Soil Compaction and Strength: Measurement Methods and Influences on Perennial Grass Growth

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Susan Marshall presented the findings of research pertaining to soil compaction and strength; its measurement and influence on perennial grass growth, done as part of Allison Tokunaga's thesis at Humboldt State University. Soil compaction is often associated with grazing, and is defined as increasing the soil bulk density, and concomitantly decreasing the soil porosity, by the application of mechanical forces to the soil. Bulk density is a mass/volume relationship that is commonly expressed as g/cm^3 by soil scientists or lbs/ft^3 for engineering applications. The direct measurement of soil compaction is often expressed as bulk density (Db), which is defined as the mass of dry soil per unit volume. Coarse fragments greater than two millimeters in diameter are excluded from this measurement; only the fine-earth fraction is quantified, which can be problematic since range soils often contain rocks. Soil strength is the capacity of a soil to resist a force without rupture, fragmentation, or flow. Strength is directly correlated with penetration resistance, the soils resistance to penetration by roots. Soil strength and penetration resistance are affected by several factors including soil moisture, which can provide lubrication for roots. Strength fluctuates with soil moisture, but bulk density is measured on a dry soil basis and is therefore unaffected by moisture content.

The effects of compaction on plant growth have been studied most often in an agricultural context primarily focusing on tap-rooted species or C_4 warm season grasses. Root-limiting densities have been reported as 1.5 g/cm^3 in fine textured soils and 1.9 g/cm^3 in coarsely textured soils, however there is no single critical bulk density reported in the literature that limits plant growth. Part of the research presented aimed to investigate root limiting bulk densities pertaining to perennial grasses, and whether they can tolerate more dense soil conditions than previously researched plant species. In the case of plant growth limiting soil strengths values range from 2.5 to 3 mega-pascals (MPa) (363 to 435 psi) for finely textured soils, and from 6 to 7 mega-pascals for more coarsely textured soils, which tend to have more macro-pores that roots can wind their way down. Soil strength varies with bulk density and water content and in rangelands it may vary seasonally. Soils tend to exhibit increased strength when they are denser and drier. Besides physical root impedance compaction can also lead to decreased infiltration rates and slower rates of water and gas movement through the soil. In most rangeland settings the uppermost ten centimeters tend to be compacted by grazing animals, compared to the more deeply seated compaction created by heavy equipment or glaciers for example.

Tokunaga's research aimed to investigate how root and shoot biomass production varies across a range of bulk densities and soil strengths. The research also sought to determine whether there is a threshold bulk density and/or soil strength that limit biomass production of roots and or shoots for perennial grasses, specifically blue wildrye.

The experiment was conducted in a greenhouse at Humboldt State University using soil collected from Nixon ridge, about twenty-five miles east of Arcata, California. The soil was sieved to exclude particles larger than two millimeters in diameter; in the case of the Nixon Ridge soil a lot of rocks were removed during this process. Three bulk density treatments were analyzed: one “loose” with a bulk density of one g/cm^3, one group “medium” having a bulk density of 1.25 g/cm^3, and the other “dense” with a bulk density of 1.55 g/cm^3 (the root-limiting density cited in previous studies). The soil samples were compacted following standard engineering ASTM protocols. Each bulk density treatment block also had three water potential treatments: “wet” at –33 kPa (field capacity), “moist” at –500 kPa (moderate water stress), and “dry” –1500 kPa (permanent wilting point). The moisture contents of each treatment were maintained three days a week by weighing each replicate to the nearest gram, and utilizing soil moisture retention curves. The experimental set-up consisted of growing Blue Wildrye a perennial cool-season grass, for four months. The replicates were rotated and watered three times a week, and randomized weekly. Each bulk density/moisture combination consisted of twenty-five replicates.

The variables that were measured included shoot biomass (clipped and dried), root biomass (washed and dried), soil strength (utilizing a penetrometer for lower bulk densities, and a hydraulic press for higher bulk densities), and rooting depth (split core). Visual observations demonstrated that as expected the moist and wet treatments were more productive than the dry treatment blocks.

Results pertaining to shoot biomass demonstrated that drier more compact treatments produced less shoot biomass. Results for root biomass demonstrated that both the loose and intermediate treatments tended to produce good amounts of roots. However, the root biomass across all three moisture treatments decreased for the “dense” bulk density treatments. The results were analyzed utilizing ANOVA and significant differences were found at $p=0.05$ for each treatment block analyzed.

The root:shoot ratios for the grasses in this study were observed to be surprisingly high. The maximum rooting depths varied significantly across the bulk density treatments; the “loose” treatment demonstrated roots growing to the bottom of their containers (10 cm) across all three moisture treatments. In comparison the “dense” treatments’ rooting depths were significantly restricted and were only about 3 cm deep for the “wet” treatment. The rooting depths were shallower for the “moist dense” and the “dry dense” treatments.

A penetrometer was utilized to quantify penetration resistances for the loose and medium bulk density treatment blocks, but was unable to provide meaningful measurements for the dense treatment block. As expected, penetration resistance was demonstrated to be inversely proportional to moisture content, in other words as moisture content increased penetration resistance decreased. The effect of moisture on penetration resistance was more pronounced for the medium bulk density treatments compared to the loose treatment blocks. A hydraulic press was required to obtain penetration resistance values for the more compact, “dense” treatments. Root limiting soil strengths have been reported at around 3 MPa; in this study the dense and dry treatments corresponded to soil strength values as high as 18 MPa.

Soil strength values obtained with the penetrometer and hydraulic press were compared. The values obtained utilizing the press tended to be slightly higher than those recorded with the penetrometer; demonstrating that different values for soil strength are obtained depending on the methodology utilized to assess the strength. The difference in values can prove quite significant. For example, root penetration was at its maximum at penetration resistances of approximately 3 MPa when measured with a penetrometer. However, when the hydraulic press was utilized to quantify penetration resistance roots were observed penetrating soil with penetration resistances as high as 6.4 MPa, much higher than penetration resistance values reported to be root limiting in existing literature.

In summary, lower root biomass production was observed for treatments with higher bulk densities, higher soil strength, and shallower rooting depth. Higher root biomass production was reported for treatments with less water stress including those with higher soil strengths. Furthermore, this research indicates that root penetration and biomass production can potentially be high over a wide range of soil strengths exceeding 2.5 MPa. Higher shoot biomass production was observed for treatments under less water stress and with deeper rooting depth. Good shoot biomass production was observed under conditions of higher soil strength than previously reported. Similar shoot production was reported to occur under contrasting belowground conditions; different bulk densities and moisture levels yielded similar shoot biomass, the productivity did not significantly drop off except for treatments with high bulk densities.

The research indicates that in general increasing bulk density and soil strength results in decreased biomass production and root penetration. However, high production and deep root penetration can occur in soils with soil strengths in excess of 2.5 MPa, although these effects are likely moderated by water availability. The research also demonstrated that it is unclear whether or not there is a threshold bulk density or soil strength that will limit productivity. Furthermore, results indicated that similar production can occur across a range of bulk densities, although it is important to keep in mind that bulk density and water availability interact to affect productivity.

The research also demonstrated that methods of measuring soil strength in the field are far from precise and notoriously variable. The study reconfirmed the physical difficulty of obtaining quantitative data on highly compacted, strong soils; even those without rocks. As a result the penetrometer appears to be a useful tool under agricultural conditions, but much less so in rangeland settings that often contain rocks and display highly variable penetration resistances across the landscape. A hydraulic press, although of little value in the field, can be effectively utilized in the laboratory to quantify a wide range of soils including those that are very dense and strong.

In conclusion, the interactions of bulk density, soil strength, and moisture status are especially important for annual plants that must re-germinate and complete their life cycles each year. However, Dr. Marshall stressed that these same interactions influence perennial grasses differently, since once they germinate and extend roots deep into the soil profile they are better buffered from seasonal variations in soil moisture. Despite the resilience of perennial grasses compared with annual species, high bulk densities and soil strengths can limit the volume of soil available to be utilized by roots to obtain water and nutrients that are critical for their continued survival. However, as long as water is available perennial grass roots have demonstrated the ability to penetrate beyond what has been recorded as restricting for many agricultural crops. Therefore, high bulk densities seem to be more important in terms of affecting water infiltration and percolation as opposed to actual physical impedance of root growth in field settings.