No root penetration, 25 bars penetrometer resistance	Taylor et al. 1966
7) Tripps Sandy Loam	Corn-Soybean	63	25	12	0.33	1.60	No root elongation, 22 bars penetrometer resistance	Mazurak and Pohlman 1968
8) Tripps Loam	Corn-Soybean	41	41	18	0.33	1.40-1.60	No root elongation, 11-28 bars penetrometer resistance	Mazurak and Pohlman 1968
9) Urrbrae Fine Sandy Loam	Pea	16	19	65	0.05	1.46	No root elongation - void ratio- 0.81	Cockroft et al. 1969
10) Sandy Loam	Red Alder Lodgepole Pine Douglas-Fir	52	31	17	1.00	1.59	No root penetration	Minore et al. 1969
11) Sand	Sorghum Beans, Millet Sudangrass	96	2	2	--	I.74	No root penetration	et al. 1973

Table 1.--Soil and plant data related to growth-limiting bulk density values (Continued)

SOIL TYPE	PLANT	SAND (%)	SILT (%)	CLAY (%)	MOISTURE (Bars)	LIMITING BULK DENSITY	COMMENTS	REFERENCE
12) Sverdrup Sandy Loam	Pea	63	27	10	1.00	1.61	Severe reduction (79%) in primary root elongation	Voorhees et al. 1975
13) Nutley Clay	Pea	6	39	55	1.00	1.37	Severe reduction (70%) in primary root elongation	Voorhees et al. 1975
14) --	Apple	64 ± 5	25 ± 3	11 ± 3	--	1.75	Restricted root growth, porosity - 34%	Webster 1978
15) --	Apple	61 ± 8	29 ± 5	10 ± 5	--	1.72	Restricted root growth, porosity - 35%	Webster 1978
16) --	Apple	58 ± 9	31 ± 7	11 ± 4	--	1.85	Restricted root growth, porosity - 30%	Webster 1978
17) --	Apple	69 ± 5	18 ± 4	13 ± 3	--	1.77	Restricted root growth, porosity - 33%	Webster 1978
18) --	Apple	86 ± 4	9 ± 4	5 ± 3	--	1.62	Restricted root growth, porosity - 39%	Webster 1978
19) --	Apple	75 ± 11	19 ± 8	6 ± 3	--	1.88	Restricted root growth, porosity - 29%	Webster 1978
20) Nixon Silt Loam	Pitch Pine Austrian Pine Norway Spruce	22	64	14	0.33	1.40	Severe reduction (75%) in root penetration	Zisa et al. 1980
21) Lakewood Sandy Loam	Pitch Pine Austrian Pine Norway Spruce	66	26	8	0.33	1.60-1.80	Severe reduction in root penetration	Zisa et al. 1980

-- Not available.

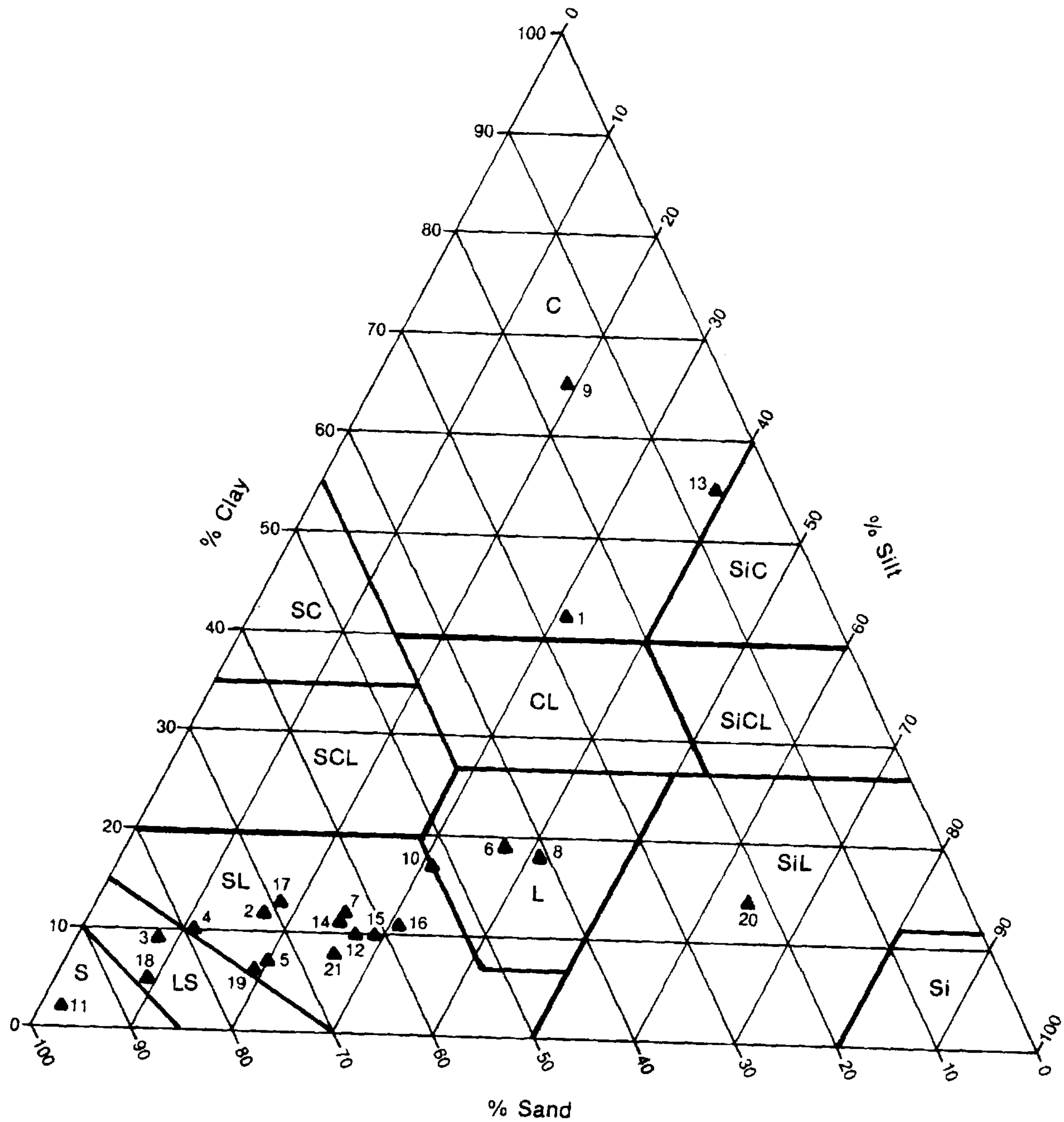

Figure 1.--Distribution of soil textures having growth-limiting bulk density values. Numbers 1-21 inside the triangle refer to soil data numbers in Table 1.

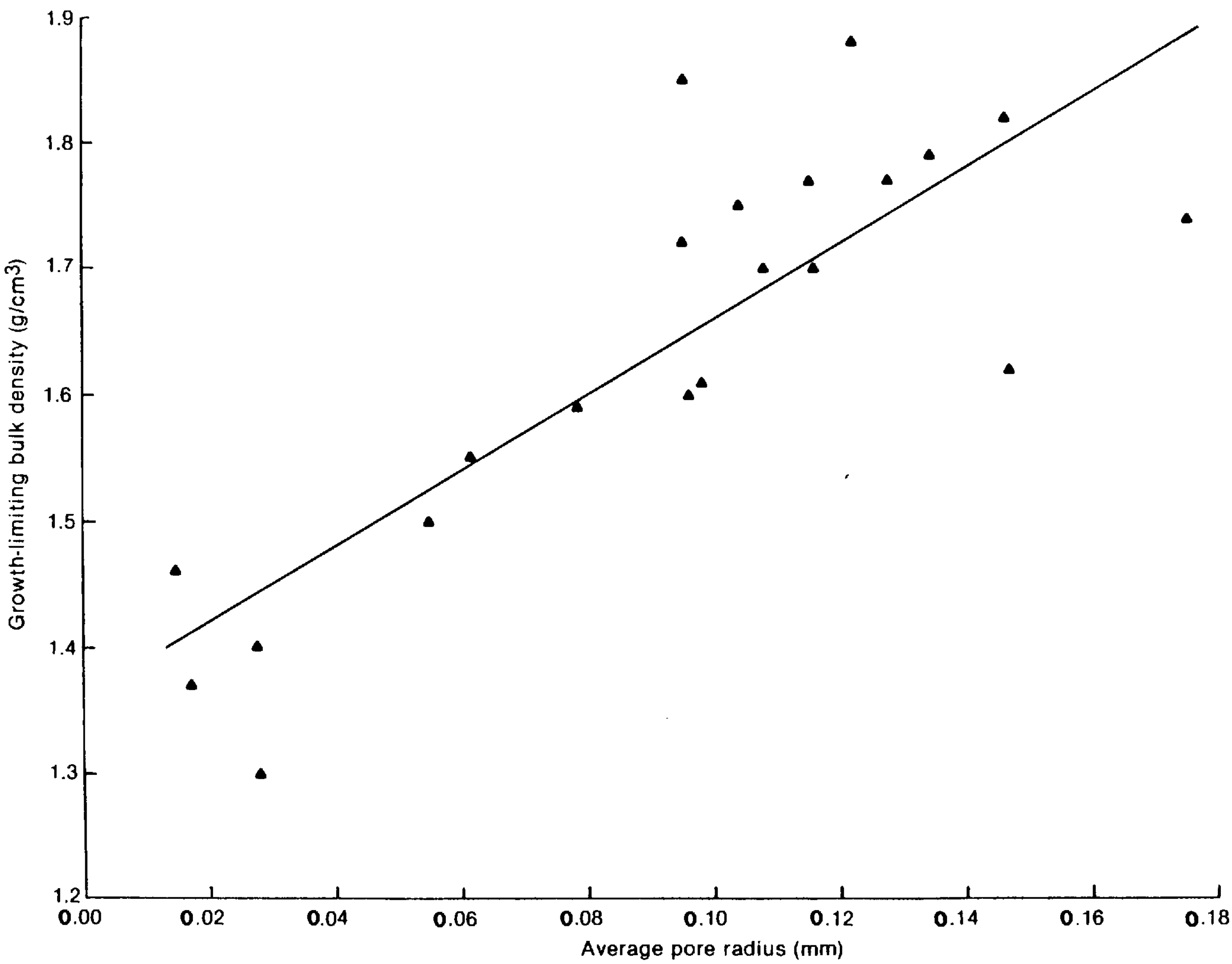

Figure 2.--Relationship between growth-limiting bulk density and calculated average pore radius.

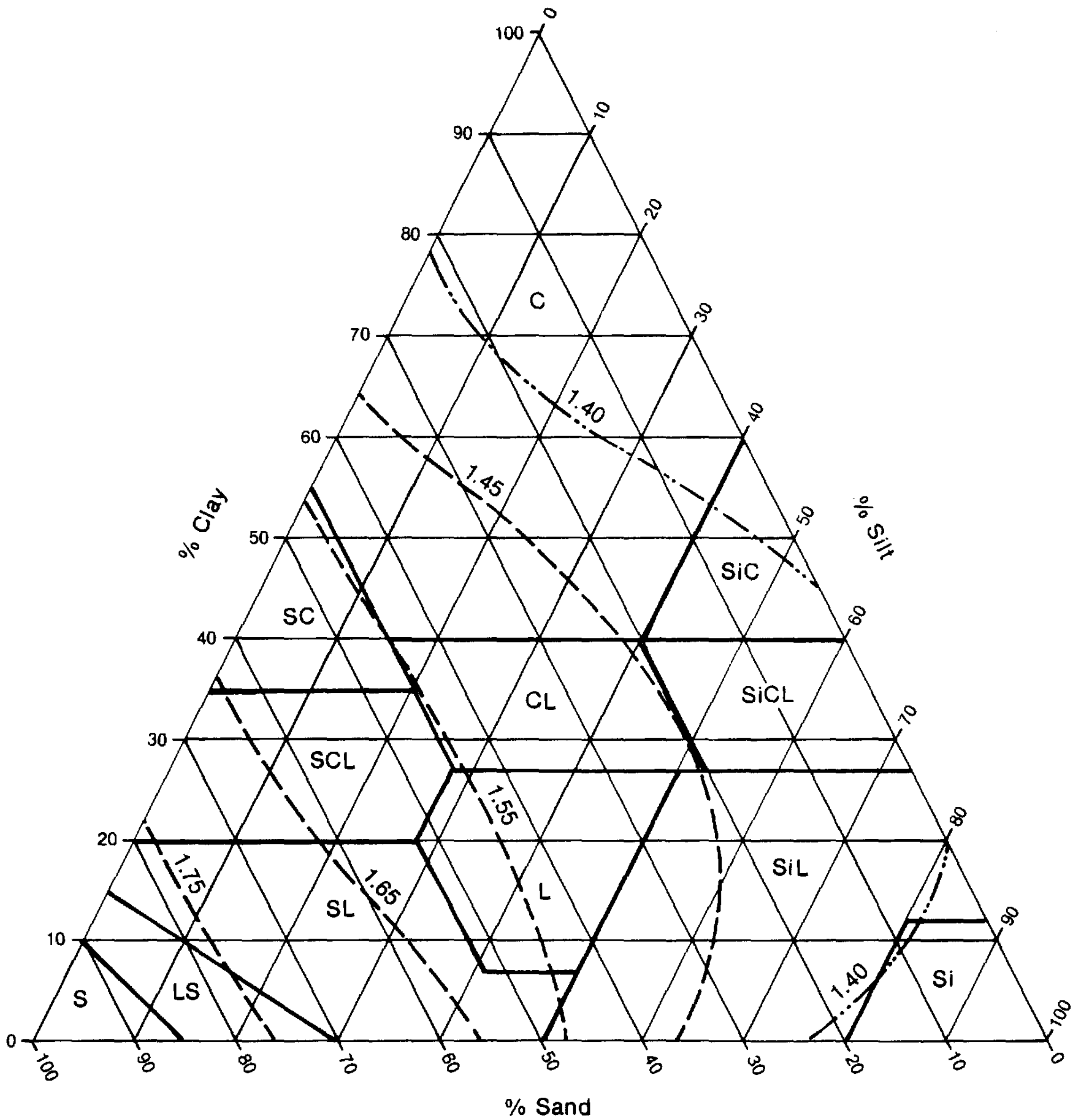

Figure 3.--Growth-limiting bulk density textural triangle.

4.0 Estimation of Growth-Limiting Bulk Densities

The GLBD for a given soil can be estimated by locating its percent sand, silt, and clay on Figure 3 and determining the appropriate GLBD value associated with that textural point. For example, a clay loam soil has 30 percent sand, 34 percent silt, and 36 percent clay. Figure 3 shows this textural point located between the 1.45 g/cm^3 and 1.55 g/cm^3 isodensity lines. Interpolation between the two lines indicates this soil can be assumed to have a GLBD of about 1.50 g/cm^3.

5.0 Limitations and Assumptions

Careful consideration and professional judgment should be exercised in using the GLBD textural triangle. Limitations and assumptions used in developing the GLBD textural triangle are:

1. The GLBD values shown in Figure 3 are applicable only on soils with less than 3 percent organic matter, less than 10 percent coarse fragments, and particle densities near 2.65 g/cm^3. The reason for these limitations is that most of the data used to develop the GLBD textural triangle were obtained from agricultural soils which had particle densities of about 2.65 g/cm^3 and were low in organic matter and coarse fragments. At this time, there is not enough research data to establish absolute GLBD values for soils outside the specified limits.
2. Individual forest species may have different responses to high soil bulk densities and may have higher or lower growth-limiting values than those shown in Figure 3 (Forristall and Gessel 1955, Minore et al. 1969). Most of the data used in this report is

from short-term growth records of agricultural plants with very little quantitative research about long-term effects of bulk density on the growth of forest and range plants.

3. GLBD relationships are assumed to be based on a soil water content at or near field capacity (0.33 bar). Soil water conditions reported for soils used to develop the growth-limiting textural triangle ranged from 0.05 to 1.00 bar. If the soil water content is near saturation or is approaching permanent wilting, soil aeration or water stress may be more limiting to plant growth than a high soil bulk density 1972).

4. The isodensity values in Figure 3 do not account for effects of soil structure when root growth occurs along ped faces. Strong structure could result in individual structural units having internal densities near the growth-limiting bulk density but with enough structural openings to allow some root growth along ped faces. This is one reason why maintaining good soil structure is an important consideration for soil management. If soil structure is altered or destroyed by soil compaction the result could be a large reduction in plant growth. Most of the soils data used for this paper were from structureless soils.

5. Most of the soil bulk density data used for growth-limiting bulk density values came from core bulk density measurements. Soil bulk density values determined by other methods may result in values substantially different from core bulk density measurements.

6.0 Management Implications of the Growth-Limiting Bulk Density Textural Triangle

The GLBD textural triangle shows that soil texture is an important property to consider when evaluating the effects that various land management practices have on compaction of specific sites. For example, timber harvest and site preparation practices can cause varying amounts of soil compaction. If the bulk density in the seedling root zone of a clay-textured soil is near 1.40 g/cm^3, this site would be very close to its growth-limiting threshold value. Under this condition, severe reduction of root growth might occur. Some type of compaction-mitigating practice may be needed to promote seedling establishment and improve growth. However, if this same bulk density were measured for a sandy-textured site, most likely there would be little if any adverse compaction effects on root growth.

A soil at its GLBD value is highly compacted, and this condition should be avoided if at all possible. However, in terms of evaluating, protecting, and improving the soil productivity of a site, it is probably more important to know the relationship between plant growth and bulk densities at less than the growth-limiting value. For example, in many soils there appears to be an "optimal" bulk density or narrow range of bulk densities at which plant growth is maximized (Rosenburg 1964, Greacen and Sands 1980). Unfortunately, because of lack of data for a wide range of soil textures and forest plants, no generalized quantitative relationships can be established. Some research studies (Phillips and Kirkham 1962b, Taylor et al. 1966, Foil and Ralston 1967, Mazurak and Pohlman 1968, Cockroft et al. 1969, Zisa et al. 1980, Heilman

1981) have shown that small increases in bulk density can cause large reductions in root growth at bulk densities substantially lower than the growth-limiting values. This emphasizes that bulk densities approaching growth-limiting values should also be avoided to minimize the potential reduction in root growth and impairment of vegetative productivity.

7.0 Summarv and Conclusion

The GLBD textural triangle illustrates the relationship between growth-limiting bulk density and soil texture. This textural triangle may be used by forest soil scientists as an aid in evaluating the impact of soil compaction on plant growth through the effects on root growth. The limitations and assumptions used to develop the growth-limiting bulk density textural triangle must be carefully considered when using this tool.

A soil at or above its GLBD value is at a highly compacted condition where root growth is essentially stopped. This condition should be avoided if at all possible. In general, a soil approaching its GLBD value may be also considered at a physical state where vegetative productivity could be seriously impaired. Because of this possibility, it would be preferable from a soil management standpoint to keep a soil's bulk density well below its GLBD value. Therefore, any planned practices that may increase a soil's bulk density to a value near its GLBD should be fully evaluated.

Ideally, in terms of protecting and improving the soil productivity of a site, it would be desirable to know more about the re-lationships between soil compaction and total plant growth at bulk densities less than the GLBD values. However, a lack of data for different forest soils and plants precludes establishing any general quantitative relationships. This lack of data points out a need for more research on the relationship between soil compaction and forest plant growth. Forest management could benefit from quantitative investigations of bulk density effects on the growth of important forest tree species on forest soils with large amounts of coarse fragments, organic matter, or volcanic ash.

Literature Cited

Aubertin, G. M., and L. T. Kardos. 1965. Root Growth Through Porous Media Under Controlled Conditions. I. Effect of Pore Size and Rigidity. Soil Science Society of America Proceedings 29:290-293.

Barley, K. P., D. A. Farrell, and E. L. Greacen. 1965. The Influence of Soil Strength on Penetration of a Loam by Plant Roots. Australian Journal of Soil Research 3:69-79.

Cockroft, B., K. P. Barley, and E. L. Greacen. 1969. The Penetration of Clays by Fine Probes and Root Tips. Australian Journal of Soil Research 7:333-348.

Eavis, B. W. 1972. Soil Physical Conditions Affecting Seedling Root Growth. I. Mechanical Impedance, Aeration, and Moisture Availability as Influenced by Bulk Density and Moisture Levels in a Sandy Loam Soil. Plant and Soil 36:613-622.

Foil, R. R., and C. W. Ralston. 1967. The Establishment and Growth of Loblolly Pine Seedlings on Compacted Soils. Soil Science Society of America Proceedings 31:565-568.

Forristall, F. F., and S. P. Gessel. 1955. Soil Properties Related to Forest Cover Type and Productivity on the Lee Forest, Snohomish County, Washington. Soil Science Society of America Proceedings 19:384-389.

Froehlich, H. A. 1979. Soil Compaction from Logging Equipment on Growth of Young Ponderosa Pine. Journal of Soil and Water Conservation 34:276-278.

Gill, W. R., and G. E. Vanden Berg. 1967. Soil Dynamics in Tillage and Traction. U.S. Department of Agriculture. Handbook No. 316, p. 22.

Greacen, E. L., and R. Sands. 1980. Compaction of Forest Soils - A Review. Australian Journal of Soil Research 18:163-189.

Gupta, S. C., and W. E. Larson. 1979. A Model for Predicting Packing Density of Soils Using Particle Size Distribution. Soil Science Society of America Journal 43:758-764.

Hatchell, G. E., C. W. Ralston, and R. R. Foil. 1970. Soil Disturbances in Logging: Effects on Soil Characteristics and Growth of Loblolly Pine in the Atlantic Coastal Plain. Journal of Forestry 68:772-775.

Heilman, P. 1981. Root Penetration of Douglas-Fir Seedlings into Compacted Soil. Forest Science 27:660-666.

Lull, H. W. 1959. Soil Compaction on Forest and Range Lands. U.S. Department of Agriculture. Miscellaneous Publication No. 768.

Mazurak, A. P., and K. Pohlman. 1968. Growth of Corn and Soybean Seedlings as Related to Soil Compaction and Matric Suction. Ninth International Congress of Soil Science Transactions 1:813-820.

Minore, D. C., E. Smith, and R. F. Woollard. 1969. Effects of High Soil Density on Seedling Root Growth of Seven Northwestern Tree Species. USDA Forest Service Research Note PNW-112. Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Mulqueen, J., J. V. Stafford, and D. W. Tanner. 1977. Evaluation of Penetrometers for Measuring Soil Strength. Journal of Terramechanics 14:137-151.

O'Connell, D. J. 1975. The Measurement of Apparent Specific Gravity of Soils and Its Relationship to Mechanical Composition and Plant Root Growth. In Soil Physical Conditions and Crop Production, p. 298-313. Ministry of Agriculture, Fisheries, and Food. Technical Bulletin 29. H.M.S.O., London.

Phillips, R. E., and D. Kirkham. 1962a. Soil Compaction in the Field and Corn Growth. Agronomy Journal 54:29-34.

Phillips, R. E., and D. Kirkham. 1962b. Mechanical Impedance and Corn Seedling Root Growth. Soil Science Society of America Proceedings 26: 319-322.

Rosenburg, N. J. 1964. Response of Plants to the Physical Effects of Soil Compaction. Advances in Agronomy 16:181-196.

Schuurman, J. J. 1965. Influence of Soil Density on Root Development and Growth of Oats. Plant and Soil 22:352-374.

Taylor, H. M., G. M. Roberson, and J. J. Parker, Jr. 1966. Soil Strength-Root Penetration Relationships for Medium- to Coarse-Textured Soil Materials. Soil Science 102:18-22.

Veihmeyer, F. J., and A. H. Hendrickson. 1948. Soil Density and Root Penetration. Soil Science 65:487-493.

Voorhees, W. B., D. A. Farrell, and W. E. Larson. 1975. Soil Strength and Aeration Effects on Root Elongation. Soil Science Society of America Proceedings 39:948-953.

Webster, D. H. 1978. Soil Conditions Associated with Absence or Sparse Development of Apple Roots. Canadian Journal of Plant Science 58:961-969.

Wert, S., and B. R. Thomas. 1981. Effects of Skid Roads on Diameter, Height, and Volume Growth in Douglas-Fir. Soil Science Society of America Journal 45:629-632.

Wiersum, L. K. 1957. The Relationship of the Size and Structural Rigidity of Pores and Their Penetration by Roots. Plant and Soil 9:75-85.

Wilshire, H. G., J. K. Nakata, S. Shipley, and K. Prestegaard. 1978. Impacts of Vehicles on Natural Terrain at Seven Sites in San Francisco Bay Area. Environmental Geology 2:295-319.

Worker, G. F., Jr., R. S. Ayers, M. A. Karah, and R. E. Thomason. 1973. Effect of Dense Stratified Sandy Soil on Crop Roots. Journal of Agricultural Science 81:513-516.

Zisa, R. P., H. G. Halverson, and B. Stout. 1980. Establishment and Early Growth of Conifers on Compact Soils in Urban Areas. USDA Forest Service Research Paper NE-451. Northeastern Forest Experiment Station, Broomall, PA.