CHAPTER V

Root growth potential as a function of soil density and water content for four forest soils

INTRODUCTION

Intensive forest management can compact soils, thus impacting the soil air/water balance and potential for root growth. Studies conducted throughout North America have shown decreases in tree growth and forest productivity due to compaction. For example, soil compaction in southwest Oregon reduced ponderosa pine height and volume growth 17 and 48 %, respectively, and the effect was still evident 17 years later (Froehlich, 1979). Growth reductions have also been observed in the South where one-year old loblolly pine height growth on compacted skid trails on a lower Coastal Plain site was less than on non-compacted areas (Hatchell et al., 1970), and loblolly root growth declined after one year due to compaction in Texas (Simmons and Ezell, 1982). In the Northeast, diameter growth of several hardwood species growing on loamy sand soils in Vermont, 5 years after compaction, was reduced by 36 and 31 % for red maple and black oak, respectively; however red oak was not affected (Donelly and Shane, 1986). White spruce and lodgepole pine root weight and depth, and shoot weight and height were less due to compaction of several soils from Alberta (Corns, 1988).

Although reduced growth from compaction has been reported across many regions, the effect on individual tree growth parameters is variable, and overall growth response varies for different species and soil types. For example, Douglas-fir and western white pine seedlings grown in compacted soil had no significant root or shoot weight decreases after one growing season, but root volume was 41 % less for the Douglas-fir seedlings and seedling height was 6 % greater for western white pine ($p = 0.05$) (Page-Dumerose et al., 1997). Corns (1988) reported that lodgepole pine had decreases for several growth parameters on all four soils tested, but white spruce growth was not different on two of the soils. Furthermore, differences varied with soil type, for example lodgepole pine shoot weight decreased 64 % on a silty clay soil when density increased from 1.2 to 1.5 Mg m^{-3}, while shoot weight decreased 86 % when a clay loam soil was compacted to 1.5 Mg m^{-3}. Wasterlund (1985) also reported species differences with Norway spruce growth being more impeded than Scots pine growth. On several California sites, Gomez et al. (2002) that compaction effects on four-year-old ponderosa pines varied with soil texture and soil water regime. Stem volume on compacted soils had decreased, remained the same, and increased on clayey, loamy, and sandy loam soils, respectively. Compaction was also found to be beneficial to black spruce and jack pine growth on a coarse textured soils classified as humo-feric podzols in northwestern Quebec (Brais, 2001). Growth increases on these soils were linked to increased microporosity caused by harvest traffic, similar to the findings by Gomez et al. (2002).

Furthermore, the persistence of compaction effects on tree growth and soil properties has been found to vary over time for different sites and species. Height growth declines resulting from bulk density increases lasted only one to two seasons for Douglas-fir, but persisted more than two years for western hemlock (Miller et al., 1996). In addition, the bulk density increases, ranging from 2 to 40% for different soil types, persisted 8 yr after a logging operation in coastal Washington (Miller et al., 1996). Although height growth reductions were found in the main harvested area for several years after logging on a coastal Washington site, they persisted for 8 to10 yr on inland Oregon sites (Heninger et al., 2002). Tree heights on the harvested area were similar after 10 yr; however, trees on skid-trail ruts were still smaller with greater reductions in volume growth (28%) than height growth (10 %).

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. 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 soil bulk density, 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 bulk density 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 soil density 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; (i) soil water contents at field capacity and permanent wilting point (potentials of -0.01 MPa and -1.5 MPa respectively), (ii) air filled porosity less than 10%, and (iii) soil strength of >2.0 MPa (da Silva and Kay, 1994). 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 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.

For a given region, soil type, and tree species, forest productivity is a function of volumetric water content as it varies with climate across the growing season, and a function of the interrelated factors of bulk density, soil strength and porosity. Root growth has been found to be a more sensitive indicator of soil disturbance than shoot growth (Singer, 1981; Heilman, 1981). Additionally, reductions in root growth occur long before extreme soil strength or moisture conditions are reached (Eavis, 1972; Voorhees et al., 1975; Russell, 1977; Simmons and Pope, 1987). Developing soil- and species-specific root growth responses for a range of soil water, aeration and bulk density conditions would be valuable for assessing potential productivity declines due to compaction.

The USDA Forest Service Long-Term Forest Productivity Study, composed of large-scale field experiments located at sites across the United States, was developed to assess the effects of soil compaction and surface organic matter removal on site productivity across a range of forest sites (Powers, 1990). Similar projects on industry lands have also been developed. To better understand the management implications of compaction, we used representative soils and tree species from across the LTSP site network to test the hypothesis that best growth would occur at low bulk densities and moderate water content, while as density increases, aeration becomes limiting to growth on wetter soils, and soil strength becomes limiting for dryer soils.

Our specific research objectives were to: (i) develop a response surface describing tree seedling root growth as a function of soil ρ_b and θ_v; (ii) characterize the relationship of shoot growth to root growth for the tree seedlings grown on the four contrasting forest soils; and (iii) examine seedling growth using the LLWR.

RESULTS

Least Limiting Water Range

We compared root length density (RLD) of seedlings grown in and out of LLWR (Fig. V.1; Table V.1). RLD of ponderosa pine in Dome and shortleaf pine in Clarksville, growing within the LLWR range, was twice that of those growing outside the range on the Dome soil. The RLD of ponderosa pines grown within the LLWR on Cohasset soil was 43 % greater, but not significant ($p = 0.108$). There was no RLD difference between roots in and out of the LLWR for loblolly pines on Argent soil.

We tested the root growth-tree growth relationship depicted in Greacen and Sands (1980) model (Fig. II.1) by also comparing seedling growth in and out of the LLWR range with a t-test and by visually assessing how well the LLWR fit measured seedling

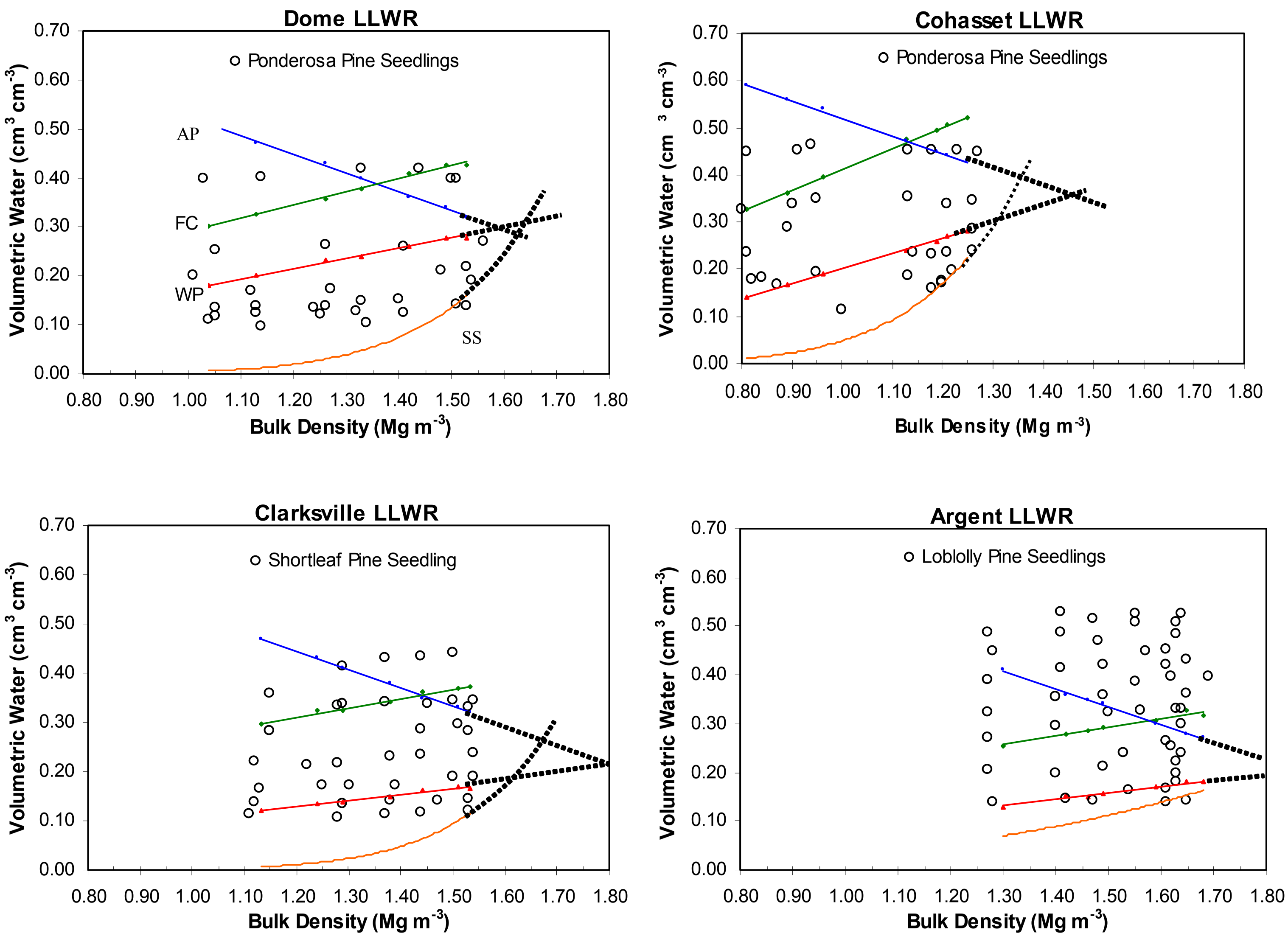

Figure V.1. Least limiting water range (LLWR) of several forest soils depicts the field capacity (FC), wilting point (WP), aeration porosity < 10% (AP) and soil strength >2.0 MPa (SS) limit lines. Points on the graph represent seedlings grown at certain water contents and bulk densities. Dotted lines extrapolate limits beyond maximum soil bulk densities found in this study.

Table V.1. Mean root length density and shoot weight of tree seedlings growing in and out of the least limiting water range of four forest soils.

			Mean Root Length Density ($cm\ cm^{-3}$)		
Soil	Tree Species	Number Trees (In/Out)	In LLWR	Out LLWR	P value
Dome	Ponderosa Pine	4/27	0.28 (0.07)	0.14 (0.02)	0.029*
Cohasset	Ponderosa Pine	17/14	0.20 (0.02)	0.14 (0.03)	0.108NS
Clarksville	Shortleaf Pine	21/17	0.23 (0.03)	0.11 (0.02)	0.003**
Argent	Loblolly Pine	14/35	0.14 (0.02)	0.13 (0.01)	0.812NS

			Mean Shoot Weight (g)		
Soil	Tree Species	Number Trees (In/Out)	In LLWR (SE)	Out LLWR (SE)	P value
Dome	Ponderosa Pine	4/27	0.526 (0.089)	0.267 (0.032)	0.008**
Cohasset	Ponderosa Pine	17/14	0.326 (0.036)	0.208 (0.033)	0.025*
Clarksville	Shortleaf Pine	21/17	0.493 (0.091)	0.218 (0.033)	0.009**
Argent	Loblolly Pine	14/35	0.441 (0.056)	0.721 (0.066)	0.002**

*,** indicate significance at the P = 0.05 and 0.01 levels

shoot growth response surfaces (Table V.1; Fig. V.2). Measured shoot growth for the Dome-ponderosa pines, Cohasset-ponderosa pines and Clarksville-shortleaf pines responded as predicted within and without the LLWR. The ponderosa pines growing within the LLWR on both Dome and Cohasset soils had greater biomass than those growing out of the range (Table V.1). The mean weight of Dome-ponderosa pine seedlings within the LLWR was 0.53 g, while those outside the range weighed 0.27 g. Cohasset-ponderosa pine seedlings growing within the range were also larger than those outside the range at 0.33 g and 0.21 g, respectively, but seedlings within the range were slightly smaller than those on the Dome soil. Most ponderosa pine seedlings on Dome and Cohasset soils were limited by high soil strength and inadequate water based on the LLWR limits. However, ponderosa pine seedlings growing outside the aeration porosity limit on the Cohasset soil had greater root and shoot growth than trees growing within the LLWR at the same density (Table V.1). Mean shortleaf pine shoot weight growing within the LLWR range was twice that of those outside the range ($p = 0.009$) (Table V.1; Fig. V.1). These seedlings were most limited by aeration and inadequate water. The shoot growth response surface for the Clarksville-shortleaf pine is shown as an example in Fig. V.2.

The LLWR did not define loblolly pine growth on the Argent soil as predicted (Table V.1; Fig. V.1). The shoot weight of loblolly pine seedlings within the LLWR was less than those outside the range despite the fact that they grew at less than 10% aeration porosity. Mean shoot weight of seedlings growing within the LLWR was 0.44 g while it was 0.72 g for seedlings growing out of the LLWR. The LLWR underestimates the ability of loblolly pine to grow across a wide range of soil moisture conditions in the Argent soil. The LLWR did not correspond to the best growth range; the θ_v contents associated with the standard limits are too low for the Argent soil growing loblolly pines (Fig.V.2)

Root Length Density Models

Root length density of shortleaf pine growing in the Clarksville soil and loblolly pine growing in the Argent soil responded to the soil water and density gradients as predicted (Fig. V.3). The RLD residuals plotted as a function of the predicted values for each soil were well distributed, indicating that there was no reason to believe that other

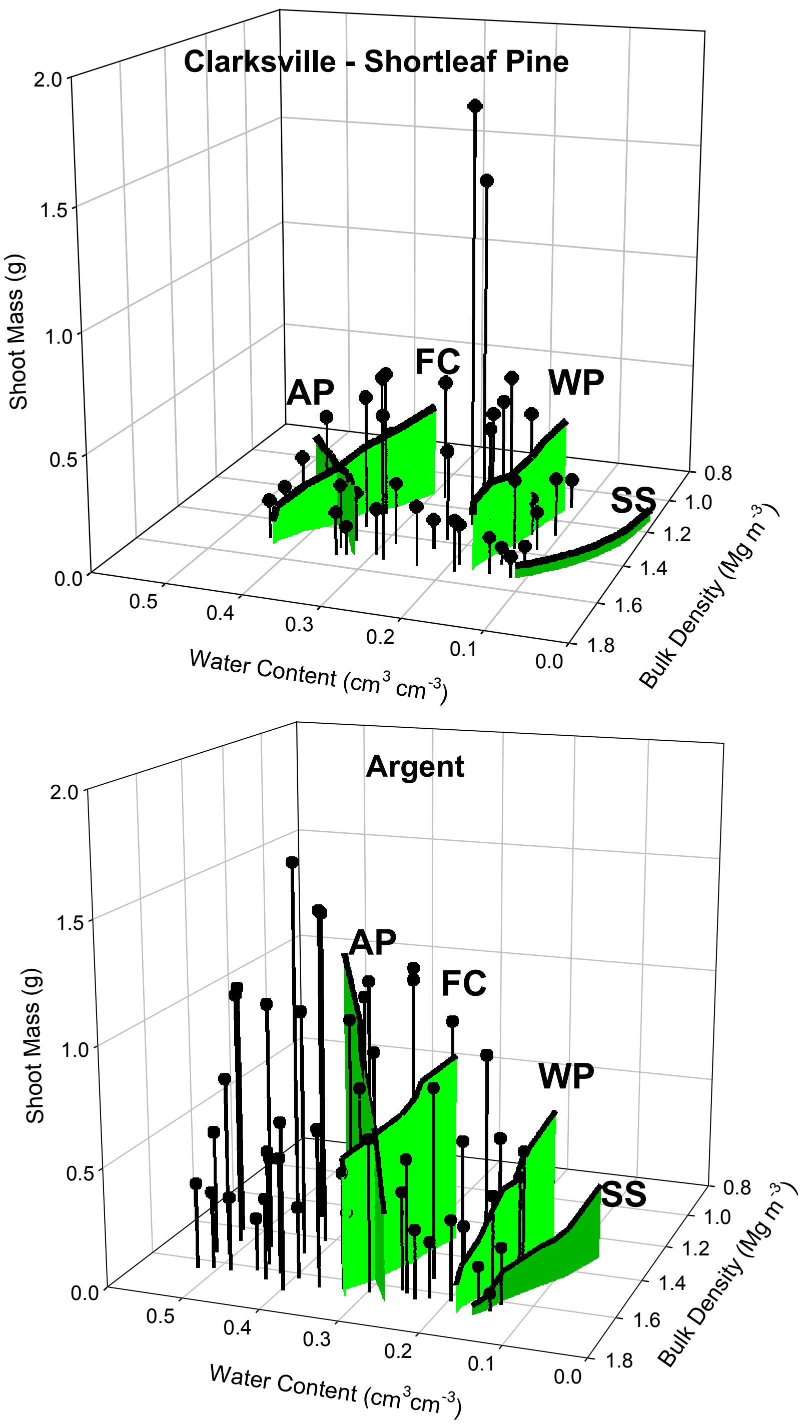

Figure V.2. Least limiting water range (LLWR) superimposed on shoot mass growth as a function of bulk density and water content for shortleaf pine on Clarksville soil and loblolly pine seedlings on Argent soil. Upper LLWR boundary limits are aeration porosity < 10% (AP) and field capacity (FC). Lower LLWR boundary limits are wilting point (WP) and soil strength > 2.0 MPa (SS).