BIOL 695

THE SOIL AS A PLANT NUTRIENT MEDIUM

CHAPTER 2
Mengel et al., 5th Ed

WEATHERING OF ROCKS & MINERALS

Weathering is the physical and chemical breakdown of particles

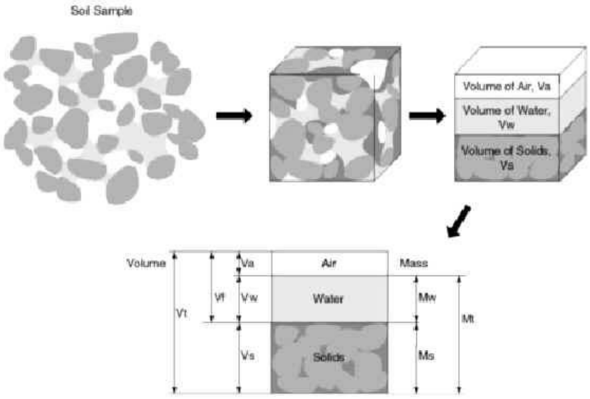
Rock classes:

Igneous - formed from cooled magma
- comprised of primary minerals
- basalt, granite, gabbro, diorite, peridotite

Sedimentary - compacted, cemented, weathered particles
- sandstones, shales, limestones

Metamorphic - altered by heat and/or pressure
- gneiss, schist, marble, slate, quartzite

THE SOIL

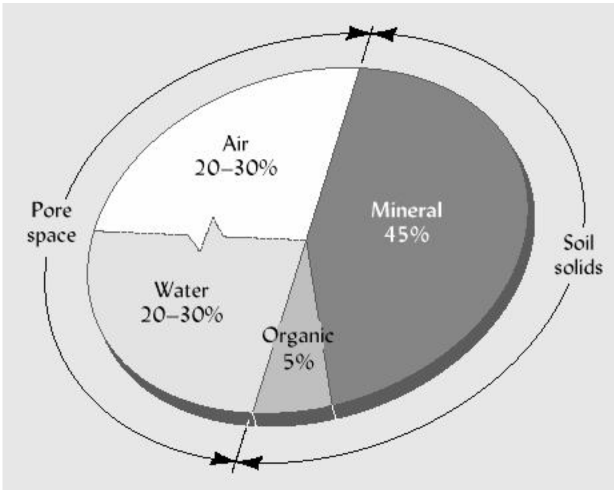


A schematic of soil as a 3-phase system: solids, water, air. Basic soil mass and volume relationships may be conceptualized based on 'separating' the three components.

Source: Or and Wraith, 1999

THE SOIL

Volume composition of a loam surface soil when conditions are good for plant growth. The broken line between water and air indicates that the proportions of these two components fluctuate as the soil becomes wetter or drier. (FIGURE 1.17, Brady & Weil)



FACTORS INFLUENCING SOIL FORMATION

1. Parent materials (geologic or organic precursors to the soil

2. Climate (primarily precipitation & temperature)

3. Biota (living organisms, especially native vegetation, microbes, soil animals & humans

4. Topography (slope, aspect & landscape position)

5. Time (the period of time since the parent materials became exposed to soil formation factors)

PRIMARY SOIL HORIZONS

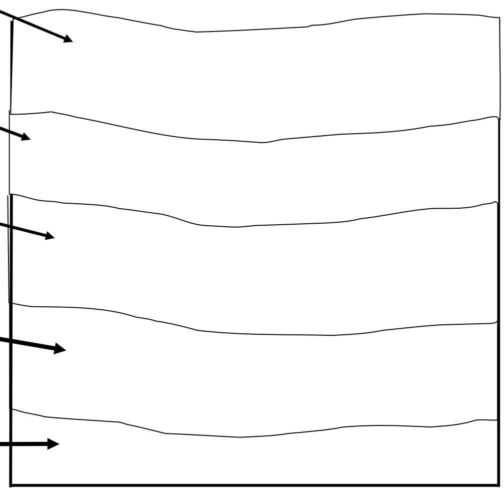
A Horizon
Organic rich
Highest organism activity

E Horizon
Zone of leaching, eluviation

B Horizon
Weathered, Accumulation of Clays, oxides

C Horizon
Parent Material; May be multiple layers

R Horizon
Bedrock
In Hampton Roads: 2000 ft deep



Alluvial soil

Note many layers of very different types of parent material

From Maryland

Note buried A and B Horizons

SOIL ORGANIC MATTER

- **Living soil organisms**
  - **invertebrates**
  - **bacteria & fungi**
- **Plant roots**
- **Decomposing dead organic matter**
- **Humus (highly decomposed organic matter)**
- **Transitory component - continually being decomposed, thus must constantly be renewed**

SOIL ORGANIC MATTER

Functions:

- **granulator of soil particles into aggregates**
- **major source of P and S**
- **increases water holding capacity**
- **primary source of energy for microorganisms**
- **major "sink" for chemicals, nutrients & contaminants**

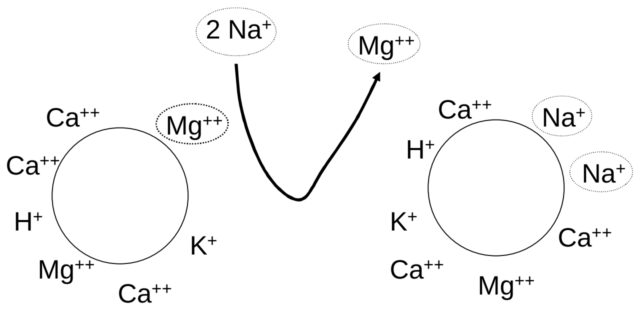
IMPORTANT PHYSICO-CHEMICAL PROPERTIES

- **Cation sorption and exchange**
- **Cation replacement order**
- **Cation adsorption vs desorption**
- **Ion exchange equation**
- **Anion adsorption**
- **Water adsorption**

SOIL CHEMICAL FACTORS

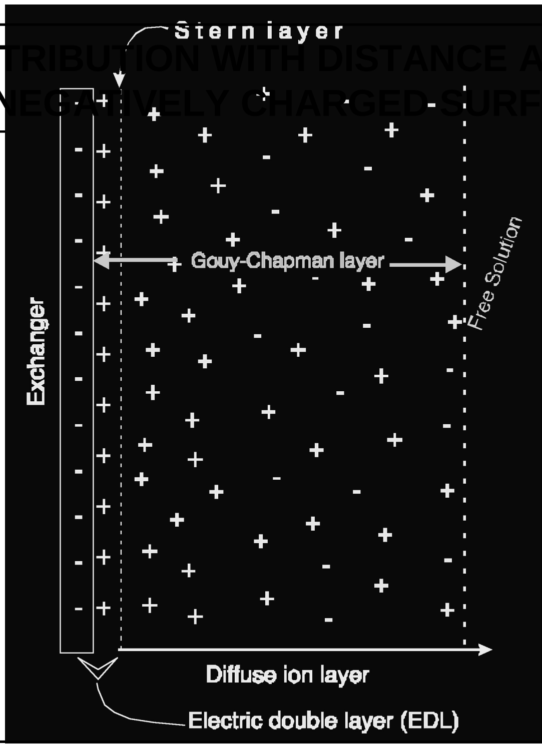
- Cation exchange capacity (CEC)
  - slight negative charge: holds + ions
  - Ex: Ca^{++}, Mg^{++}, K^{+}
- High CEC:
  - inorganic clays
  - (colloidal) organic matter
- Soil pH (acidity or alkalinity of soils)
  - affects availability of nutrients

CATION EXCHANGE



Principle of Cation Exchange: Mg^{++} is Replaced by Na^{+}

IONIC DISTRIBUTION WITH DISTANCE AWAY FROM A NEGATIVELY CHARGED SURFACE



REPRESENTATIVE CATION EXCHANGE CAPACITIES OF COMMON MATERIALS IN SOILS (pH 7.0)

Exchanger (Soil Phase)	**Cation Exchange Capacity (CEC)** Cmols kg^{-1}
Organic matter	100 - 300
Vermiculite	100 - 150
Allophane	100 - 150
Smectite (montmorillonite)	60 - 100
Chlorite	20 - 40
Illite	20 - 40
Kaolonite	2 - 16
Hydrous oxides	2 - 8

SELECTIVITY OF TRACE METAL CATIONS FOR DIFFERENT SOIL MATERIALS

Material	Selectivity Order
Kaolinite clay (pH 3.5-6)	Pb>Ca>Cu>Mg>Zn>Cd
Montmorillonite clay (pH 3.5-6)	Ca>Pb>Cu>Mg>Cd>Zn
Illite clay (pH 3.5-6)	Pb>Cu>Zn>Ca>Cd>Mg
Soil organic matter	Cu>Ni>Pb>Co>Ca>Zn>Mn >Mg
Mineral soils (pH 5)	Pb>Cu>Zn>Cd

SOLUTION CONCENTRATION AND THE CONCEPT OF ACTIVITY

- **At low concentrations, ionic behavior is "ideal" and predictable**
- **At higher concentrations, ionic behavior deviates from "ideal" and is less predictable**
- **Ionic activity, not concentration, is most important in explaining and predicting effects**

ACTIVITY

a = f x c

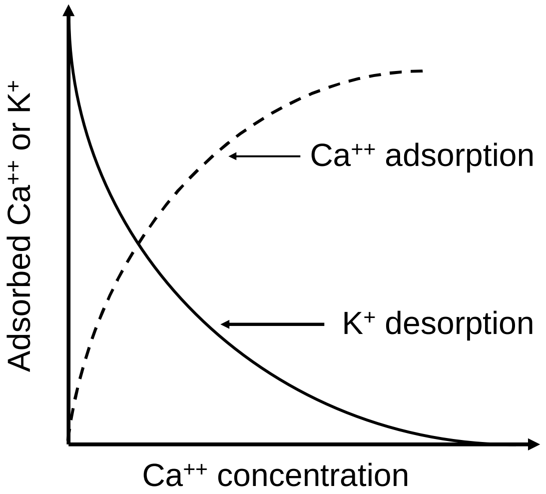
where:
c = activity

c = concentration

f = activity coefficient

The activity coefficient decreases as the ionic strength (concentration) of the solution increases

RELATIONSHIP BETWEEN INCREASING Ca^{++} CONCENTRATION, Ca^{++} ADSORPTION And K^{+} DESORPTION



CATION EXCHANGE

- Occurs on the basis of chemical equivalents (ionic charges)
- 1 mole H^+, K^+, Na^+ = 1/2 mole Ca^{++}, Mg^{++} = 1/3 mole Al^{+++}
- CEC = TEB + EA
- CEC = Cation Exchange Capacity, centimol kg^{-1} (meq 100 g^{-1})
- TEB = Total Exchangeable Bases (Na^+, K^+, Mg^{++}, Ca^{++})
- EA = Exchangeable Acidity (Al^{+++}, H^+)

CATION EXCHANGE

The Gapon Equation

$$\frac{C^+_{ads}}{Ca^{+2}} = k \frac{a_c^+}{\sqrt{a_c^{+2}}} \qquad \frac{a_c^+}{\sqrt{a_c^{+2}}} = AR$$

Where:

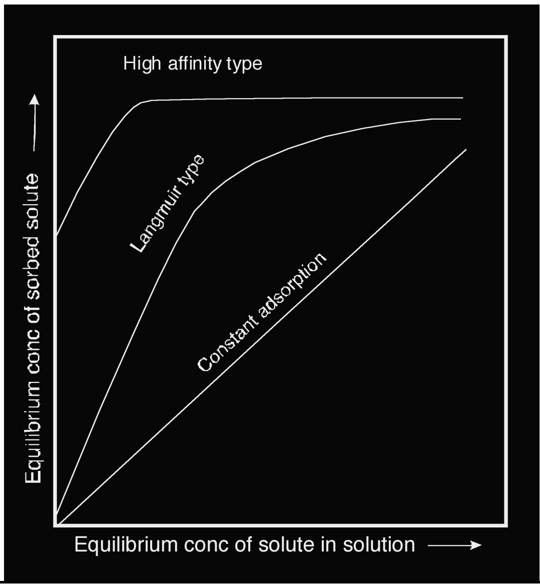
C^+_{ads}, C^{+2}_{ads} = adsorbed monovalent and divalent cations

a_c^+ , a_c^{+2} = activity of the monovalent and divalent cations

AR = Activity ratio = ratio of the activities of the two cation species in the equilibrium solution

k = Gapon or selectivity coefficient

GENERAL ADSORPTION ISOTHERMS OF THREE CLASSICAL TYPES



What is significance of different types?

IMPORTANT SOIL CHARACTERISTICS

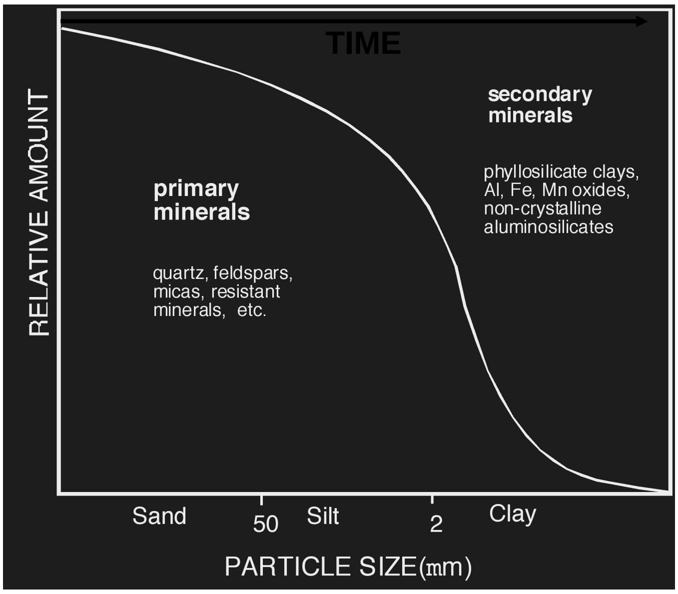
- **Soil texture and clay minerals**
- **Soil structure**
- **Soil water**
- **Soil atmosphere**
- **Soil pH**
- **Salinity**

SOIL COMPOSITION:
Mineral soil particles

Sand - (coarse particles):
50 to 2000 micrometers (µm) diameter
Silt - (medium sized particles):
2 to 50 µm diameter

Clay - (fine particles):
< 2 µm diameter

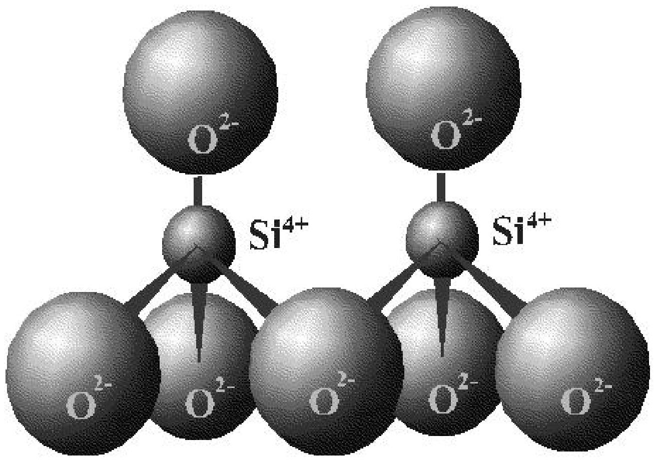
RELATIVE ABUNDANCE OF PRIMARY AND SECONDARY MINERALS



SOIL CLAY MINERALS

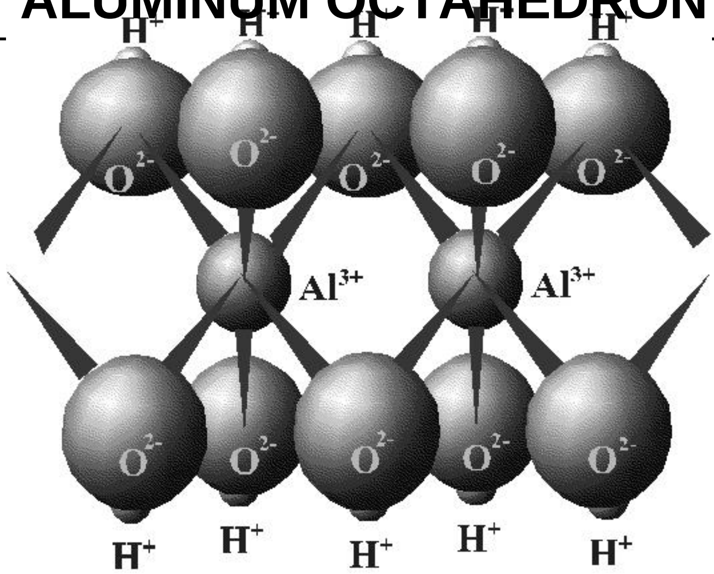
- Layered silicate minerals (most important)
- Basic building blocks:
  - Silica tetrahedron
  - Aluminum octahedron
- Bond sharing is key to structural properties
  - Most bond sharing is <u>within</u> layer

SILICA TETRAHEDRON



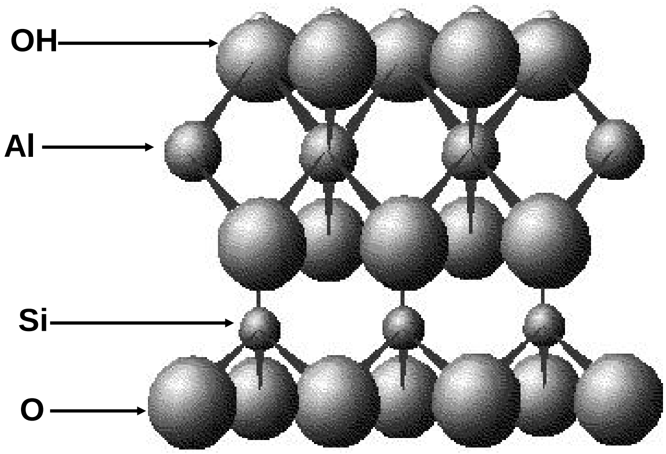
Two tetrahedral units - sharing of Si and most O

ALUMINUM OCTAHEDRON

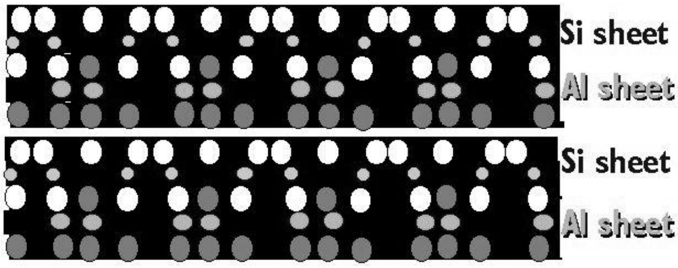


Two octahedral units - sharing of Al and most OH

TETRAHEDRON PLUS OCTAHEDRON

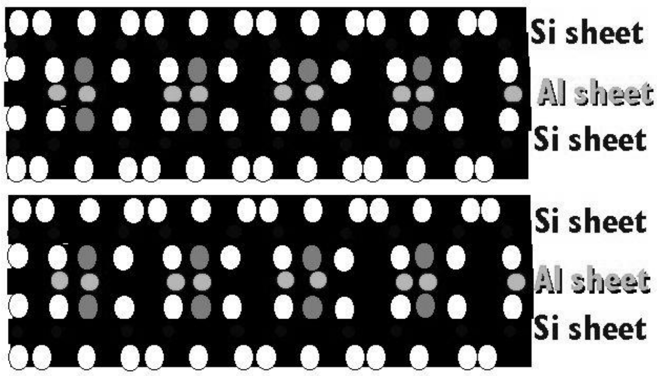


1:1 TYPE CLAY



I:I type clay - kaolinite

2:1 TYPE CLAY

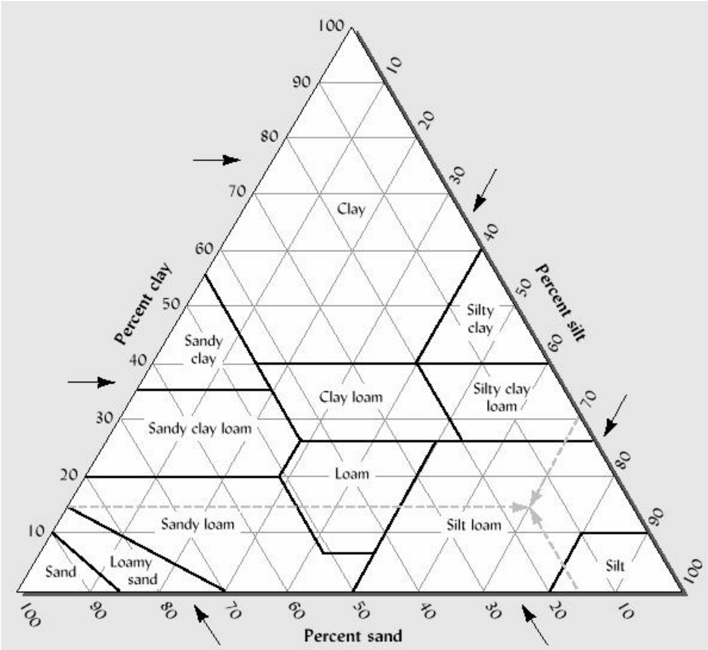


2:I type clay - montmorillonite

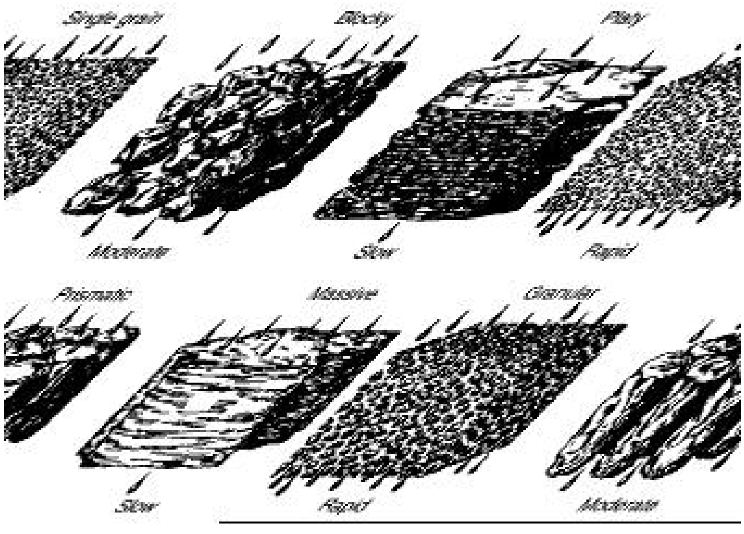
SOIL TEXTURAL CLASSES

The major soil textural classes are defined by the percentages of sand, silt, and clay according to the heavy boundary lines shown on the textural triangle.

(Brady & Weil, FIG 4.6)



SOIL STRUCTURE AND PERCOLATION OF WATER



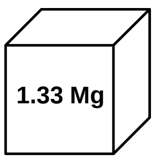
SOIL COMPACTION

- **Define/describe/explain**
- **What are the properties of a compacted soil?**
- **How does compaction affect the soil environ?**

SOIL BULK DENSITY

In field, 1 m^3 of Soil:

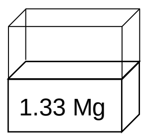
Solids and
Pore Spaces



All Solids Compressed
To Bottom:

1/2 Pore Spaces

1/2 Solids



$$D_b = \frac{\text{Wt. Oven dry soil}}{\text{Volume of soil}}$$

$$D_b = \frac{1.33}{1} = 1.33 \text{ Mg m}^{-3}$$

Mg - megagram - 10^6 g

Solid Particle Density:

$$D_p = \frac{\text{Weight of solids}}{\text{Volume of solids}}$$

$$D_p = \frac{1.33}{0.5} = 2.66 \text{ Mg m}^{-3}$$

SOIL BULK DENSITY

SOIL TYPE	BULK DENSITY
Clay, clay loam, silt loam	1.00 - 1.55 Mg m^{-3}
Sands, sandy loams	1.20 - 1.75 Mg m^{-3}
Very compact subsoils	> 2.0 Mg m^{-3}
Root growth impairment	=u1.6 Mg m^{-3}

High Db restricts water and air movement and root growth

High Db could maintain wet soils and enhance anaerobic conditions develop

SOIL BULK DENSITY

Factors that will improve (lower) Bulk Density:

- **increased organic matter content**
- **healthy root growth and soil penetration**
- **physical disturbance, especially with incorporation of O.M.**

Practical applications:

- **calculation of amount of fill soil needed**

SOIL BULK DENSITY

Calculation of needed soil:

- **Units: kg/m^3 or lb/yd^3 of lb/ft^3**
- **Typical medium-textured soil, Db = 1.25 Mg/m^3, which is 1250 kg/m^3 or 2105 lb/yd^3**
- **Half-ton (1000-lb) load capacity pickup truck carries < 0.5 yd^3 of this soil**
- **Remember that soil volume expands (=N125%) when removed from natural setting**

SOIL COMPOSITION: PORE SPACES

Approximately 50% of soil volume

Air or water depending upon conditions

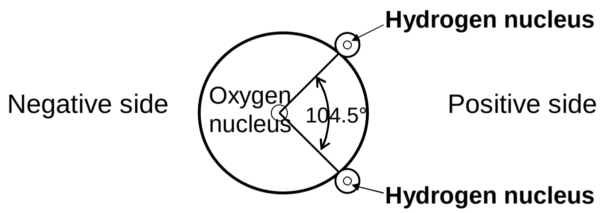
Affects O_2 diffusion to roots

Clay soils: small pores hold water tightly

Sandy soils: rapid drainage, little remains

SOIL WATER

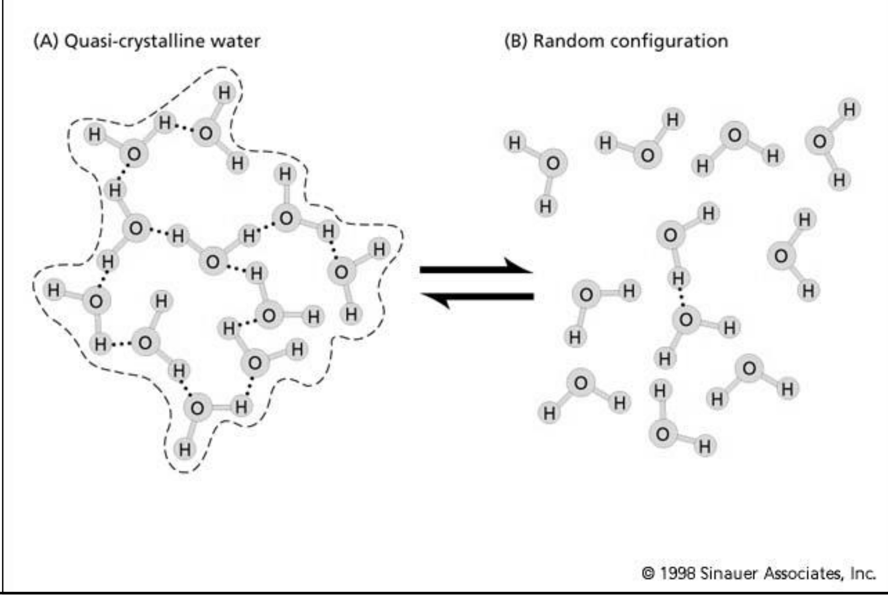
Polarity of the Water Molecule



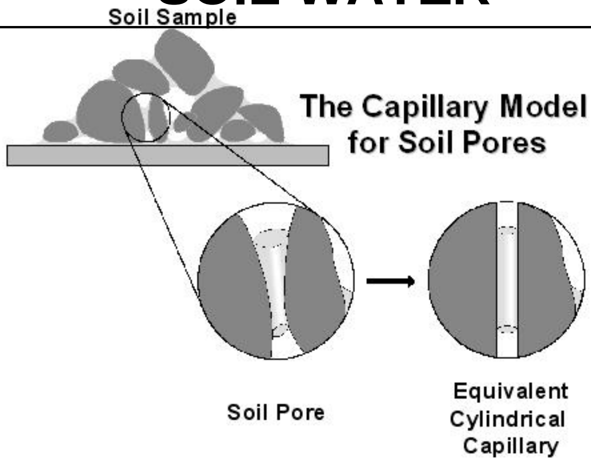
Properties of:

H-bonding - bonding of H^+ to O^{-2}
Cohesion - like-to-like - H_2O to H_2O
Adhesion - unlike - H_2O to (soil) solids
Surface tension - H_2O to H_2O vs H_2O to air
Capillarity - H_2O rise in capillary tube

SOIL WATER



SOIL WATER



Conceptual representation of soil pores as equivalent capillaries. This concept is applied in many of our conceptual and mathematic/simulation models to describe and quantify soil hydraulic properties.

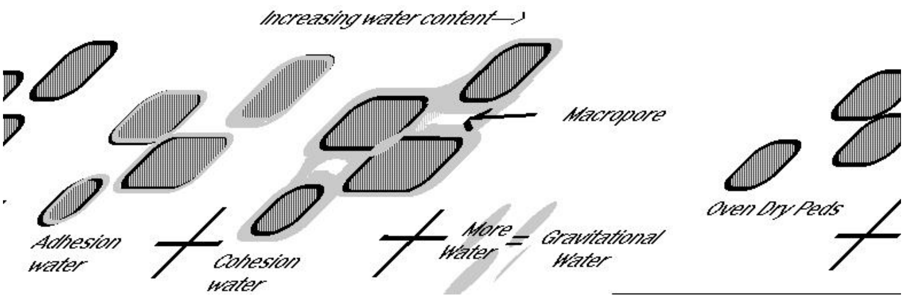
Source: Or and Wraith, 1999

SOIL WATER

- **Saturation (flooding rain or irrigation):**
  - **all soil pores filled with water**
- **Field capacity:**
  - **moisture content when excess has drained away (from gravity force)**
- **Permanent wilting capacity:**
  - **soil so dry that plants cannot remove remaining water**

SOIL WATER

Soil Tension and Availability of Soil Water



SOIL ATMOSPHERE

Characteristics, Compared to Open Atmosphere:

- **Higher concentration of water vapor (may be ~ 100%)**
- **Higher concentration of CO_2**
- **Lower concentration of O_2 - may become anoxic**
- **Variable composition of soil gases**

SOIL pH

$$pH = \log\left(\frac{1}{[H^+]}\right)$$

or:

$$pH = -\log [H^+]$$

Example:

$[H^+] = 0.001$ or 10^{-3} *M*, pH = 3

[H+] = 10 or 10^{1} *M*, pH = -1

pH scale on instruments is 0 to 14 - why?

SOIL pH, continued

Types of Acidity:

- **Actual (active) - H^+ in soil solution**
- **Potential (reserve) - H^+ and Al^{+3} sorbed to colloids**

Concept of Buffering:

- **Resistance to change in soil pH**
- **Occurs with high amounts of exchangeable H^+**
- **Greatest (potential) for soils of high CEC**

SOIL pH, continued

Sources of Soil Acidification

- H^+ from O.M. decomposition
- H^+ from rainfall (acidic and acid)
- H^+ from microbial activity
- H^+ from hydrolysis of Al^{+3}

SOIL pH, continued

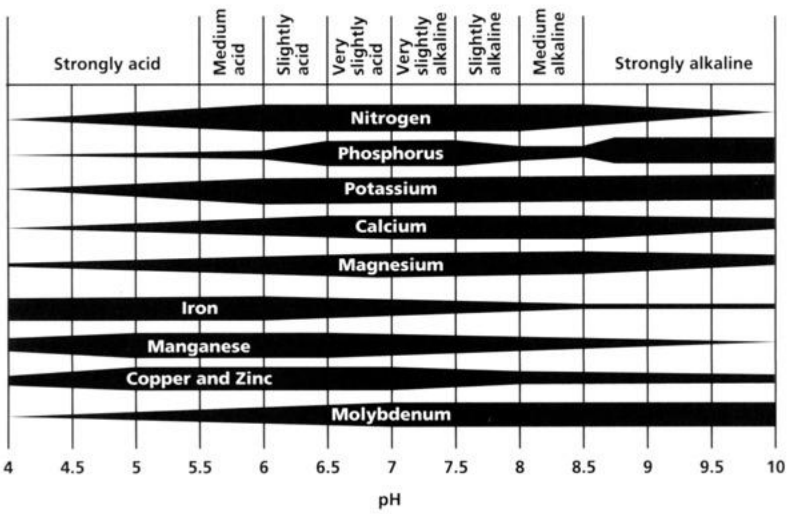


FIGURE 1. The availability of a number of ions in the soil as dependent on soil pH.

Solubility of Al

- Soils < pH 5.5 cation exchange sites occupied by Al^{3+}
  - Replaces Mg^{2+} & Ca^{2+}
  - Strong adsorber of P & Mo
- % exchangeable Al^{3+} correlated with pH (Fig. 2.20).

AL INHIBITION OF ROOT GROWTH

- Severity of inhibition is indicator of genotypic differences in Al toxicity
- Drought stress increased
- $AlOH^{+2}$ more toxic than Al^{+3}
- Many theories, but none confirmed.

AMELIORATION OF AL TOXICITY WITH $CASO_4$

- $CaSO_4$ ameliorates phytotoxicity of Al.
- $CaSO_4$ because of higher water solubility and S.
- Better than $CaCO_3$. (Why?; where to use?)
- Addition of O.M. ameliorates phytotoxicity of Al. (How?)

SALINE SOILS

- Saline areas
  - Salt marshes - Temperate Zone
  - Mangrove swamps - Sub Tropics and Tropics
  - Interior salt marshes adj salt lakes
  - Semiarid & arid regions
    - Rainfall insufficient for leachng
  - Urban construction sites

SALINITY A SERIOUS PROBLEM

- Frequently destroyed ancient agrarian societies
- Large areas of Indian sub-cont lost
- 15 M Ha of Pakistan canal-irrigated
- 33% irrigated land affected in world
  - More salting out than new land
  - Even "good" water adds salt requiring leaching

DEFINITION OF A SALINE SOIL

- Saturation extract (solution extracted from a soil at its saturation water content) of a saline soil has an electrical conductivity (EC) > 4 mmho cm^{-1} or 4 deciSiemens m^{-1} (4 $dS \cdot m^{-1}$)
  - ~40 mM NaCl $liter^{-1}$
  - Exchangeable Na % (ESP) < 15

MAJOR CONSTRAINTS - SALINITY

- Drought stress
  - Low (more negative) H_2O potential
- Ion toxicity associated with excessive uptake of Cl^- and Na^+
- Nutrient imbalance
  - Depression of uptake and/or shoot transport
  - Impaired internal distr (Ca in particular)

IRRIGATION WATER QUALITY

- Salinity
  - Class 1 (C-1) Low Salinity - Safe
  - Class 2 (C-2) Medium Salinity- Leaching needed
  - Class 3 (C-3) High Salinity - Special drainage needed
  - Class 4 (C-4) Very High Salinity - Only very tolerant crops
- Consideration for Reuse Water

Factors Relating to Nutrient Availability

- Contact theory accounts for some K
- Mass flow (movement with water)
- Diffusion
  - Ions from higher to lower conc.
  - High plant requirement
    - Strong sink
      - Adjacent soil nutrients?

NUTRIENT AVAILABILITY, continued

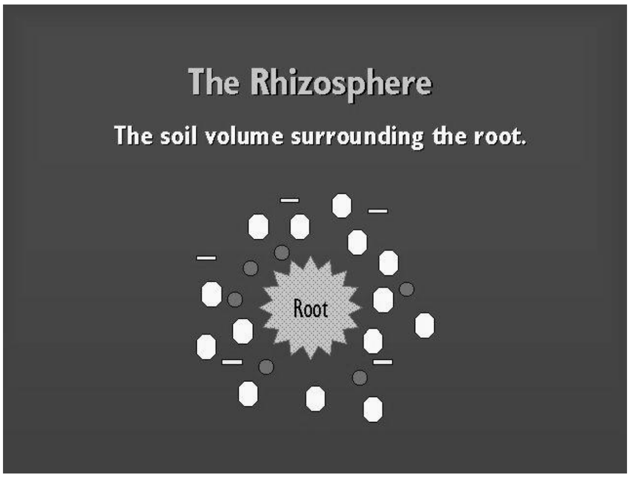
- Soil Solution
  - Comparisons must be at FC
  - Some ions reach conc higher than solubility products
  - NO_3 - rapid fluctuation
  - Quantity - amount of available nutrient
  - Intensity - retention strength of nutr. by soil
- pH influences
  - soil ion concentration
  - nutrient availability

NUTRIENT AVAILABILITY, continued

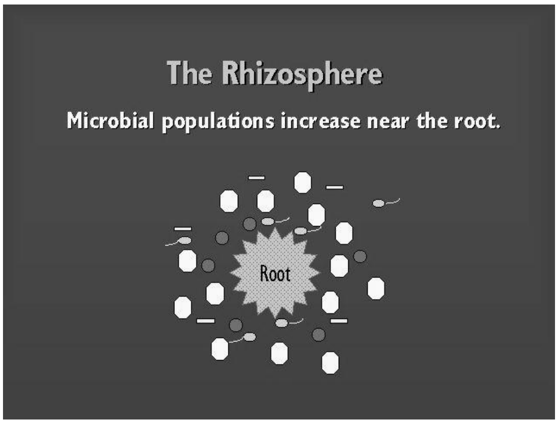
- **Ability of soil to buffer**
- **Soil diffusion condition**
- **Root growth & develop. - root density**
  - **Variability with type and species**
    - **Monocot vs. diacot**
    - **Annuals vs. perennials**
  - **Compaction zones**
  - **Available nutrient variability**
  - **Available water variability**

NUTRIENT AVAILABILITY, continued

Root exudation and the rhizosphere



NUTRIENT AVAILABILITY, continued



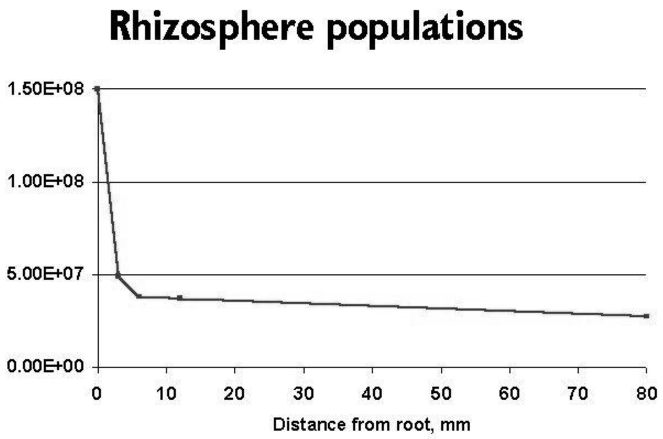
Root Exudates:

- Polysaccharides
- Amino acids
- Sugars
- Organic acids

Gen. Lower pH

Rhizosphere important to plant health:
- disturbed during transplanting
- reason for extra care after transplanting

NUTRIENT AVAILABILITY, continued



NUTRIENT AVAILABILITY, continued

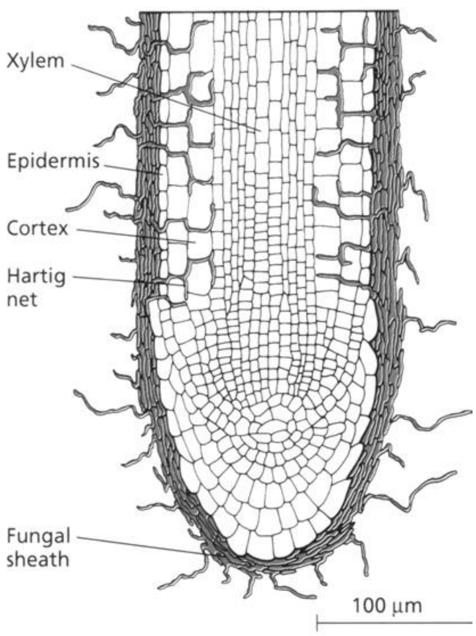
Mycorrhizal fungi:

Ectotrophic - fungi hyphae grows between cortical cells of roots and around roots

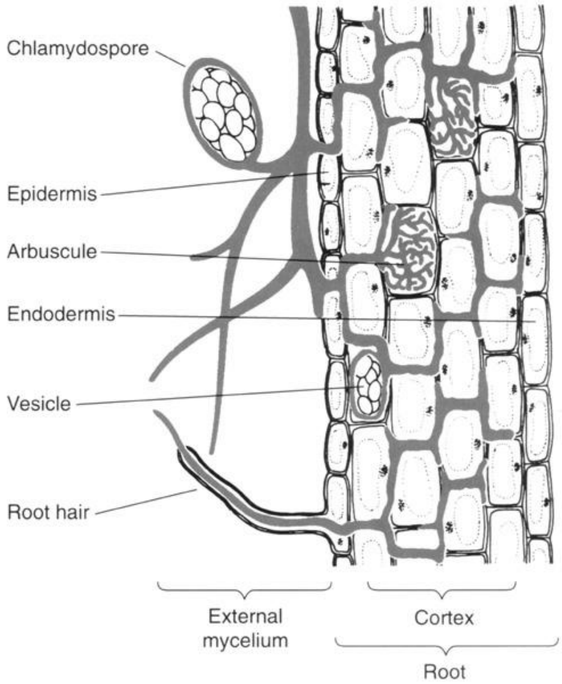
Endotrophic - fungi hyphae penetrate cells of root cortex and grow within

Predominate type is vesicular arbuscular mycorrhiza (VAM) (Text, Fig. 2.31)

Ectotrophic Mycorrhizal Fungi



Endotrophic Mycorrhizal Fungi



NUTRIENT AVAILABILITY, continued

Mycorrhizal fungi:

- Important for adaptation to acid mineral soils with low P & high Al
- Evident in cassava (coarse root syst)
- Important where root system
  - is impaired by Al toxicity
  - No enhanced organic acids
- Ectomycorrhiza on tree sp dec Al tox

Determination of Nutrient Availability in Soil

- **Estimation of cations**
  - **Available cations**
    - **In solution**
    - **Adsorbed - exchange complexes**
      - **Removed by excess cations**
      - **K^+ & Mg^{2+}**
        - » **replaced by NH_4^+ or NH_4Cl**

DETERMINATION OF AVAILABLE NUTRIENTS, cont.

- **Estimation of phosphates**
  - **Acid extractant (Bray's; Truog's)**
  - **Varying availability**
    - **Ca, Fe, Al, or Org. phosphates**
  - **0.5 M $NaHCO_3$**
    - **Extractant in calcareous soils**
  - **H_2O best in greenhouse media**
- **Estimation of available N**
  - **Electro-ultrafiltration technique**
  - **NaCl + $CaCl_2$ extraction**

TRACER TECHNIQUES

Radiotracer : radioactive isotope of an element under investigation

Advantage : ease and sensitivity of measurements

<u>For a system at equilibrium:</u>

$$\frac{\text{Total unlabelled substance}}{\text{Total labeled substance}} = \frac{\text{Unlabelled substance in sample}}{\text{Labeled substance in sample}}$$

<u>For a soil at equilibrium:</u>

$$\text{M exch.} + \text{M* sol.} \rightleftharpoons \text{M* exch.} + \text{M soln.}$$

TRACER TECHNIQUES

<u>Technique used to determine “soil labile pools” of:</u>

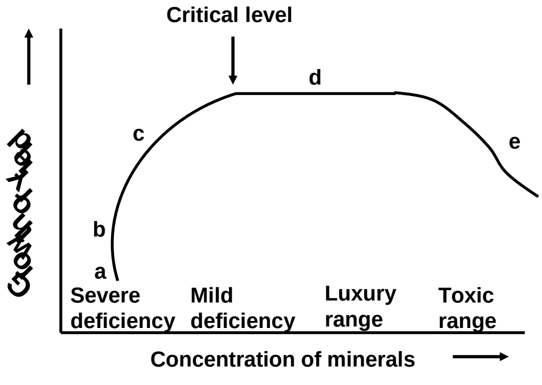
P - Larsen (1972)*
K - Graham and Kampbell (1968)
Co, Mn, Fe- Lopez and Graham(1970)
Fe, Mn, Zn - Rule and Graham (1974)*

***Also included plant growth**

TISSUE ANALYSIS

- **"Ask the patient"**
- **Reflects uptake**
  - **Not ions tied to the soil**
- **Less nutrient content variation at critical levels**
- **Perennial plants especially adapted**

TISSUE ANALYSIS



Relationship between the nutrient content of the tissue and the growth of the plant. (Fig. 2.34)

TISSUE ANALYSIS

Correct time

Crop	Stage of growth	Plant part	Samples
Tree fruit	Current season July 1-15	Midpoint of new shoots	4 leaves from 10 trees
Raspberry	August 10 to Labor Day	Leaf & petiole #5-12 from tip	2-3 leaves from 10 canes
Strawberry	At renovation before mowing	Young leaves & petiole	2 leaves from 20-25 plants
Grapes	Bearing primary shoots	Petioles from young leaves	5 petioles from 10 vines

DYNAMIC METAL EQUILIBRIUM BETWEEN MAJOR SOIL PHASES VIA THE SOIL SOLUTION