CHAPTER IV

Physical Characterization of Four Compacted Forest Soils for Root Growth Potential

INTRODUCTION

Intensive forest management practices can compact soil, which affects the ability of trees and other forest vegetation to exploit the soil volume for water and nutrients. Several key soil properties such as soil strength, water, aeration, and their interactions are affected by compaction (Greacen and Sands, 1980). Soil compaction commonly occurs when heavy machines are used in forests for harvesting, site preparation and mid-rotation management. Many studies have shown that tree growth and productivity decreases with compaction (Froehlich, 1976; Hatchell et al., 1970; Cochran and Brock, 1985). Furthermore, recovery and amelioration of compacted soil is normally slow, if it occurs at all (Hatchell and Ralston, 1971; Froehlich, 1985; Davis, 1990). Therefore, it is critical to thoroughly understand the effects of compaction on soil and plant growth to minimize its effects.

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. A measure of soil bulk density alone does not capture the dynamics of this interactive process. As volumetric water content changes, the opportunity for root growth changes. 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. Each soil has unique properties that interact in different ways as a function of its response to soil forming factors. For example, in a field trial conducted on several Forest Service Long-Term Soil Productivity (LTSP) plots in California, compaction reduced growth on a fine textured soil due to increased soil strength, but increased growth on a sandy textured soil due to increased water holding capacity (Gomez et al., 2002).

A series of federal mandates including 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 the Forest Service to maintain and protect the productivity of the land and provide the research and monitoring necessary for this protection (Powers, 1990). The USDA Forest Service Long-Term Soil Productivity (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 soil bulk density and surface organic matter removal on site productivity. Other similar site/soil productivity sites have also been developed on private-industry land.

The overall purpose of this work was to compare representative soils from across the network of LTSP sites and measure the relative physical response of these soil types to compactive forces to better understand the management implications of soil disturbance in the National Forests. The specific objective was to compare and contrast soil compactibility and compaction effects on various soil properties that affect root growth. For four forest soils from various forest regions in the United States we: (i) characterized the primary soil physical properties that affect or are affected by compaction including soil texture, bulk density, soil strength related to density and moisture, and soil porosity; (ii) determined optimum water content for compaction and developed a compaction curve for each soil relating compactive effort with bulk density; (iii) developed soil water release curves for a range of bulk densities for all four soils to help assess the relationship between soil water, density and strength; and (iv) developed least limiting water ranges as a function of soil strength, aeration, field capacity and wilting point for each soil.

RESULTS

Soil Characteristics and Properties

The four soils used in this study represent a soil development spectrum from an entisol to an ultisol (Table IV.1). The Dome soil is the youngest soil; it was formed from granitic parent material. Its clay fraction is characterized by a mixed mineralogy, and its CEC activity class is superactive. Dome, Cohasset and Argent soils all have mixed mineralogy, but the two California soils have a cation exchange activity class of superactive while the Argent is active (Soil Survey, 2001). Clarksville, an Ultisol derived from highly weathered sandstones and dolomites, is the most different of the four with siliceous mineralogy and a semiactive CEC activity class (Soil Survey, 2001).

Three of the soils, Argent, Dome and Cohasset, were sandy loams while the Clarksville was a silt loam (Fig. IV.1). Sand content was similar for the Dome and Argent (63 and 64 %, respectively), while the Cohasset soil had 56 % sand. The primary differences in the sand fraction were found in the sand size distribution (Fig. IV.1).

Coarse sands (coarse + very coarse) dominated the sand fraction for both California soils. The Argent soil, by contrast, had 69% of the sand fraction dominated by fine and very fine sands, classifying it as a fine sandy loam. Percent silt varied slightly between the Argent, Dome and Cohasset, but it dominated the soil matrix of the Clarksville soil. Clay contents varied only 4 % for the four soils, ranging from a low of 8 % for Dome to a high of 12 % for both Argent and Clarksville. The widest distribution of all particle size classes was found for the three sandy loam soils which, though dominated by sands, had significant proportions in each particle size class from coarse sand to clay. The Clarksville soil, in contrast, was dominated by fines (silts and clays) and thus had the narrowest distribution. The Cohasset soil had the highest organic matter content (9 %) of the sandy loam soils with Dome and Argent having contents of 6 and 5 %, respectively (Fig. IV.1). The Clarksville soil had the lowest organic matter content of the four soils.

Table IV.1. Classification and site characteristics of four forest soils from regions across the United States.

Soil Series	Taxonomic Class	Great Group	Parent Material	Mean Annual Precipitation (mm)	Mean Annual Air Temp (^{o}C)	Location/ Landform	Drainage	Typical Vegetation
Dome	Coarse-loamy, mixed, superactive, mesic	Typic Dystroxerrepts	Granodiorite Residuum	890	10	Sierra Nevada Mountains Hillslopes	Well drained	Sierra Nevada Mixed-Conifer
Cohasset	Fine-loamy, mixed, superactive, mesic	Ultic Haploxeralfs	Andesitic Mudflow Residuum	1320	11	Sierra Nevada Mountains Hillslopes	Well drained	Sierra Nevada Mixed-Conifer
Argent	Fine, mixed, active, thermic	Typic Endoaqualfs	Marine Sediments	1220	19	Southeast Coastal Plain	Poorly to Very Poorly Drained	Loblolly Pine - Hardwoods
Clarksville	Loamy-skeletal, siliceous, semiactive, mesic	Typic Paleudults	Dolomite, Chert and Sandstone Residuum	1070	13	Ozark Mountains Hillslopes	Somewhat excessively drained	Oak-Hickory Hardwoods

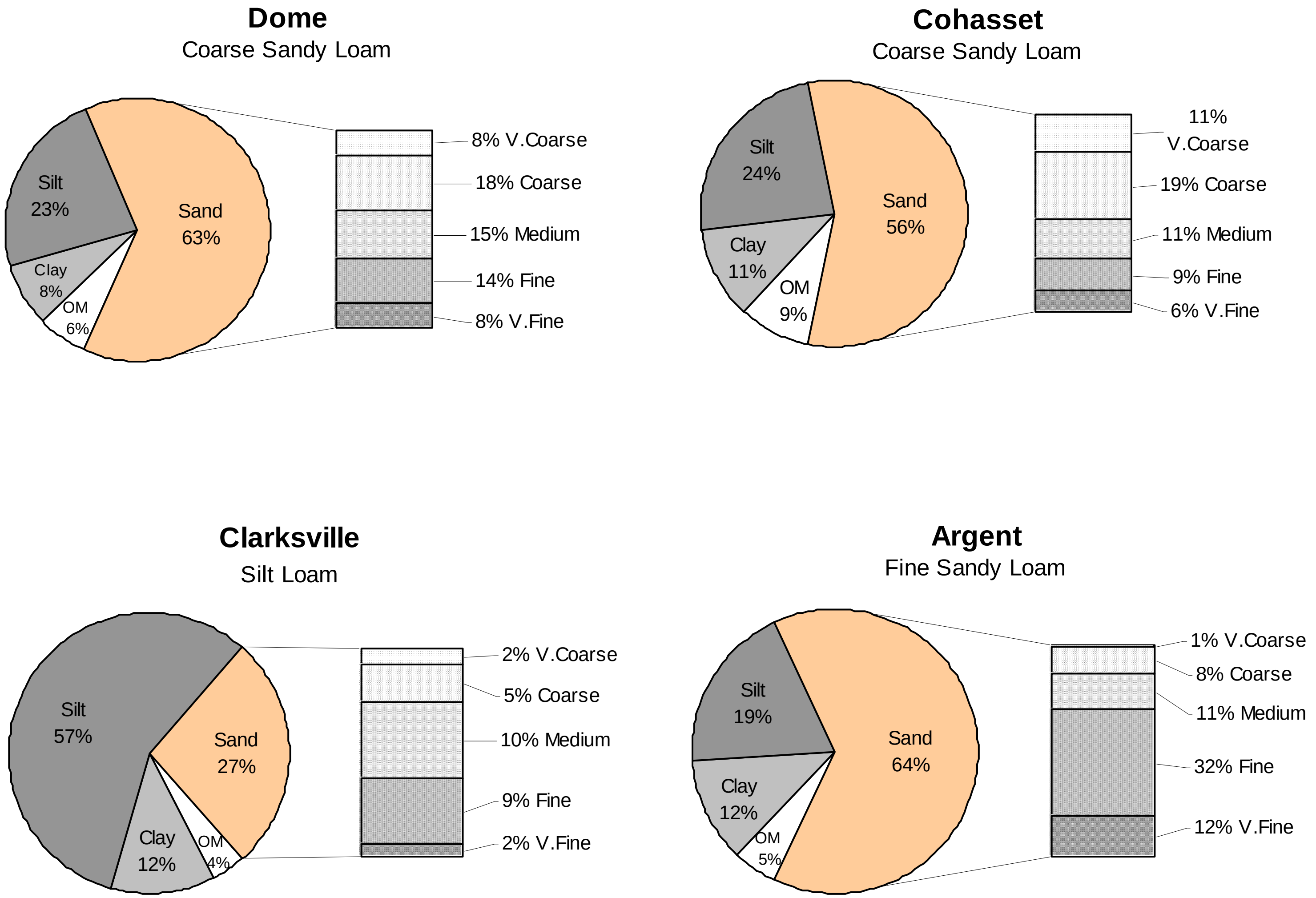

Figure IV.1. Particle size distribution and organic matter content of A horizon samples from four forest soils.

Compaction Characteristics

Soil OWC, compactive effort and CI were measured. Each soil had it's own unique compaction (proctor) curve which depicts OWC for compaction. OWC of these soils ranged from 19 % for Argent to 34% for Cohasset (Fig. IV.2). Bulk density as a function of compactive effort differed for each soil (Fig. IV.3). The minimum bulk densities when 24 kN m^{-3} (one hammer blow) was applied varied from 0.94 Mg m^{-3} for Cohasset to 1.25 Mg m^{-3} for Argent. Although these values may not be representative of field minimum bulk densities, they provided a uniform minimum standard density for each soil.

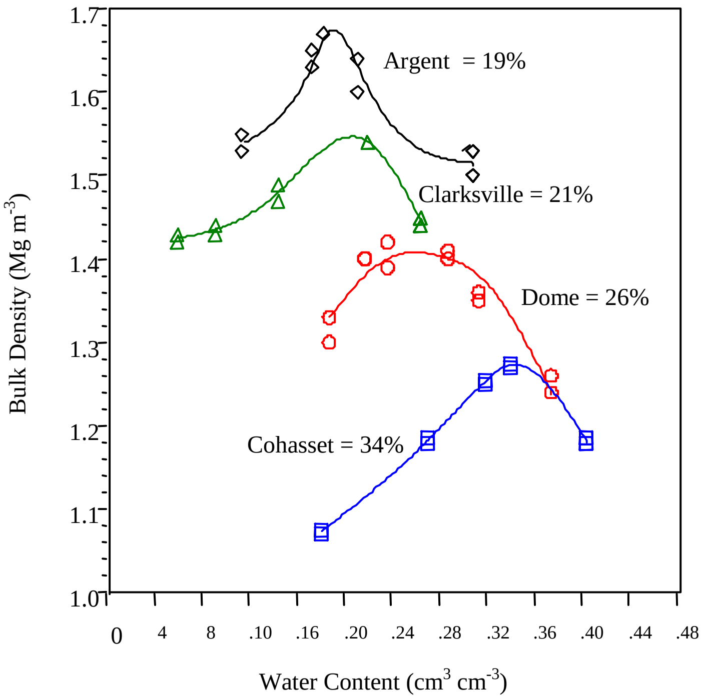

Figure IV.2. Optimum water content curves for A horizon samples from four forest soils.

Maximum values were determined by estimating the asymptote of density with increasing blows. They were 1.33, 1.52, 1.58 and 1.63 Mg m^{-3} for Cohasset, Dome, Clarksville and Argent, respectively (Fig. IV.3). Cohasset had the lowest CI and was different than the Dome and Clarksville soils, which both had CI's of 0.38 (P = 0.1). There were no significant differences among the other three soils (Fig. IV.4).

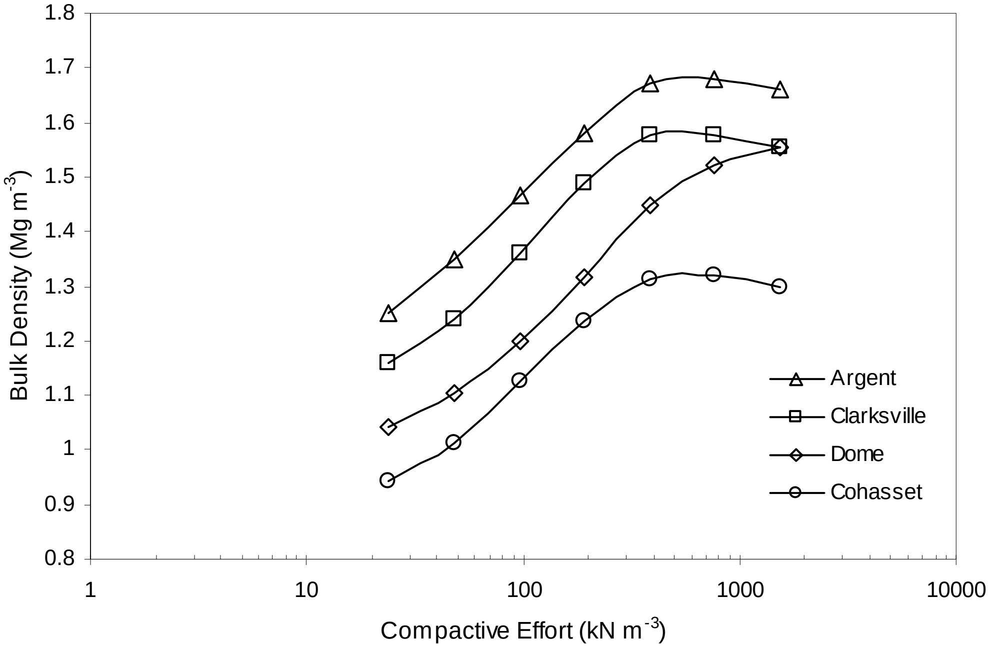

Figure IV.3. Compaction curves for four forest soils compacted at optimum water content.

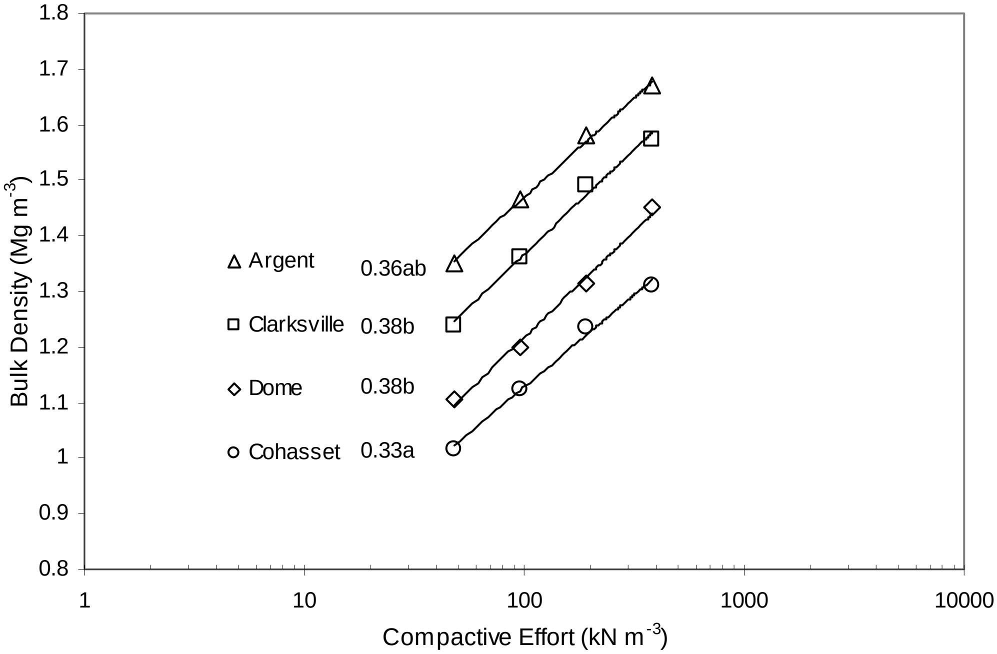

Figure IV.4. Bulk density as a function of compactive effort applied as blows with a compaction hammer at optimum water content for four forest soils. Linear portion of the curve depicted to determine compression index (CI) for each soil. Compression index values followed by the same letter are not significantly different (P = 0.1).

Soil Strength, Water and Aeration Characteristics

Soil Strength

Soil strength as a function of soil density and water content was plotted for each soil (Fig. IV.5). Volumetric water contents when strength was measured varied between 0.07 and 0.43 cm^3 cm^{-3}, a range that reasonably covers permanent wilting point to near-saturation for our soils. In general, as bulk density increased, soil strength increased, but the effect was moderated by water content. Regression equations describing soil strength as a function of bulk density and water content were developed for each of our soils (Table IV.2). We found significant relationships between soil strength, bulk density, water content and the interaction of bulk density and water content (P = 0.0001) (Table IV.2). Sample size varies for each soil because soil strength was measured only on soil columns that had living seedlings at the end of the experimental growth period. To further assess trends and qualitative differences between different density levels within a soil, we developed regression equations that described soil strength as a function of water content for each density level (Table IV.2). At the lower densities, water content had little effect on strength for the Cohasset and Clarksville soils (Table IV.3). At the higher densities, strength was greatest at lower water contents and was correlated with water content for all soils with the exception of Dome (Table IV.3). Soil strength was linearly related to soil water content above bulk densities of 0.96 and 1.37 Mg m^{-3} for Cohasset and Clarksville, respectively. In contrast, water content appeared to have a strong linear effect on Argent soil strength throughout the entire density range. This relationship for the Dome soil was more variable and not significant at most bulk density levels (Table IV.3).

Soil strength ranges found for each of the four soils were similar with the exception of Argent. None of the Argent cores had strengths in excess of 2.0 MPa (Fig. IV.5). Only the driest and most compacted treatments of the other three soils exceeded this limit (Fig. IV.5). Strength exceeded, or had potential to exceed, 2.0 MPa when bulk density was greater than 1.13, 1.33, 1.43 and 1.55 Mg m^{-3}, for Cohasset, Dome, Clarksville and Argent, respectively (Table IV.3). For the Cohasset soil, there appeared to be a clear discontinuity in strength above 1.0 Mg m^{-3}. Soil strength was less than 0.5 MPa below a bulk density of 1.0 Mg m^{-3} and above 1.5 MPa for densities above 1.13 Mg m^{-3}, except at the very highest water contents.

Soil Water Release Curves

Soil water release curves for the four soils at each of seven densities were developed (Figure IV.6). The soil water content associated with each soil water potential value varied for each soil and density level. Field capacity water content (-0.01 MPa) increased 43, 57, 23, and 23% from the lowest to highest densities for the Dome, Cohasset, Clarksville and Argent, respectively. Compaction had a greater effect on water content at -1.5 MPa, a potential at which water is considered to be plant unavailable. Percent increases ranged from 38% for Argent to 100% for Cohasset. The greatest soil water content change (the steepest portion of the SWRC curve) occurred in the range between 0 and -0.01 MPa at the lower bulk densities for all four soils; increasing compaction had the effect of flattening the curve (Figure IV.6).

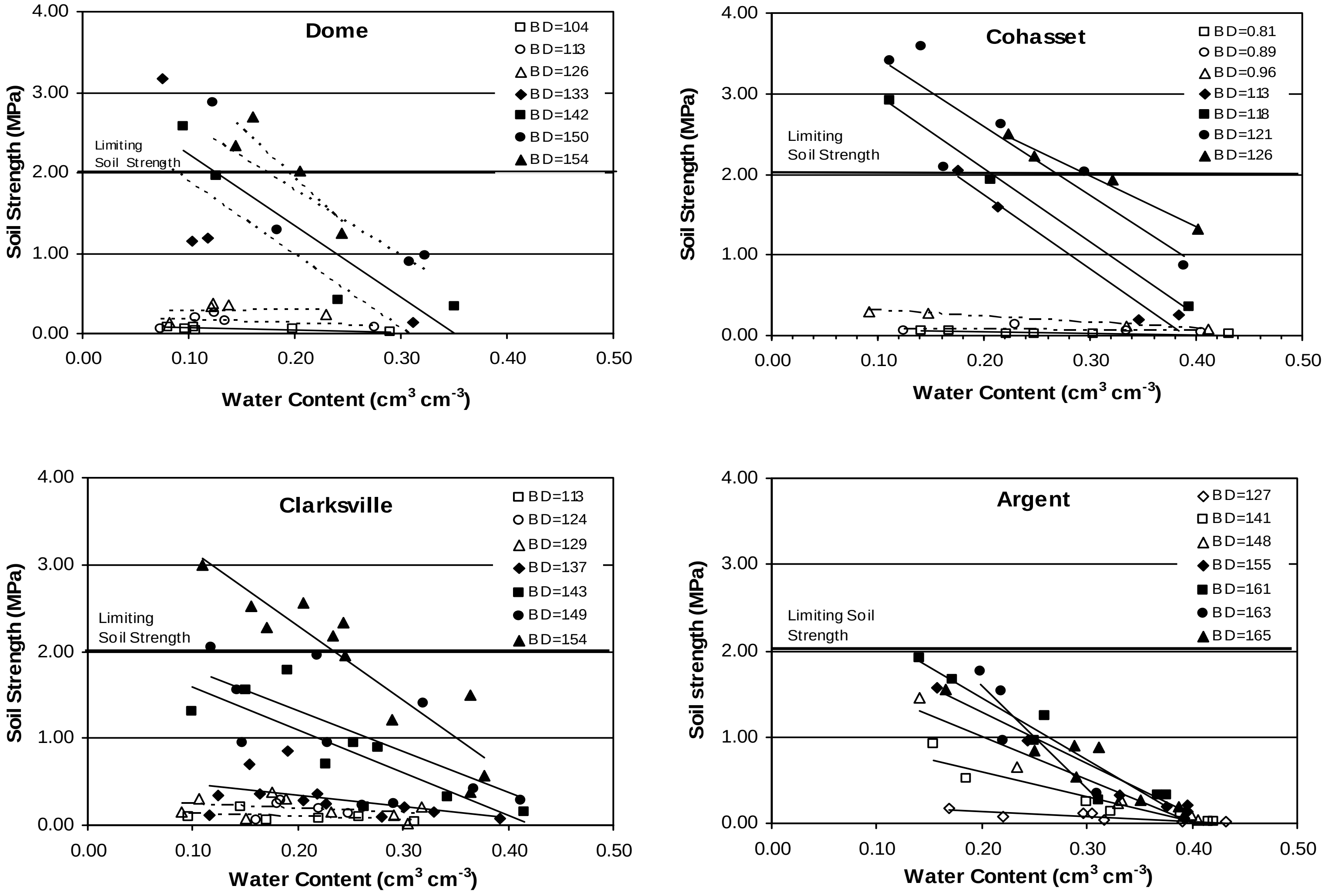

Figure IV.5. Soil strength of compacted soil columns as a function of bulk density (Mg m^{-3}) and water content for four forest soils. Each point is the average of three strength measurements. Solid lines indicate that the model of soil strength as a function of volumetric water content for a particular bulk density level was significant (P = 0.1).

Table IV.2. Regression parameters describing soil strength as a function of bulk density and water content for four forest soils. †

		Model Parameters					
Soil	n	b_0	b_1	b_2	b_3	P-value	r^2
Dome	32	-8.900	8.286	21.762	-20.666	0.0001	0.77
Cohasset	31	-10.083	11.702	21.179	-24.486	0.0001	0.90
Clarksville	62	-9.774	8.250	16.821	-14.817	0.0001	0.69
Argent	47	-9.055	7.343	23.273	-18.763	0.0001	0.91

† Model: Soil Strength = b_0 + b_1(Bulk Density) + b_2(Volumetric Water) + b_3 (Bulk Density x Volumetric Water)

Table IV.3. Regression parameters describing soil strength as a function of water content for various bulk densities of four forest soils. †

Soil	Bulk Density ($\mathrm{Mg\ m^{-3}}$)	n	Intercept Parameter b_0	Slope Parameter b_1	P-value	r^2
Dome	1.04	6	0.092	-0.227	0.053	0.65
	1.13	5	0.198	-0.332	0.6181(NS)	0.09
	1.26	5	0.275	0.123	0.9184(NS)	0.00
	1.33	4	2.785	-9.131	0.2141(NS)	0.62
	1.42	4	3.178	-9.066	0.075	0.86
	1.50	4	3.390	-8.113	0.1353(NS)	0.75
	1.54	4	4.266	-11.676	0.1292(NS)	0.76
Cohasset	0.81	6	0.078	-0.170	0.071	0.60
	0.89	4	0.102	-0.110	0.700(NS)	0.09
	0.96	4	0.376	-0.740	0.003	0.99
	1.13	4	3.617	-9.285	0.014	0.97
	1.18	3	3.902	-9.157	0.019	0.99
	1.21	6	4.262	-8.322	0.018	0.79
	1.26	4	3.883	-6.351	0.007	0.99
Clarksville	1.13	6	0.179	-0.412	0.2759(NS)	0.28
	1.24	6	0.133	0.268	0.8087(NS)	0.02
	1.29	9	0.296	-0.510	0.3282(NS)	0.14
	1.37	12	0.624	-1.358	0.104	0.24
	1.43	9	2.077	-4.882	0.011	0.63
	1.49	9	2.268	-4.710	0.033	0.50
	1.54	11	4.043	-8.693	0.000	0.84
Argent	1.27	7	0.263	-0.603	0.018	0.71
	1.41	7	1.179	-2.879	0.001	0.89
	1.48	7	1.971	-4.922	0.000	0.94
	1.55	7	2.429	-5.894	0.000	0.97
	1.61	7	2.843	-7.030	0.001	0.91
	1.63	4	3.939	-11.746	0.097	0.82
	1.65	8	2.539	-6.213	0.001	0.85

† Model: Soil Strength = b_0 + b_1(Volumetric Water)

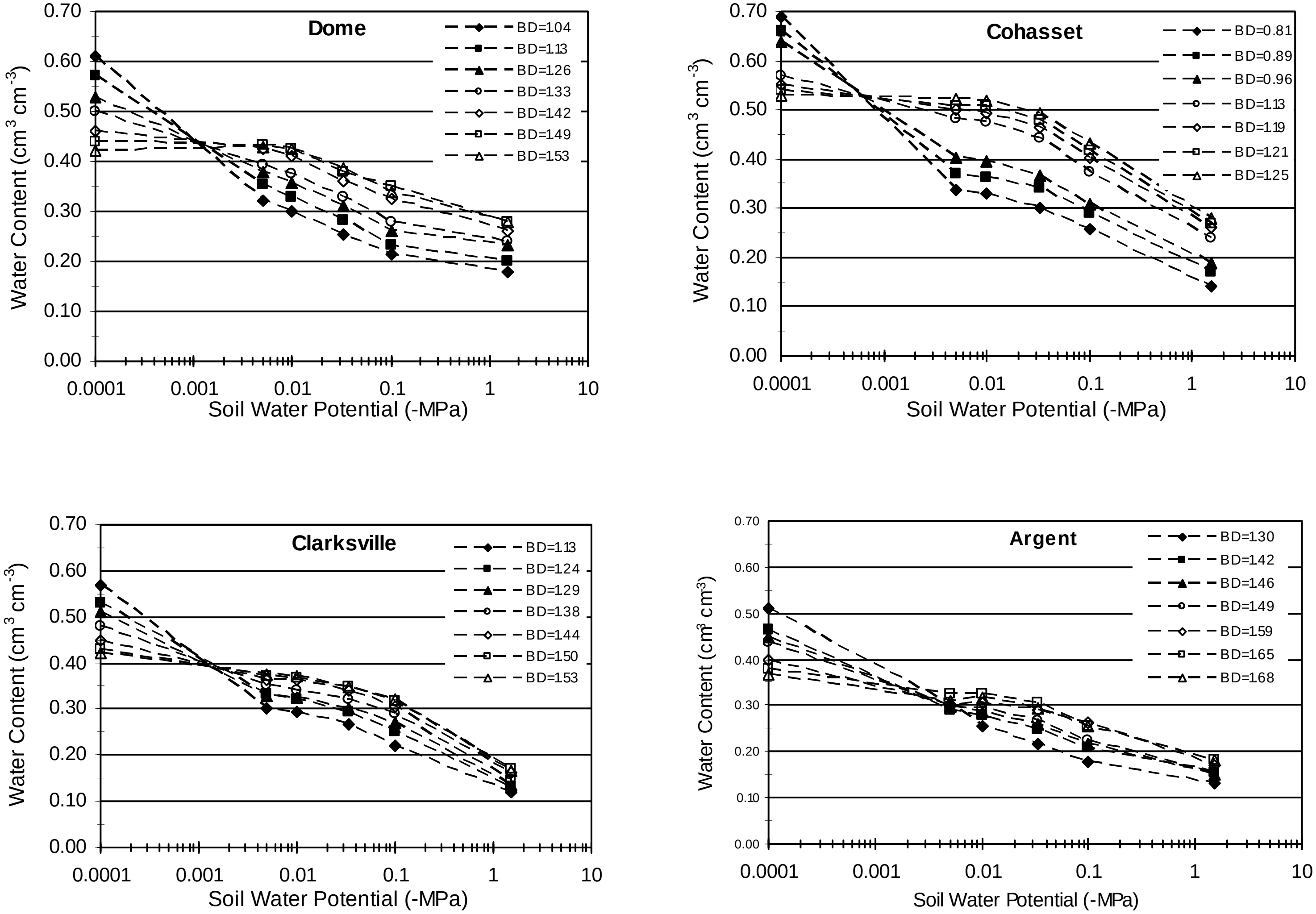

Figure IV.6. Soil water release curves for four forest soils. Each soil was compacted to seven different bulk densities.

Porosity and Aeration

The effect of SWRC changes due to compaction on plants can be better visualized by determining porosity changes and the resulting effects on the soil air/water balance (Figure IV.7). Total pore space is depicted by the height of the histograms. Aeration porosity represents the macropore space (Ψ of 0 to -0.01MPa), while plant available water is the difference between that held at field capacity (-0.01MPa) and wilting point (-1.5 MPa). Unavailable water is the water content when Ψ is less than -1.5 MPa.

Compaction had the effect of reducing total porosity and aeration porosity, while increasing microporosity for all of our soils. Regression analyses showed a strong negative correlation of aeration porosity with increased soil density ($p = 0.0001$) for all soils. Available water increased as a function of bulk density ($p = 0.003$, 0.0001, 0.0001, 0.084 for Dome, Cohasset, Clarksville, and Argent, respectively). However, the actual overall increase was relatively small, ranging from 2 to 5 %. Unavailable water also increased with increasing density for all soils ($p = 0.0001$).

The Dome soil had a total porosity of 0.61cm^3 cm^{-3} at the lowest density (1.04 Mg m^{-3}), of which approximately half (0.30 cm^3 cm^{-3}) was macropore space. At or above densities of 1.53 Mg m^{-3} macropore space was eliminated. Available water increased with increasing compaction, although the volumetric water content at which water became available was higher. The Cohasset soil had the highest total porosity, available water, and aeration porosity of the four soils. Compaction reduced total and aeration porosity, which was most pronounced for this soil. Clarksville and Argent had the lowest total porosity.

Total porosity change was similar for all of our soils, averaging around 16%, but marked differences were found for macroporosity (associated with aeration) and microporosity (associated with unavailable water). The greatest reduction in macroporosity occurred for the Cohasset soil (35%), followed by Dome (32%), Clarksville (22%) and Argent (20%). Microporosity increased 100, 55, 42 and 38%, respectively. An aeration porosity of 10% is often considered a critical limit for growth. This limit was reached at densities of 1.13, 1.42, 1.44, and 1.55 Mg m^{-3} for Cohasset, Dome, Clarksville and Argent, respectively (Fig. IV.7).

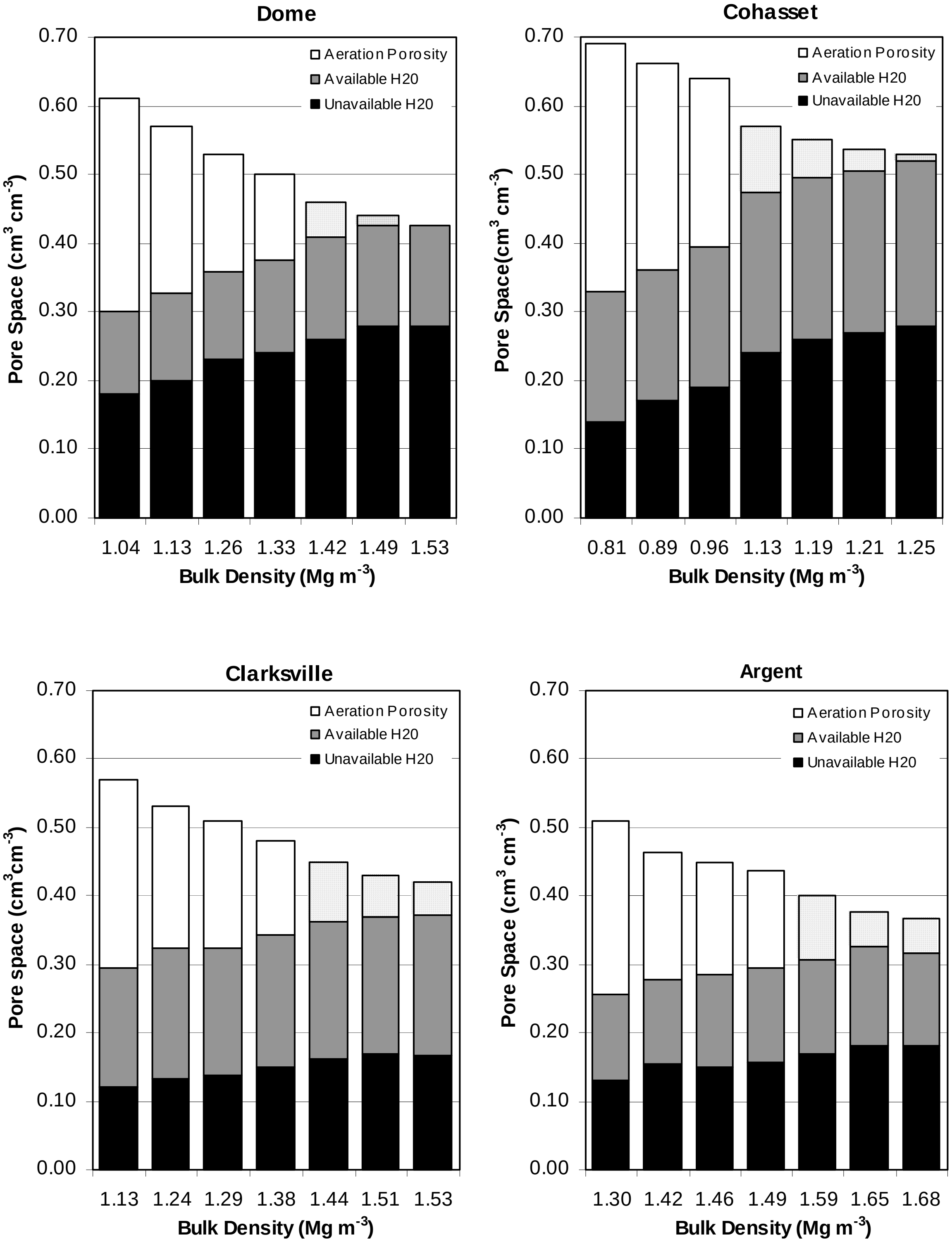

Figure IV.7. Soil porosity changes resulting from compaction of four forest soils. Patterned aeration porosity bars denote aeration porosities less than 10%.

Least Limiting Water Range

Least limiting water range, the soil water content range within which growth restrictions due to water availability, aeration and soil strength are minimal, was determined for all four soils (Fig. IV.8). LLWR was lowest for the Dome and Argent soils, averaging 0.13 cm^3 cm^{-3} for the lower soil densities. The Dome LLWR increased slightly with increasing density and then decreased after aeration porosity became limiting; Argent's LLWR did not increase with soil density increases. Cohasset and Clarksville also had similar LLWRs both averaging 0.19 cm^3 cm^{-3}, however, the Cohasset soil increased to 0.23 cm^3 cm^{-3} as density increased.

Several critical bulk densities were derived from the LLWR diagram: a) the bulk density at which aeration porosity becomes limiting, b) the bulk density at which strength becomes limiting and c) the point at which LLWR becomes zero (LLWR$_{zero}$). The critical limits defining the LLWR varied among the four soils. Field capacity was the main upper limit for all soils and aeration porosity became limiting at densities exceeding 1.14, 1.35, 1.45 and 1.58 Mg m^{-3} for the Cohasset, Dome, Clarksville and Argent, respectively. Wilting point was the lower limit for all soils within the ranges we measured; extrapolated data show strength becoming limiting at densities higher than we achieved. The extrapolated LLWR$_{zero}$ occurred at bulk densities of 1.36, 1.58, 1.66 and 1.84 Mg m^{-3} for the Cohasset, Dome, Clarksville and Argent, respectively.

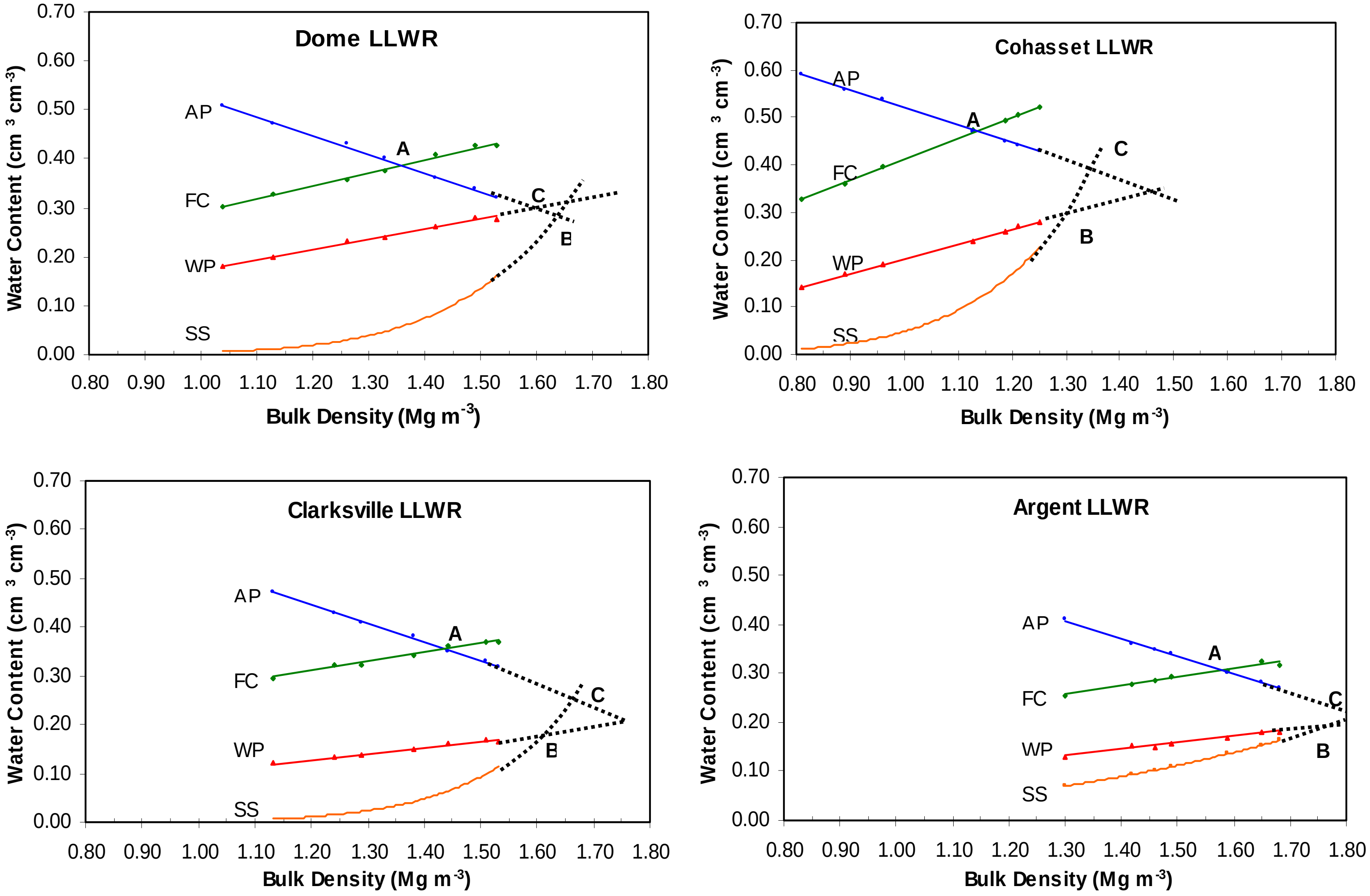

Figure IV.8. Least limiting water range (LLWR) of four forest soils. Limit lines are aeration porosity < 10% (AP), field capacity (FC),wilting point (WP), and soil strength > 2.0 MPa (SS). Dotted lines extrapolate limits beyond maximum soil bulk densities found in this study. (A) represents the point at which aeration porosity becomes limiting, (B) represents the point at which strength becomes limiting, and (C) is the point at which LLWR is zero.

DISCUSSION

The four forest soils used in this study were formed from different parent materials and exposed to different pedogenic processes. Forest vegetation, climate and physiographic region differed for each soil with the exception of Dome and Cohasset soils which are both found in the California Sierra Nevada Mountains supporting the same vegetation type. The different soil forming factors to which these soils were exposed caused differences in mineralogy, texture, and organic matter content and contribute to the soils' response to compaction and thus root growth potential.

Soil compaction had various effects on the properties of these soils. Furthermore, the different combinations of each soil's properties influenced soil compactibility. Texture is one of the most important soil properties influencing soil compaction and resulting water-air balance of the soil. Usually, the clay fraction is considered to have the most influence on compaction properties, however, for coarser textured soils, sandy loam and coarser, the sand fraction also appears to be important. Bodman and Constantin (1965) found highest densities for loamy sands, regardless of sand component particle size. Three of our soils were sandy loams; clay percentages differed no more than four percent. However, soil bulk densities and other related properties of these three soils were very different. The silt loam soil had comparable densities to the Dome sandy loam. Howard et al. (1981) determined that fine plus very fine sand content was more strongly correlated to dry density ($r = 0.727$) than clay content in Californian forest and range soils. However, clay content and texture alone could not adequately explain compactibility differences of these soils.

In addition to texture, the distribution of the particle size classes influences compactibility. Soils with a wide distribution of different particle size classes achieved the greatest soil density because the fines filled in the spaces created by the larger particles (Marshall, 1959). Furthermore, the sand distribution is important because 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). Our three sandy loam soils all had a fairly wide distribution of particle sizes with the sand fraction dominating, thus we hypothesize that Dome and Argent would be the most compactible, Cohasset intermediate and Clarksville the least. However, this was not the case, suggesting that other soil properties, besides texture, were influencing compressibility.

During the sand fractionation procedure we observed interesting differences in the shapes of the sand particles. The granitic Dome soil was dominated by flat, micaceous sand particles while the andesitic Cohasset sample was composed of a variety of rounded and subangular particles of mixed mineralogy. The sand fraction of the Argent soil consisted of very uniform, white, rounded quartz particles, as would be expected from a marine environment. 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). Our soils had very different particle sizes, shapes and surface roughness. We attributed some of the compressibility differences to particle shape and roughness, and believe that these factors greatly influence the soil's shear strength.

Clay hydrated radius, CEC and shrink/swell properties also contribute to soil compressibility (Horn, 1988). Although clay mineralogy was not characterized for these particular samples, the four soils formed from different parent materials and pedologic processes, and we assume that it may be a factor in compressibility differences. Larson et al. (1980) found that medium textured soils with highly weathered clays tend to be moderately compressible (as indicated by the CI), but less compressible than soils dominated by 2:1 type clays and more compressible than soils volcanic soils with allophane as the dominant mineral. Therefore, we would expect the highly-weathered siliceous clays of the Clarksville soil to compact differently than the Cohasset soils with younger clays formed from volcanic parent material, which was the case. The Clarksville soil had intermediate bulk densities increasing from 1.13 to 1.54 Mg m^{-3} and a higher CI, while the Cohasset had much lower bulk densities and a lower CI.

Compactibility is affected by organic matter content, which has very important effects on soil structure, aeration, water holding capacity, and chemical properties. Bulk density and soil porosity and become lower and higher, respectively, with increasing organic matter contents (Childs et al., 1989). For our soils, organic matter content is clearly an important factor affecting compactibility, given that textures and clay contents are reasonably similar while organic matter contents differed by 5%. A difference of 2 to

5% can significantly affect soil properties such as density and porosity for sandy soils (Rawls, 1983). The Cohasset soil with the highest organic matter content had the lowest soil densities and generally responded differently to compaction than the other soils. In studies of Californian forest and range soils, organic C content was the most strongly correlated (r = -0.981) soil property to dry density (Howard et. al, 1981) and the best predictor of bulk density (Alexander, 1980). Organic matter effects on the compactibility of the other three soils, which differed by only 1 to 2% organic matter content, are not as clear.

Of the soil physical properties previously described it appears that organic matter is a primary factor controlling compressibility. However, particle size distribution uniformity, particle shape and roughness and mineralogy all appear to be factors as well. Additional controlled experiments would be necessary to elucidate the roles of each factor on compressibility more clearly; however, based on our observations, it is clear that soil textural class alone is not adequate for predicting soil compactibility. McNabb et al. (2001) also concluded that texture and bulk density 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 may integrate clay type and content and soil surface area (Ball et al., 2000).

Each of our four soils responded differently to compaction as measured by several soil properties including soil bulk density. It is well known that compaction increases bulk density; however, the extent of the increase varies for different soil types and soil moisture contents. Each of our soils, compacted at its OWC, had its own unique density range. The Argent soil achieved the highest minimum and maximum densities while the Cohasset achieved the lowest. However, within their respective density ranges, the Cohasset bulk density increased by 55 % while Argent increased 30 %. Clarksville and Dome had similar maximum densities, but Dome had a lower minimum density. Based on density alone we would consider the Cohasset soil to be the least compactible and Argent the most, with the other two soils being intermediate.

Our soils were compacted at optimum water content to achieve maximum soil densities. However, OWC can also 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. Based on the SWRC curves developed for these soils, OWC is approximately -0.01 MPa for the Cohasset and Dome soil, but is closer to -0.1 MPa for the Clarksville and Dome soils. This is the window of soil wetness when these soils would be most susceptible to compaction; however, field compaction cannot be fully predicted with static lab compaction tests (Froehlich and McNabb, 1984). 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).

The OWC of our soils appeared to be influenced by organic matter content; OWC generally increased with increasing organic matter content. The soils with the highest organic matter contents in our study, Cohasset and Dome, had the highest OWCs and lowest bulk densities. This relationship did not hold for the Argent and Clarksville soils, but the OWC difference was only 2% and organic matter content differed by only 1 %. In studies by Soane (1990), high levels of organic matter and further organic matter additions have reduced maximum bulk density and increased the OWC of soils. 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.

The compaction index is a 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. All of our soils fall in the mid to upper intermediate compressibility range suggesting that forest operations will increase soil density with just a few trips, and thus impact other soil properties and potential root growth on the site. The Cohasset soil would be the least susceptible to compaction of the four soils, based on CI, but still falls within the intermediate compactibility range.

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). Our Clarksville soil, most closely fits class 2, yet its CI was much less than 0.45. Since our three sandy loam soils are coarse textured with low clay content and mixed mineralogy we might expect CI values closer to class 4, yet our values ranged from 0.33 to 0.38, closer to the CI described for the volcanic-derived class. Although the Cohasset soil is derived from volcanic parent material, it is an alfisol and old enough that the clays are mixed and weathered. Overall, our soils did not fit well into any of the four categories described by Larson et al. (1980), probably because these forest soils have higher organic matter contents than the agricultural soils with comparable textures. On the other hand, our CI values are higher than those found by McNabb and Boersma (1993) who 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 may have contributed to this soils resistance to compaction. The CI can be a tool to describe soil compactibility. However, direct comparisons of soils should include the influence of sieving, soil mineralogy and water content differences.

Although the previously described indices and properties indicate a soils compactibility, they don’t necessarily indicate the effect that compaction may have on the soil air/water balance. Compaction can greatly affect Ψ_w due to changes in pore size distribution. In our study, compaction had the greatest effect on the SWRC's for Cohasset and Dome soils and the least effect on Argent. On average, compaction increased soil water contents at each Ψ_w measured, once the Ψ_w was lower than -0.05 MPa, when most macropores have drained. As Ψ_w soil water potential decreased, the soil water content decreased more gradually. This effect was most pronounced for the Cohasset and Dome soils. These soils had higher initial total porosities and macropore space. Compaction reduced the macropore space so that micropores were dominant. The steepest portion of the SWRC curve occurred in the range between 0 and -0.01 MPa at the lower bulk densities for all four soils. Studies have shown that for many soils the greatest change in soil volumetric water content generally occurs between 0 and -0.1 MPa (Richards, 1959; Black, 1968; Reicosky et al. (1981). Increasing compaction had the effect of flattening the SWRC curve. Water was held more tightly under these conditions until lower potentials were applied. Startsev and McNabb (2001) reported that flattening of the SWRC and a shift of the steepest part of the slope resulted from increasing skidder passes on Boreal forest soils. Although our Cohasset soil had the lowest bulk densities, its SWRC curves were most affected by compaction. This suggests that forest operations on this soil may impact water relations of the soil more than is indicated by changes is bulk density.

We found that compaction significantly decreased aeration porosity, and moderately increased unavailable and available water. The effects of compaction on field capacity, permanent wilting point and AWC were non-significant, but were significant for air-filled porosity for boreal forest soils (Startsev and McNabb, 2001). Although available water increased with density, the absolute increase was relatively small, ranging from 2-5 %. Even this relatively small increase can be beneficial to plant growth in typically droughty soils such as the Dome soil found in a Mediterranean climate. For example, ponderosa pine growth increased on a compacted sandy textured soil due to more available water (Gomez et al., 2001). However, at the highest densities, aeration porosity reductions will likely offset the benefits of more plant available water. The relative balance of air to water most suited to plant growth needs to be considered. Compaction of a Cohasset soil from another California LTSP site resulted in reductions in total and macroporosity, negatively correlated with soil bulk density, shift in pore size distribution, increase in smaller pores and reduction in median pore size (Paz, 2001).

It is important to understand how different soil properties and their interactions affect soil compactibility to further understand how tree growth will be affected. Many researchers have attempted to relate bulk density, 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 bulk density (GLBD)" determined by soil texture, was developed based primarily on agricultural and range soil growth data (Daddow and Warrington, 1983). Using their model, the Dome, Cohasset, Clarksville and Argent soils would be growth-limiting at 1.70, 1.67, 1.46 and 1.66 Mg m^{-3}, respectively. These values exceed the Dome and Cohasset soil maximum densities and are only slightly lower than the Argent and Clarksville maximum densities we achieved. The growth limiting densities of our forest soils are probably lower than predicted due to organic matter contents exceeding 3%, the maximum organic content of the soils used to develop the GLBD model. Our results emphasize the influence of organic matter content on soil compactibility, and they show that agricultural data regarding density and growth relationships are probably not appropriate for forest soils. In addition, density alone does not appear to be an adequate indicator of a soils susceptibility to compaction (McNabb et al., 2001).

Soil strength encompasses the effects of density and moisture and is often considered a better measure of dynamic root growth potential than bulk density. Soil strength values above 2.0 MPa have been shown to decrease root length and elongation for a variety of plant species (Atwell, 1993; Greacen and Sands, 1980). Overall, few of our soil columns had strengths greater than 2.0 MPa. As soil density increased, strength values exceeded 2.0 MPa at progressively higher water contents from 0.07 to 0.21, 0.11 to 0.32, 0.12 to 0.26, and 0.03 to 0.13 cm^3 cm^{-3} for Dome, Cohasset, Clarksville, and Argent, respectively. These water contents are generally below wilting point for the Dome and Argent soils, suggesting that as long as there is available water in the soil, strength will not limit root growth. However, at the highest densities, water content at which strength becomes limiting is within field capacity for the Cohasset and Clarksville soils.

At comparable water contents, the Argent soil, with the highest bulk densities, had much lower average soil strengths than the Cohasset soil with the lowest bulk densities and average highest soil strengths, which we attribute to particle shape and size distribution effects on shear strength. The highest soil strength measured was 3.6 MPa for the Cohasset soil at a water content around 14 %. At bulk densities between 1.0 and 1.13 Mg m^{-3}, there were no strength readings between the range of 0.5 and 1.5 MPa at the lower water contents. This discontinuity seems to be associated with a dramatic change in pore-size distribution as seen in the SWRC curves of this soil. It appears that the packing of particles with a certain applied stress level changes rapidly from the previous condition, causing changes in pore-size distribution and greatly increased soil strength. Due to a combination of unique physical properties and experimental conditions, Argent approached but never exceeded 2.0 MPa. The regression equations describing soil strength as a function of water content for soil densities greater than 1.55 Mg m^{-3} have intercepts greater than 2.0 MPa, suggesting that the Argent soil would exceed 2.0 MPa under very dry conditions (Table IV.3). Based on observations of particle shape, distribution and mineralogy we suspect that Argent has a lower shear strength combined with a clay mineralogy that may account for the overall low strengths we found.

Under disturbed field conditions, Burger (1994) found strengths exceeding 2.0 MPa and for this same soil. In general, if water content was greater than 0.30 cm cm^{-3} only a few of the thousands of measurements taken had strengths > 2.0 MPa; when water contents were between 0.20 and 0.30 cm cm^{-3}, the majority of strength measures were < 2.0 MPa; and when soil water was < 0.20 cm cm^{-3} strength values were scattered relatively evenly throughout the entire range (Burger, 1994). In contrast, on another nearby coastal plain site, penetration resistance was generally well below the critical level, ranging from 0.37 to 0.75 MPa for surface soil due to the consistently high water content on this site (Tippet, 1992). In situ soil water contents are much more variable, soil structure is significant and tillage treatments mix subsurface soil of higher clay content with the surface horizon.

Howard et al. (1981) used change in total porosity for ranking soil compaction susceptibility. If you consider the Cohasset soil, the total porosity change was similar to the other soils at 0.16 cm^3 cm^{-3}, but macropore space was most reduced, resulting in limited aeration at bulk densities as "low" as 1.13 Mg m^{-3}. The bulk density is relatively low and total porosity change minimal, but it appears that the compaction effects on air/water balance and thus tree growth may be more important. Again, a single property, either total or macroporosity did not adequately reflect a soil's compaction response and the resulting affect on root growth potential.

For our soils, compaction affected soil properties such as soil strength, aeration and porosity differently, thus, the potential consequences to plant growth should differ. At a given bulk density, soil water content determines root growth potential by influencing soil strength, aeration, and plant available water. Although time consuming, testing compaction effects on multiple soil physical properties and air-water relations provides a better comprehensive understanding of compaction effects on soil and the resulting affect on plants. The LLWR depicts these interactions by showing that as bulk density increases, the range of soil water content within which roots can grow narrows because aeration porosity decreases and soil strength increases.

For all four soils, the available water limits (FC and WP) were the primary determinants of the LLWR; therefore, water availability appears to be the most likely factor affecting growth until the soil becomes very compacted. Aeration did not become limiting until the soils were quite compacted, and strength was limiting only at densities beyond the maximum densities we tested. However, there are limitations inherent to extrapolating lab results to field situations.

The strength results were surprising. Given field strength data for several of these soils, we might expect to find strength decreasing the LLWR at lower densities. A possible explanation for the differences in strengths found in this experiment and those expected for field measurements is that field soils have structural aggregates and much greater variation in pore space distribution. Also, individual soil aggregates may have greater bulk densities, and thus greater strength than the bulk soil (Larson and Gupta, 1980).

The narrower LLWR's of Dome and Argent soils suggest they have greater potential for growth limitations due to soil water content. Also, compaction appears to have a potential positive effect by increasing LLWR at moderate densities for the Dome and Cohasset soil. LLWR generally decreased with compaction for several New Zealand forest soils with the exception of increases from low to moderate compaction for a coarse-textured pumice soil and a fine-textured loess (Zou et al., 2000). Further work looking at how vegetation responds to these varying soil physical properties needs to be done in addition to finding ways to extrapolate results to field situations.

CONCLUSIONS

The interactive effects of soil texture, organic matter content, mineralogy, particle size distribution, particle shape and surface roughness on compaction determined the degree of compaction of the four forest soils examined in this study. Differences in the inherent compactibility of each soil, in turn, affected properties such as soil strength and air/water balance which most influence tree growth. For our soils, strength was limiting (>2.0 MPa) for the higher bulk densities when soil was at water contents less than wilting point, or in the case of Argent, not at all. Compaction reduced aeration porosity and slightly increased available water for all the soils, with Cohasset being most affected. Both of these factors were good indicators of compaction; however, it is not clear which one would most limit root growth potential. The LLWR appears to be a promising tool for integrating the influence of these two soil properties. The LLWR's show that for our soils available water and aeration limitations were critical along with soil strength. However, little work has been done with forest species. Testing the usefulness of the LLWR for each soil with plant growth data would better partition root growth response among limiting soil properties.

Many studies regarding compaction and growth have been conducted during the last 50 years, yet most growth models and compaction susceptibility rating systems seem to have limited applicability. Forest soils are particularly complex systems for which a “one-size fits all” approach is not adequate. It is important to go beyond basic texture and bulk density data when developing criteria for minimizing compaction on forest soils and thus maintaining or improving forest productivity. We need to understand the factors contributing to soil compactibility and we need to develop and apply integrative techniques that better assess compaction effects on plant growth. The LLWR is one such technique that is a promising tool for assessing soil physical properties as affected by compaction. However, we don't know how well LLWR data apply to growth of forest tree species. We need to test these approaches under field conditions and find ways to utilize easily-available soils data specific to a soil type or locations to develop such tools.