CHAPTER I

INTRODUCTION

Study Rationale

Forest management practices can compact soil, which affects the ability of roots to exploit the soil volume for water and nutrient uptake. Several key soil properties such as soil strength, water, aeration, and their interactions are affected by soil compaction. Many studies have shown that tree growth and productivity decrease with compaction (Froehlich, 1976; Hatchell et al., 1970; Cochran and Brock, 1985). Furthermore, recovery and amelioration of compacted soil can be slow, if it occurs at all (Froehlich, 1979; Heninger et al., 2002). Therefore, it is critical to thoroughly understand compaction processes, their effects on soil and plant growth, and the extent to which compaction effects can be minimized.

Soil is compacted to varying degrees when driven upon by heavy machinery. In general, root growth opportunity is diminished proportionally with increasing soil density due to excessive soil strength as a soil dries, or inadequate aeration when a soil becomes too wet. These physical processes have been conceptualized by Greacen and Sands (1980). The slower roots grow, and the less soil volume they exploit, the slower the growth of trees above ground (Halverson and Zisa, 1982; Tuttle, et al., 1988).

A measure of soil bulk density alone does not capture the dynamics of this interactive process. For a given region, soil type, and tree species, forest productivity will be a function of volumetric water content as it varies with climate across the growing season. As volumetric water content changes, the opportunity for root growth changes. Increasing soil density changes the soil's porosity and its ability to hold water, leading to reduced opportunity for root growth. The top 20 cm of the soil profile is most important, as most tree species have the majority of their roots in this zone (Gale and Grigal, 1987; Sands and Bowen, 1978; Kozlowski, 1999).

The United States Forest Service (USFS) is required by law to maintain the long-term productivity of public lands within the National Forest system. The effects of management practices on soil, and subsequent influences on forest productivity, need to be determined so that preventative measures can be applied to minimize site-damaging activities. The Long-Term Soil Productivity (LTSP) study is a USFS effort designed to quantify and increase our understanding of the effects of soil disturbance on productivity. It seeks to elucidate key controlling site processes as well as develop and validate soil disturbance standards. There have been many studies relating soil bulk density and/or soil strength with water potential, yet relatively few have related root growth to both strength and water.

Objectives

The overall objective of this research was to develop models to predict soil compaction effects on root growth opportunity and processes across a range of soil types and tree species. The effects of compaction on several soil properties such as soil density on soil strength and soil aeration were quantified, and a model was developed that enabled predictions of forest productivity decline as a function of root growth opportunity. The working hypothesis was that root growth opportunity changes when compacted soils dry due to increasing soil strength, and inadequate aeration becomes limiting when soils are wet or become saturated. Furthermore, it was hypothesized that this compactive effect may vary with soil type and tree species.

The national network of long-term soil productivity sites provided a unique opportunity for testing the key soil physical factors affecting root growth and their interactions across a broad range of soil, forest tree species, and climatic conditions. This research utilized the across-site opportunity created by the LTSP study by developing a root growth opportunity model, based on a controlled greenhouse experiment.

The specific objectives of this research were to:

i. Characterize soil compaction characteristics and soil physical parameters for four soils from a range of forest and climatic regions.

ii. Develop a root growth opportunity model as a function of soil strength and soil aeration for tree species associated with each of four forest soils.

iii. Determine the extent to which compactive effect is soil-specific, and the extent to which regional standards for forest soil disturbances are valid.

CHAPTER II

LITERATURE REVIEW

Historical Perspective and Overview

Forest management practices under some circumstances can damage forest sites in ways that can reduce long-term site productivity. As early as 1947, it was recognized that logging can damage the soil by affecting soil structure and moisture relations (Munns, 1947). Soil compaction has been a concern in forestry and agriculture for decades in the United States and numerous studies have attempted to determine compaction effects on soil and plant growth. Early researchers typically focused on compaction effects and soil bulk density on agricultural plants. Veihmeyer and Hendrickson (1948) tested the effects of soil density on water relations and determined a threshold density above which sunflower roots would not grow. In the forestry area, E.C. Steinbrenner and S.P. Gessel did early research on the effects of logging on forest soil properties during the 1950's. They published several studies looking at the effects of logging on soil physical properties in the Pacific Northwest (Steinbrenner and Gessel, 1955ab). Furthermore, Steinbrenner (1959) developed a portable air permeameter to measure changes in soil porosity and suggested it would be a useful tool for detecting soil compaction.

Forest soil compaction studies continued during the 1960's and 1970's. Loblolly pine seedlings grown in compacted soils of several types showed a linear, negative root length response to increasing soil density (Foil and Ralston, 1960). The authors concluded, "even though causative factors could not be isolated, retardation of seedling growth was quite substantial and this points to the need for further study of forest soil compaction problems". Many researchers began to look more closely at the causative effects of growth declines due to compaction. For example, Sands et al. (1979) measured radiata pine growth as a function of resistance to penetration and found critical soil strength values of about 3.0 MPa, beyond which pine root growth was restricted.

During the past two decades, the focus has shifted from looking at single variables (i.e. bulk density thresholds) to integrative approaches such as the conceptual model by Greacen and Sands (1980). Work by Letey (1985) on the non-limiting water range

(NLWR) amounted to a quantification of Greacen and Sand's model, and Letey's work was furthered by da Silva and Kay's (1994) least limiting water range (LLWR) approach. More recent studies have begun to look at how interrelated soil factors affect tree growth. In addition, the work is being expanded to many different forested regions, soil types and species.

After 50 yr of research, we are still uncertain of the ultimate effect of compaction on forest productivity. Federal mandates to maintain forest health and productivity such as the Multiple Use-Sustained Yield Act of 1960, National Environmental Policy Act of 1969, Forest and Rangeland Renewable Resources Planning Act of 1974 and the National Forest Management Act of 1976, require federal land managers to maintain and protect the productivity of the land and provide the research and monitoring necessary for this protection (Powers, 1990).

Furthermore, world-wide interest in conserving forest resources and managing forest lands sustainably has been a strong focus, leading to several conferences, such as the 1992 Earth Summit, from which stemmed the Montreal Process (Ramakrishna and Davidson, 1998). The Montreal process provided guidelines for developing criteria and indicators that could be used to assess forest productivity and sustainability (Ramakrishna and Davidson, 1998). Soil compaction was determined to be one of the soil indicators of forest health. Forest managers want to know how to best avoid the deleterious effects of compaction on their land, yet even after years of research there is no simple answer to the question. To meet national and world-wide mandates for protecting soil resources we must: (i) continue to further our understanding of how and why different soils have different compactibilities; and (ii) determine how the complex interaction of soil physical properties, air and water, as affected by compaction, ultimately affect tree growth. Greacen and Sands (1980) conceptualized the effect of compaction on growth as shown in Fig. II.1. We used this model as the fundamental underpinning of our research. The remainder of the literature review will focus on the various components of this model.

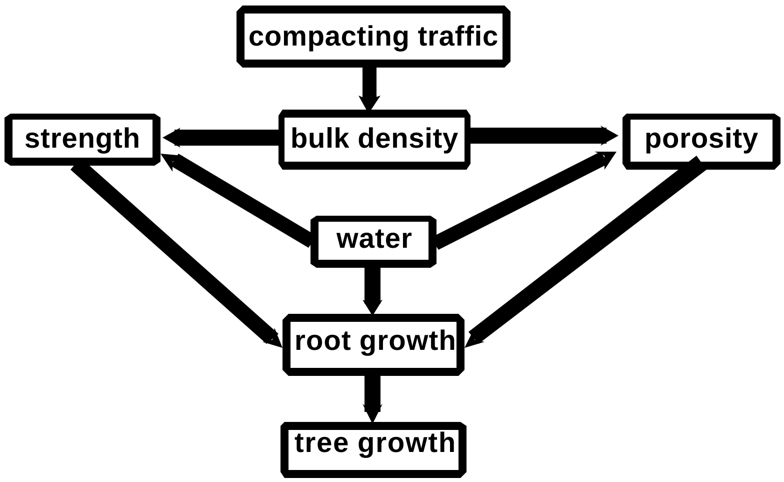

Fig. II.1. Tree growth as a function of soil compaction (after Greacen and Sands, 1980)

Soil Compaction and Compressibility

Soil compressibility is affected by both internal soil factors and external factors. Horn, 1988, lists the following as those internal soil factors that affect compressibility: (i) grain size distribution; (ii) clay mineral type, and sort and amount of adsorbed cations; (iii) content of organic substances; (iv) soil structures and their strength induced by swelling and shrinking and stabilization by roots or humic substances; (v) bulk density, particle density and pore continuity; and (vi) water content and water suction. External factors include the load, intensity and timing and duration of the load. For example, different machines, or even the same machine, with different tires apply different loads and stresses to the soil. It is not surprising that it is difficult to find a single parameter that best represents compaction given the great number of variables that determine the compressibility of the soil. However, there are several key properties that determine a soils compactibility: organic matter, mineralogy, texture, particle size distribution uniformity, particle shape and surface roughness are all factors controlling compressibility.

Soil organic matter content, which has very important effects on soil structure, aeration, water holding capacity, and chemical properties greatly affect soil compactibility. Bulk density (BD) and soil porosity become lower and higher, respectively, with increasing organic matter contents (Childs et al., 1989). A difference of 2 to 5 % can significantly affect soil properties such as BD and porosity for sandy soils (Rawls, 1983). Studies have also shown organic C content to be the most strongly correlated soil property with dry density for Californian forest and range soils (Howard et. al, 1981) and the best predictor of BD (Alexander, 1980).

Clay hydrated radius, cation exchange capacity (CEC) and shrink/swell properties also contribute to soil compressibility (Horn, 1988). Larson et al. (1980) found that medium textured soils with highly weathered clays tend to be moderately compressible (as indicated by the compression index), but less compressible than soils dominated by 2:1 type clays, and more compressible than volcanic soils with allophane as the dominant mineral.

Texture and the distribution of the particle size classes also influence forest soil compaction and BD (Froehlich and McNabb, 1984). In a study of the influence of particle size distribution on soil compaction, loamy sands had the highest densities, regardless of sand component particle size (Bodman and Constantin, 1965). Soils with a wide distribution of different particle size classes achieved the greatest BD because the fines filled in the spaces created by the larger particles (Marshall, 1959). Furthermore, compressibility of coarse textured soils with a wide range in particle size is more influenced by particle size distribution than clay type (Larson et al., 1980).

Particle shape and surface roughness have been shown to affect densification, compressibility and shear strength of soils (Cruse et al., 1980; McNabb and Boersma, 1993). Rough-surfaced particles have greater interparticle friction and locking of edges and, therefore, are more resistant to densification (Cruse et al., 1980).

McNabb et al. (2001) concluded that texture and BD alone are not the exclusive factors contributing to the forest soil deformation processes; instead, there are many interacting soil properties that influence compactibility. Ball et al. (2000) found that readily oxidizable organic matter and the liquid limit were the two best properties describing compressibility of 156 Scottish soils. They concluded that the liquid limit might integrate clay type and content and soil surface area.

Soil Compaction Characteristics

All soils have their own unique response to compaction due to the interaction of soil properties previously described. The standard effort test, also called the Proctor test, is used to determine the optimum water content (OWC) for compaction and maximum BD for a soil. OWC can be used to assess compactibility differences between soils, as well as suggest windows of soil wetness when forest harvesting or other activities should be avoided. For each soil there is a family of compaction curves with OWC varying with the type and amount of compactive energy applied by differing compacting machinery (Froehlich and McNabb, 1984). However, Froehlich and McNabb (1984) showed that lab compaction tests such as the proctor test do not adequately predict the kind and amount of compaction occurring in the field by machinery. In studies by Soane (1990), high levels of organic matter and further organic matter additions reduced maximum BD and increased the OWC of a soil. Zhang et al. (1997) showed that for sandy soils, organic matter is most effective at reducing compaction when soil is at OWC, while for more cohesive soils it is more effective at water contents below OWC. This suggests that including the interactions of texture and organic matter on OWC would provide better information on the ideal times to harvest and minimize compaction.

The compression index (CI) is another measure of the rate at which a soil becomes compacted with repeated applications of compactive forces. For example, the CI may indicate the rate at which a soil would become compacted as a result of increasing machinery passes during a harvesting operation. Mitchell (1993) generalized that soils with CI values < 0.2 have slight to low compressibility; CI values of 0.2 to 0.4 indicate moderate to intermediate compressibility; and CI's > 0.4 indicate high soil compressibility. Larson et al. (1980), using compression curves from repacked samples, partitioned 36 agricultural soils from around the world into four compressibility groups based primarily on mineralogy: 1) soils derived from volcanic ash, allophane dominant clay mineral (CI-0.36) 2) medium textured, highly weathered soils, iron oxides dominate (CI-0.45), 3) medium-textured soils, expanding-type clays (CI-0.59) and 4) coarse-textured soils, particle size distribution dominates behavior over clay type (CI-0.22). McNabb and Boersma (1993) measured a compression index of 0.23 for a forest soil field core sample of comparable texture and organic matter content. In this case, undisturbed natural soil structure and andic soil properties may have contributed to this soil's resistance to compaction. The CI can be a useful method to describe soil compactibility; however, direct comparisons of soils should include the influence of sieving, organic matter content, soil mineralogy and water content differences.

Bulk Density

As depicted in Greacen and Sands (1980) model, compaction increases BD thus impacting soil strength, porosity, water and root growth opportunity. It is generally well documented that increasing BD decreases the ability of roots to grow. For example, length and root mass of loblolly pine seedlings decreased when BD exceeded 1.3 Mg m^{-3} for a sandy clay loam and 1.4 Mg m^{-3} for a loamy sand (Tuttle et al., 1988). In another study, BD exceeding 1.6 Mg m^{-3} caused severe root deformation and reduction of growth for loblolly pine seedlings growing in a fine sandy loam soil (Mitchell et al., 1982).

Many researchers have attempted to relate BD, porosity, strength and other single factors to plant growth limitations (Sands et al., 1979; Daddow and Warrington, 1983; Alexander and McLauglin, 1990). For example, growth-limiting BD, determined by soil texture, was developed based primarily on agricultural and range soil growth data (Daddow and Warrington, 1983).

Soil Strength

A better measure of root growth potential than BD is soil strength in that it encompasses the effects of density and moisture. A high-density soil that is wet may still be penetrable by roots due to lower soil strength, while a dry soil of the same density would limit root growth due to increased strength. Penetrometer probes have been used to measure soil strength as an analogue, although imperfect, of root resistance to penetration through a soil (Atwell, 1993; Greacen and Sands, 1980). Roots generally encounter less resistance than a penetrometer probe due to radial expansion and the ability to minimize friction with mucigel exudates.

Much of the work done relating soil strength to root growth has focused on the maximum levels causing cessation of root growth. Goss (1977) suggests that it is more important to determine the minimum soil pressures that reduce root elongation and thereby affect growth and yield of the plant. Soil strength values of around 2.0 MPa and greater have been shown to decrease root length and elongation for a variety of plant species (Atwell, 1993). Taylor and Ratliff (1969) found that increasing soil strength affected root length more than top length and weight of plants (cotton and peanuts), but soil moisture differences most affected top length and weight and not root length.

Less work has been done with forest species, and it is important to determine the extent to which soil strength diminishes root growth. In general, the soil strength at which root growth becomes limited, the critical value, has been shown to range from 2.0 to 3.0 MPa. Soil strengths in excess of 2.0 MPa were limiting for soybeans growing in four different soils (Taylor et al., 1966), while a critical soil strength of about 3.0 MPa was found for radiata pine growing in compacted sandy soils (Sands et al., 1979). da Silva and Kay (1994) used 2.0 MPa as the soil strength beyond which growth becomes limiting.

Although soil strength is generally a better measure of how roots may be affected, there are also limitations of measurement. Different penetrometers may not provide consistent results because of their varying shapes and cone angles (Fritton, 1990). Also, individual soil aggregates may have greater BD, and thus greater strength than the bulk soil (Larson and Gupta, 1980). Mirreh and Ketcheson (1972) noted that three-dimensional plots of BD, soil resistance and matric potential would be very beneficial in understanding the behavior of soils. Also, these plots would be a useful predictive tool for predicting soil strengths and effect on growth for a variety of soil conditions that could ultimately lead to better soil management programs.

Porosity and Aeration

In addition to soil strength, Greacen's and Sands' (1980) model includes porosity as a prime factor affecting root growth. Compaction changes porosity by generally reducing total porosity and macropore space and increasing micropore space. The relative balance of air and water within a soil's pore space is critical to plant growth. Grable and Seimer (1968) determined a limiting aeration porosity of 10%. Startsev and McNabb (2001) found significant decreases in air-filled porosity due to compaction for boreal forest soils, but no effects on unavailable and available water. Compaction of a Cohasset soil from a California LTSP site resulted in reductions in total and macroporosity that were negatively correlated with BD, a shift in pore size distribution, an increase in smaller pores, and reduction in median pore size (Paz, 2001). Although compaction is most often considered detrimental to growth, recent studies have shown that compaction on some coarse textured soils has enhanced conifer growth due to increased microporosity and ability of the soil to hold more available water (Brais, 2001; Gomez et al., 2002). The need for increased understanding of compaction effects on soil air water balance is evident.

Soil Water

Soil water availability is one of the most limiting factors to plant growth. Plants can be stressed by both a lack of water or saturated conditions that reduce soil aeration. Furthermore, soil water affects both soil strength and porosity and the interaction of the three determines root growth opportunity.

Soil water available to plants is generally referred to as plant available water and is the difference in soil volumetric water content (VW) at soil water potentials (WP) of -1.5 MPa (permanent wilting point) and either -0.01 MPa or -0.03 MPa (field capacity). However, the greatest change in VW generally occurs at WP between 0 and -0.1 MPa (Black, 1968). For three soil textures, clay, sand and loam, at WP up to 1.5 MPa, most water was removed below 0.1 MPa (Richards, 1959). Reicosky et al. (1981) also found that most volumetric water is removed at WP up to 0.1 MPa. Volumetric water contents at a range of WP (0.00 to -1.5 MPa) were measured for a loam soil at two bulk densities. At a density of 1.0 Mg m^{-3}, VW decreased 21% for WP up to -0.03 MPa, while from -0.03 to -0.1 MPa, VW decreased 5 %. In contrast this same soil at a density of 1.6 Mg m^{-3} started out with lower overall VW that decreased 6 % in the 0 to -0.033 MPa range, 5 % in the -0.033 to -0.1 MPa range and only 4 % for WP of -0.1 to -1.5 MPa. Since the greatest change in VW and soil strength seems to occur in the WP range up to -

0.1 MPa, it seems important to carefully characterize the interactions of soil factors in this range along with the resulting effect on root growth.

It has been shown that reductions in root growth begin occurring long before extreme soil strength or moisture conditions are reached. Barley root elongation decreased by 50 % at a WP of - 0.02 MPa, by 78 % at - 0.05 MPa and 88 % at -0.1 MPa (Russell, 1977). A marked reduction in root elongation and change in root morphology have been shown even at WP of -0.01 MPa to - 0.03 MPa with increasing BD (Eavis, 1972; Voorhees et al., 1975; Simmons and Pope, 1987). In a study with loblolly pine, root length decreased with increasing moisture stress, but was not statistically significant (Torreano and Morris, 1997). Interestingly, root growth resumed after watering, and more new growth occurred in areas that still had moisture. By the end of the 5th week, 74 % of the season's total root growth was in the surface 45 cm for the driest treatment while only 50 % for the wettest.

In another study, sorghum was grown in soil prepared at four different BD levels and four WP (-0.015, -0.033, -0.17 and -0.86 MPa) (Hemsath and Mazurak, 1974). Root elongation increased in the no compaction to moderately compacted pots up to a WP of -0.033 MPa, and then began to decrease. However, in the heavily compacted soils, root length decreased throughout the range of WP. Sunflower seedlings grown at a constant WP for 12 da had the greatest dry weight decrease while grown at WP in the -0.002 to -0.07 MPa range (Zur, 1967).

In addition to difficulties in separating different factors, assessing the effect of varying moisture levels has proven to be experimentally difficult. Ideally, it would be beneficial to maintain experiments with plant growth at a constant WP, however this is an extremely difficult task. Kramer and Boyer (1995) note that even though this is a theoretically ideal situation, in nature soil water content is continuously changing and therefore any experiment with constant water levels is artificial. Various techniques have been tried to control water content, such as split root experiments (Gowing et al., 1990) and the addition of solutes to change osmotic potential with differentially permeable membranes (Zur, 1967). However, there are limitations to these studies in that addition of salts affects plant growth (Kramer and Boyer, 1995), and the differentially permeable membranes can only be used with small amounts of soil and small plants grown for a short period of time (Zur, 1967). Due to the difficulties of controlling water continuously in plant growth studies, many studies apply water stress treatments by varying frequency and amount of water applied.

Soil water potential is more important to the ability of roots to absorb water than actual water content. Compaction can greatly affect soil water potential?due to changes in pore size distribution. Studies have shown that for many soils the greatest change in VW generally occurs between 0 and -0.1 MPa (Richards, 1959; Black, 1968; Reicosky et al. (1981). Startsev and McNabb (2001) reported that flattening of the soil water release curve (SWRC) and a shift of the steepest part of the slope resulted from increasing skidder passes on Boreal forest soils. A flattening of the SWRC causes water to be held more tightly under compacted conditions.

Root Growth

Root growth is affected by many soil factors such as porosity, pore-size distribution, water content, nutrients, strength, aeration and their interactions. In general, compaction diminishes root growth opportunity. Eavis (1972), attempted to separate the effects of aeration, impedance and moisture stress. Pea seedlings were grown at three BD and six WP. Generally, mechanical impedance affected root growth in the WP range of -0.01 to -0.1 MPa and water stress was the main factor at potentials greater than -0.35 MPa. Voorhees et al. (1975) found it was difficult to separate the effects of physical resistance to penetration and aeration on root elongation. They measured pea seedlings placed on cores of four BD equilibrated on ceramic plates to -0.01, -0.033 and -0.1 MPa. Root morphology changes were evident even at a WP of -0.03 MPa as BD increased.

Soil water deficits diminished root elongation rate, but increased the number of roots produced when WP ranged from -0.4 to -0.8 MPa (Teskey and Hinckley, 1981). In contrast, the number of new loblolly pine seedling roots significantly decreased due to mild and moderate water stress (Sword, 1995). Some species may grow more new roots as an adaptation to drought periods. This was suggested by Kleiner et al. (1992) who found that chestnut oak (*Quercus prinus*) seedlings were not affected by imposed drought while red oak (*Quercus rubra*) were affected by water stress which caused increased root production. Thus the timing of stressful conditions will affect the type of root growth occurring and water and strength effects on roots.

Roots can move through the soil by either going around soil peds or pushing them aside. When the pore space is greater than a root's diameter the root can move freely; however, when pore space decreases, root movement becomes restricted. The root must then rely on its ability to push aside the soil particles. Roots have been shown to have the ability to apply external pressures of about 0.9 to 1.3 MPa (Pfeffer, 1893; Gill and Miller, 1956; Barley, 1962; Taylor and Ratliff, 1969). With high soil densities come smaller pore spaces and greater soil strength, creating a decreased opportunity for root growth. The root is unable to push through the soil; therefore, elongation decreases but radial growth may increase. Root morphology also changes with an increase in the number of lateral roots and a proliferation of root hairs (Bengough and Mullins, 1990). Separating the causative factors of reduced root growth is often difficult. Bengough and Mullins (1990) described the difficulty in using soil as the experimental medium in measuring the effects of mechanical impedance on root growth. As the soil is compacted, porosity is changed and thus aeration may become a limiting growth factor.

Root growth opportunity is further modified by physiologically controlled factors. Root response to increasing soil strength is affected by phytohormones such as abscisic acid (ABA), indole acetic acid, cytokinins (CYT) and ethylene. As the root is exposed to increasing pressures, levels of these hormones increase, causing physiological changes such as lateral root formation, increase in root hair production, and decrease in elongation (Atwell, 1993). Furthermore, ABA and CYT are the chemical messengers that can influence leaf stomatal closing and opening (Tardieu et al., 1992).

Root growth is often seasonal and alternates with periods of shoot growth. In a study of ponderosa pine seedlings grown in pots, early season root growth occurred between February and March, with shoot growth occurring primarily between March and June, followed by another period of root growth after bud-set (McMillin and Wagner, 1995). Seasonal root growth also was noted for white oak in Missouri with main periods of root elongation occurring just prior to bud burst and then after leaf senescence (Teskey and Hinckley, 1981).

Root Growth Models

Several different approaches have been taken to assess root growth and the factors that cause limitations. Many researchers have developed models to elucidate the roles that key soils properties and their interactions have on growth. Greacen and Sands (1980) developed a conceptual model showing that compaction affects BD, which modifies both soil strength and aeration. These factors are further moderated by water content and their combined interactions affect root growth (Fig. II.1). The concept of the non-limiting water range (NLWR), introduced by Letey (1985), combined the effects of critical soil properties to root growth into a single variable. The NLWR was defined as the range in which water availability is non-limiting to plants, generally bounded by field capacity and wilting point. As BD increases, the NLWR becomes narrower, with mechanical resistance limiting at the dry end and poor aeration at the wet end.

Childs et al. (1989) used BD and porosity data from a compaction study by Reicosky et al. (1981) to develop a generalized model of root growth opportunity similar to Letey's NLWR. They also hypothesized that root growth opportunity decreased with increasing soil density due to excessive soil strength at low water contents or inadequate aeration under wet soil conditions. In their model, ideal growth is depicted within a "root growth window" bound by non-specified water contents.

da Silva and Kay (1994) furthered these conceptual ideas by evaluating the NLWR as an index of the structural quality of soil. They used the term least limiting water range (LLWR) to recognize that plant response occurs along a continuum of water contents rather than as a step function. The critical limits defining the LLWR were VW at field capacity and permanent wilting point (potentials of -0.01 MPa and -1.5 MPa respectively); VW at air filled porosity less than 10%; and VW at soil strength of >2.0 MPa (da Silva and Kay, 1994). Also, the common values of field capacity and permanent wilting point

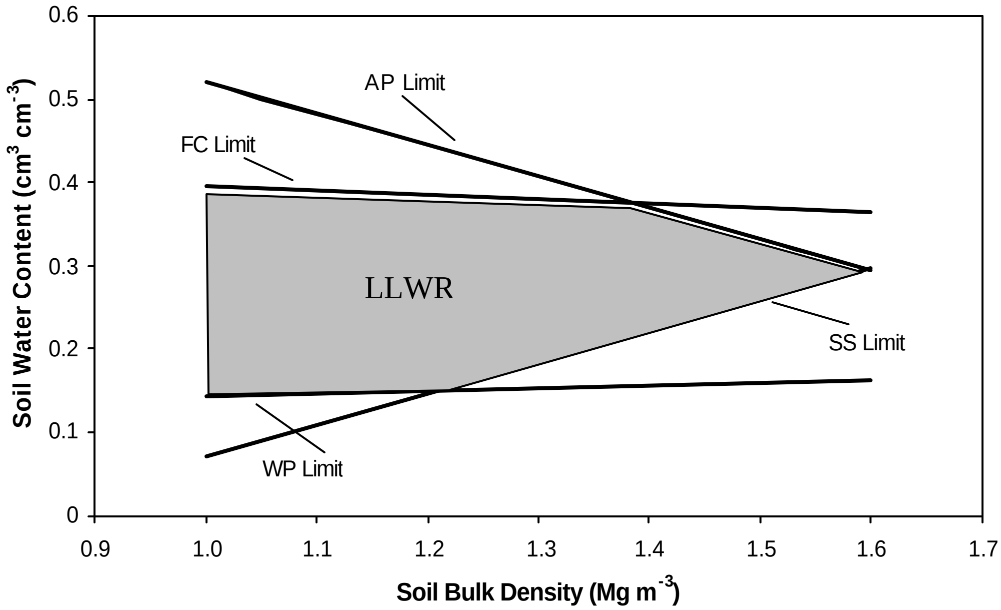

Figure II.2. Generalized least limiting water range (LLWR) model. Limits are defined by soil water contents at aeration porosity (AP), field capacity (FC), soil strength > 2.0 MPa (SS), and wilting point (WP).

are used as range boundaries, even though both parameters vary greatly with soil type and species. Wilting point is a plant phenomena, not a soil parameter. Therefore, it would be better to determine actual soil matric potentials that reduce growth for individual species. da Silva and Kay furthered this work by developing pedotransfer functions that describe these parameters based on soil clay content and organic C content. They found that these pedotransfer functions worked well for describing the range of Canadian agricultural soils they measured (da Silva and Kay, 1997a). Recently others have used the LLWR. Four New Zealand forest soils packed to low, medium and high density levels were tested using LLWR (Zou et al., 2000). They found that in general LLWR decreased with increasing compaction, however, on several soils LLWR actually increased with medium compaction on a coarse pumice soil and a fine-textured loess soil.

The concept that overall productivity is proportional to root growth has also been used to develop productivity indices (PI) for several plant species and soils (Kiniry et al., 1983; Gale et al., 1991). This type of productivity index may provide an important alternative to better describe soil and site productivities than conventional site index in that the PI can be used to predict the influence of soil modifications to root growth (Henderson et al., 1990). A soil PI based on several soil factors (available water capacity, pH, bulk density, electrical conductivity and aeration) and sufficiency for root growth was developed (Kiniry et al., 1983). In this model, the ideal soil would have no restrictions to root growth and a PI of 1.00. Burger and Kelting (1998) also developed productivity indices based on features of the PI and other soil quality models. Their model describes forest soil quality as a function of root growth sufficiency levels of water, nutrients, gas exchange and biological activity that would be weighted by the volume of each horizon.

All of these conceptual models attempt to integrate various soil property affects that, alone, do not fully account for root growth in a given environment. In a management context, one would want to maintain or improve those soil conditions that created the largest NLWR, LLWR, PI or root growth window. However, we need to determine if generalized models adequately reflect growth potential or if soil- and species-specific models need to be developed.

Management Implications

It is clear that soil compaction can have deleterious effects on tree growth, but that the effects are species specific, vary for shoots and roots, and vary as a function of several interrelated soil properties. The interaction of soil strength, water, and aeration, and the subsequent plant physiological responses to these properties is quite complex.

It is also clear that forest health, productivity and sustainability issues are of great importance and that mandates around the world are attempting to provide adequate, scientifically sound guidelines for managing our forest resources. The LTSP study was developed to address this need (Powers, 1990). The study is composed of large-scale field experiments, located across the United States, to assess the effects of BD and surface organic matter removal on site productivity. Other similar site/soil productivity studies have been undertaken on private-industry land. The opinions of forest managers and scientists in Australia and New Zealand has been that the Montreal process proposed soil criterion and indicators that are adequate, but not operationally viable for protecting soil resources (Smith and Raison, 1998). Powers et al. (1998) propose three primary indicators of soil quality: (i) soil strength for soil physical quality, (i) anaerobic nitrogen mineralization for soil nutrient supply, and (iii) measures of macroinvertebrate activity for soil faunal activity. They suggest using these indicators to establish baseline conditions to detect future change.

Because the soil system is so complex, no single indicator will be adequate to monitor soil conditions as they change. Only through the establishment of long-term studies, and a continuing focus on understanding how compaction affects soil and forest productivity, will we move closer to providing better operational guidelines for forest managers.