soil Bulk Density / Moisture / Aeration

Soil Quality Kit – Guides for Educators

United States Department of Agriculture
Natural Resources Conservation Service

Bulk density is an indicator of soil compaction and soil health. It affects infiltration, rooting depth/restrictions, available water capacity, soil porosity, plant nutrient availability, and soil microorganism activity, which influence key soil processes and productivity. It is the weight of dry soil per unit of volume typically expressed in grams/cm^3. Total volume of surface soil is about 50% solids, mostly soil particles (45%), and organic matter (generally < 5%); and about 50% pore space which are filled with air or water (Figure 1). When determining bulk density, the amount of soil moisture must be determined. Available water capacity is the amount of soil moisture available to plants, varies by texture (Figure 2), and is reduced when compaction occurs. Bulk density can be managed, using measures that limit compaction and build soil organic matter.

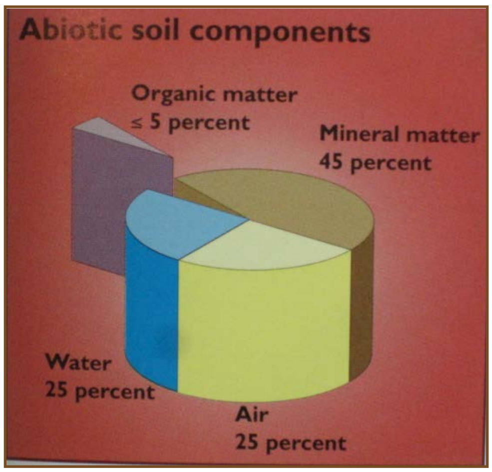

Figure 1. Four major components of soil volume (Michigan Field Crop Ecology, 1998, E-2646, p. 13).

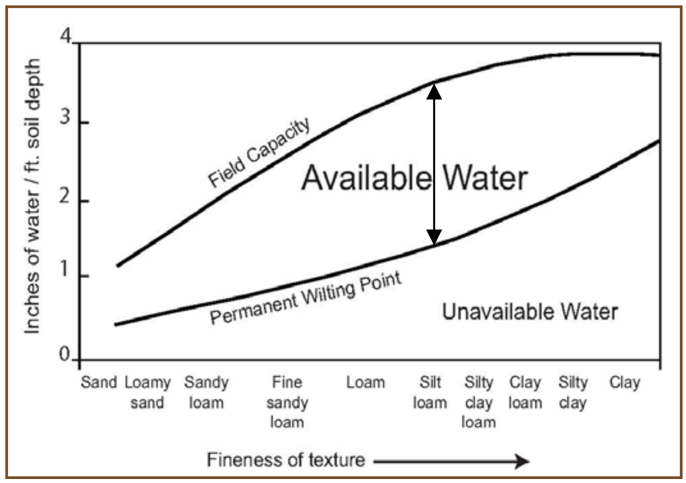

Figure 2. Relationship between available water and texture (Ohio Agronomy Guide, 14th Ed. Bull. 472-05).

Inherent Factors Affecting Bulk Density and Available Water Capacity

<u>Inherent factors</u> that affect bulk density such as soil texture cannot be changed. Bulk density is dependent on soil organic matter, soil texture, the density of soil mineral (sand, silt, and clay) and their packing arrangement. As a rule of thumb, most rocks have a density of 2.65 g/cm^3 so ideally, a silt loam soil has 50% pore space and a bulk density of 1.33 g/cm^3. Generally, loose, well-aggregated, porous soils and those rich in organic matter have lower bulk density. Sandy soils have relatively high bulk density since total pore space in sands is less than silt or clay soils.

Bulk density typically increases with soil depth since subsurface layers are more compacted and have less organic matter, less aggregation, and less root penetration compared to surface layers, therefore contain less pore space.

Available water capacity (Figure 2) is affected by soil texture, presence and abundance of rock fragments, soil depth and restrictive layers.

Bulk Density Management

Bulk density can be changed by management practices that affect soil cover, organic matter, soil structure, compaction, and porosity. Excessive tillage destroys soil organic matter and weakens the natural stability of soil aggregates making them susceptible to erosion caused by water and wind. When eroded soil particles fill pore space, porosity is reduced and bulk density increases. Tillage and equipment travel results in compacted soil layers with increased bulk density, most notably a "plow pan" (Figures 3 and 4). Tillage prior to planting temporarily decreases bulk density on the surface but increases at the depth of tillage. Subsequent trips across the field by farm equipment, rainfall events, animals, and other disturbance activities will also compact soil. Long-term solutions to soil compaction center on decreasing soil disturbance and increasing soil organic matter.

A soil's available water capacity is also affected by organic matter and compaction. Organic matter increases a soil's ability to hold water, both directly and indirectly. Compaction increases bulk density and reduces total pore volume, consequently reducing available water holding capacity.

The following measures increase organic matter, and reduce compaction, which improve bulk density and porosity:

- Practices that increase organic matter such as continuous no-till, cover crops, solid manure or compost application, diverse rotations with high residue crops and perennial legumes or grass used in rotation;
- Minimize soil disturbance and avoid operating equipment when soils are wet;
- Use designated roads or rows for equipment;
- Reduce the number of trips across a field;
- Subsoil to disrupt existing compacted layers; and
- Use multi-crop systems involving plants with different rooting depths to help break up compacted soil layers.

Compacted inter-row restricts roots, worms, aeration, and N availability.

Figure 3. Compacted soil in wheel traffic row.

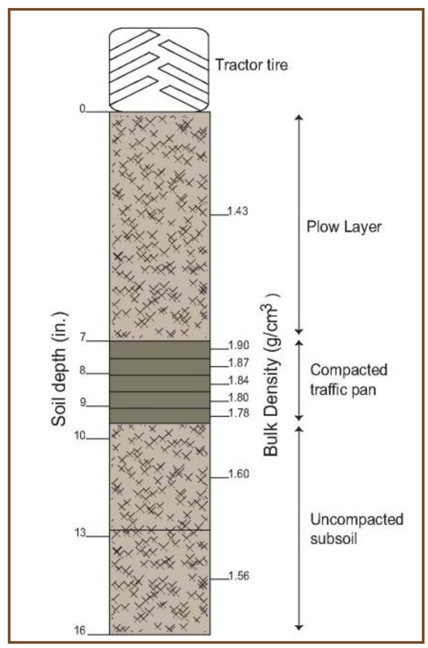

Figure 4. Compacted plow layer inhibiting root penetration and water movement through soil profile (adapted from: *The Nature and Properties of Soils*, 10th Edition).

Water-Filled Pore Space and Porosity

When determining bulk density, water-filled pore space and porosity can also be calculated. When water-filled pore space exceeds 60%, several important soil processes are impacted. Soil respiration and nitrogen cycling (ammonification and nitrification) increase with increasing soil moisture (Figure 5). Lack of aeration also interferes with a soil organism's ability to respire and cycle nitrogen. In dry soils, these processes decline because of lack of soil moisture.

As soil water-filled pore space exceeds 80%, soil respiration declines to a minimum level and denitrification occurs resulting in loss of nitrogen as gas, emission of potent greenhouse gases, yield reduction, and/or increased N fertilizer expense.

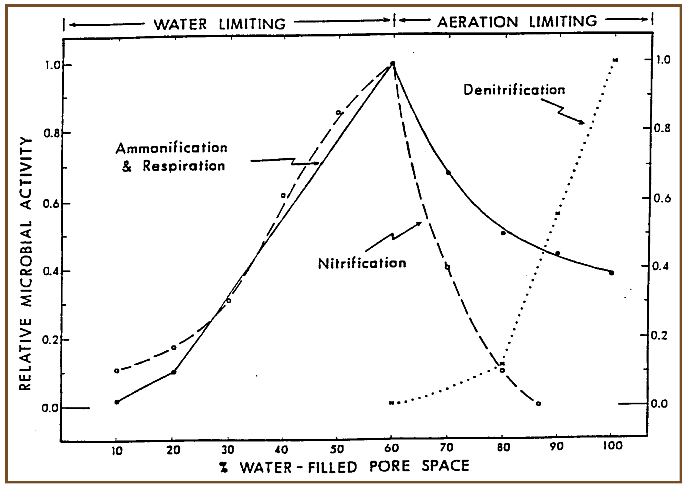

Figure 5. Relationship of water-filled pore space to soil microbial activity (Linn and Doran, 1984).

Soil Bulk Density Problems and Relationship to Soil Function

High bulk density is an indicator of low soil porosity and soil compaction. High bulk density impacts available water capacity, root growth, and movement of air and water through soil. Compaction increases bulk density and reduces crop yields and vegetative cover available to protect soil from erosion. By reducing water infiltration into soil, compaction can lead to increase runoff and erosion from sloping land or saturated soils in flatter areas. Bulk densities above thresholds in Table 1 impair root growth.

Laboratory analyses should use bulk density to adjust volume of soil to determine organic matter and nutrient content of soil. For example, a soil with a bulk density of 1.3 versus a soil with a bulk density of 1.0 would result in a 30% error in organic matter and nutrient content if the samples are not adjusted for bulk density.

Table 1. General relationship of soil bulk density to root growth based on soil texture.

Soil Texture	Ideal bulk densities for plant growth (grams/cm^3)	Bulk densities that affect root growth (grams/cm^3)	Bulk densities that restrict root growth (grams/cm^3)
Sands, loamy sands	< 1.60	1.69	> 1.80
Sandy loams, loams	< 1.40	1.63	> 1.80
Sandy clay loams, clay loams	< 1.40	1.60	> 1.75
Silts, silt loams	< 1.40	1.60	> 1.75
Silt loams, silty clay loams	< 1.40	1.55	> 1.65
Sandy clays, silty clays, clay loams	< 1.10	1.49	> 1.58
Clays (> 45% clay)	< 1.10	1.39	> 1.47

What management measures and practices do you think affect bulk density? Why or why not?

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What impact do you expect these practices on organic matter and soil porosity?

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Measuring Bulk Density and Soil Moisture

Materials Needed to Measure Bulk Density

____ 3-inch diameter aluminum ring

____ Wood block or plastic insertion cap

____ Rubber mallet or weight

____ Folding trowel

____ Flat-bladed knife

____ Sealable bags and marker pen

____ Scale (1 g precision)

____ 1/8 cup (29.5 mL) measuring scoop

____ Ceramic coffee cup or paper plate

____ 18-inch metal rod, probe or spade (to check for compaction zone)

____ Access to a microwave oven

Considerations – Bulk density can be measured at the soil surface and/or compacted tillage zone. Bulk density samples should be taken in same location as infiltration and respiration tests. It may be possible to use the infiltration test sample. For sticky clay soils a little penetrating oil applied to the ring makes it easier to remove soil.

Step by Step Procedure

1. Carefully clear all residue then drive ring to a depth of 3 inches (2 inches from top; see Figures 6 and 7) with small mallet or weight and block of wood or plastic cap (same process as used for infiltration test).

Figure 6. Drive ring to 3-inch depth.

Figure 7. Ring driven to 3-inch depth.

2. Remove ring by cutting around the outside edge with a small 4-inch serrated butter knife and using the small folding trowel underneath of it and carefully lift the ring out preventing loss of soil by holding trowel under it.

3. Remove excess soil from the bottom of cylinder with serrated butter knife as shown in Figure 8.

Figure 8. Remove excess soil from bottom of ring.

4. Place sample in plastic sealable bag and label it.

5. Weigh sample in bag and record its weight in Table 2.

6. Weigh an identical clean, empty plastic bag and record its weight in Table 2.

7. Weigh empty cup or paper plate to be used in step 8 and record its weight on Table 2.

8. Either <u>extract a subsample</u> shown in steps 8-10, or <u>dry and weigh entire sample</u> to determine water content and dry soil weight:

    a. Mix sample thoroughly in the bag by kneading it with your fingers.

    b. Take a 1/8-cup level scoop of loose soil (not packed down) from plastic bag and place it in the cup weighed in step 7 (use more than one scoop to increase accuracy).

9. Weigh moist subsample in cup before drying and record in table 2.

10. Place cup containing subsample in a micro wave and dry for two or more four-minute cycles at medium power.

11. To determine if soil is dry, weigh subsample in cup/plate after each 4-minute cycle. When the weight no longer changes after a drying cycle, it is dry, and record its weight on Table 2.

Interpretations

Complete Table 2 for bulk density and soil water content determination and compare results to the same soil texture listed in Table 1 to determine relative restrictions to root growth or compaction concerns. Complete Tables 3 through 5 for soil water and porosity determination and compare results to Figure 5. relationship of water-filled pore space to soil organism's ability to respire and cycle nitrogen Figure 2. water content. Answer discussion questions to further analyze your results.

Table 2. Bulk density and soil water content (core method). Refer to calculations below for details.

Sample site	(a) Wt of field moist soil + sample bag (grams) (entire sample)	(b) Wt of sample bag (grams)	(c) Wt of cup (grams)	(d) Wt of cup + moist soil (grams) (sub-sample)	(e) Wt of moist soil (grams) (d-c)	(f) Wt of dry soil + cup (grams)	(g) Dry Wt of soil (grams) (f-c)	(h) Soil H_2O content (grams/gram) (d - e)/(g)	(i) *Soil bulk density (g/cm^3)
Ex. 1	490 g	5 g	126 g	160 g	34 g	153 g	27 g	0.259 g/g	1.2 g/cm^3

*Soil bulk density = [(a - b)/(1 + h)] ÷ volume of soil core (Volume of soil core = 321 cm^3 for 3" core, 2" from top of soil to top of ring, refer to Figure 11 and volume calculations below)

Abbreviations for Example 1 (Wt= Weight; π = 3.14; g = grams; r = radius of inside diameter of ring/core)

Volume of Soil Core (cm^3) (refer to Figure 11)

πr^2 x height

Example 1 (refer to Figure 11)

3.14 x $(3.66\ cm)^2$ x (7.62 cm) = **321 cm^3**

Soil Water Content Using a Subsample (g/g)

(weight of moist soil - weight of oven dry soil)
Weight of oven dry soil

Example 1 (e - g)/(g)

(34g – 27g) / 27g = **0.259 g of water/g of soil**

Calculating the Dry Weight of the Bulk Sample Based on Soil Water Content of Subsample (grams)

Dry wt of soil bulk sample = [Wt of field moist soil + bag (grams) - Wt of bag (grams)] / [1 + Soil Water content (g/g)]

Example 1: dry wt of bulk sample = [(a - b)/(1 + h)] = (490 g - 5 g) / (1 + .259) = 385 g

Bulk Density Calculation (g/cm^3)

Bulk Density = Dry wt of bulk sample ÷ volume of soil core

Example 1: bulk density = 385g ÷ 321 cm^3 = **1.20 g/cm^3**

Soil Water Content and Porosity Calculations

Table 3. Soil water content.

Sample Site	Soil Water Content (by Wt) (g/g) (from h in Table 2)	Bulk density (g/cm^3) from Table 2	* Volumetric water content (g/cm^3)	** Inches of water/ft. of soil depth
Example 1	0.259	1.2 g/cm^3	0.3108 g/cm^3	3.7"/ft

* Volumetric water content (g/cm^3) = soil water content (g/g) x bulk density (g/cm^3)

** Inches of water/ft. of soil depth = volumetric water content x 12"/ft

Table 4. Soil porosity (%).

Sample Site	Bulk Density ($grams/cm^3$) from Table 2	Calculation 1 - (soil bulk density / 2.65)	* Soil porosity (%)
Example 1	1.2$grams/cm^3$	1 - (1.2/2.65)	0.547 or 54.7%

* Soil porosity (%) = 1 - (soil bulk density / 2.65). The default value of 2.65 is used as a rule of thumb based on the average bulk density of rock with no pore space.

Table 5. Soil water filled pore space (%).

Sample Site	Volumetric water content ($grams/cm^3$) from Table 3	Soil porosity from Table 4	Volumetric Water Content / Soil porosity x 100	* Soil Water-Filled Pore Space
Ex. 1	0.3108 grams/cm3	0.547	0.3108 g/cm^3 / .547 x 100	.568 or 56.8%

* Soil water-filled pore space (%) = (volumetric water content / soil porosity) x 100

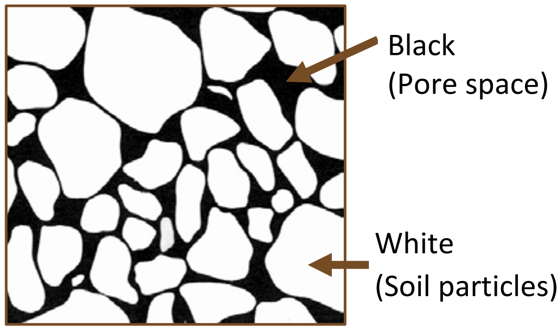

Figure 9. Soil porosity.

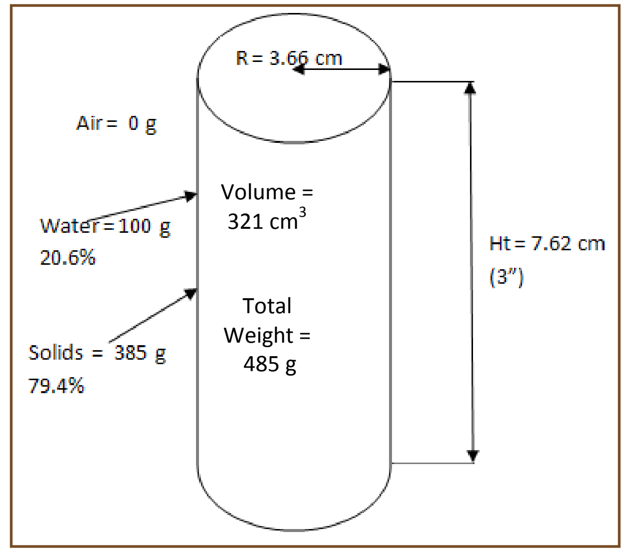

Figure 11. Soil core dimensions, volume, and weight (by component) Example 1.

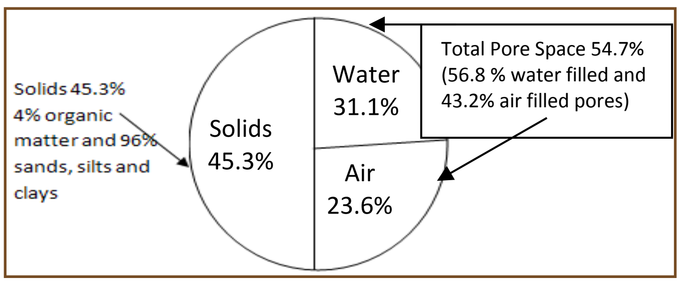

Figure 10. Volume by component of Example 1 soil core (volume = 321 cm^3).

Were results of bulk density and porosity tests what you expected? Why or why not?

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Compare results of water-filled pore space calculation to Figure 5. Is soil organism's ability to respire and cycle nitrogen impacted? If so what impact on production may occur and are these processes water or aeration limited?

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Compare bulk density results to values in Table 1 for the same soil texture on this field. Are bulk densities levels ideal based on the soil texture? Why or why not?

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Compare total water content (inches/ft soil depth) from Table 3 to available water capacity (AWC) shown in Figure 2 for the same texture. Is soil near field capacity?

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Glossary

Ammonification – Occurs in nitrogen cycle when soil organisms decompose organic-nitrogen converting it to ammonia.

Available Water Holding Capacity – Soil moisture available for crop growth (Figure 1). It is also defined as the difference between field capacity and wilting point, typically shown in inches/ft.

Nitrification – Occurs in nitrogen cycle when soil organisms convert ammonia and ammonium into nitrite and next to nitrate-nitrogen which is available to plants.

Bulk Density – Weight of dry soil per unit of volume, more compacted soil with less pore space will have a higher bulk density.

Denitrification – Conversion and loss of nitrate nitrogen as nitrogen gases when soil becomes saturated with water.

Respiration – Carbon dioxide (CO_2) release from soil from several sources: decomposition of organic matter by soil microbes, respiration from plant roots and soil fauna (requires oxygen; aerobes).

Soil Porosity – Percent of total soil volume made up of pore space (Figure 4).

Soil Water Filled Pore Space – Percent of pore space filled with water.

Soil Water Content, Gravimetric – Weight of soil water per unit of dry soil weight.

Volumetric Water Content – Amount (weight or volume) of water in soil core by volume. (1 g water = 1 cm^3).