The Tree Dilemma: Grow or Defend

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THE DILEMMA OF PLANTS: TO GROW OR DEFEND

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The Model

What is Soil?

What is the Role of Soil?

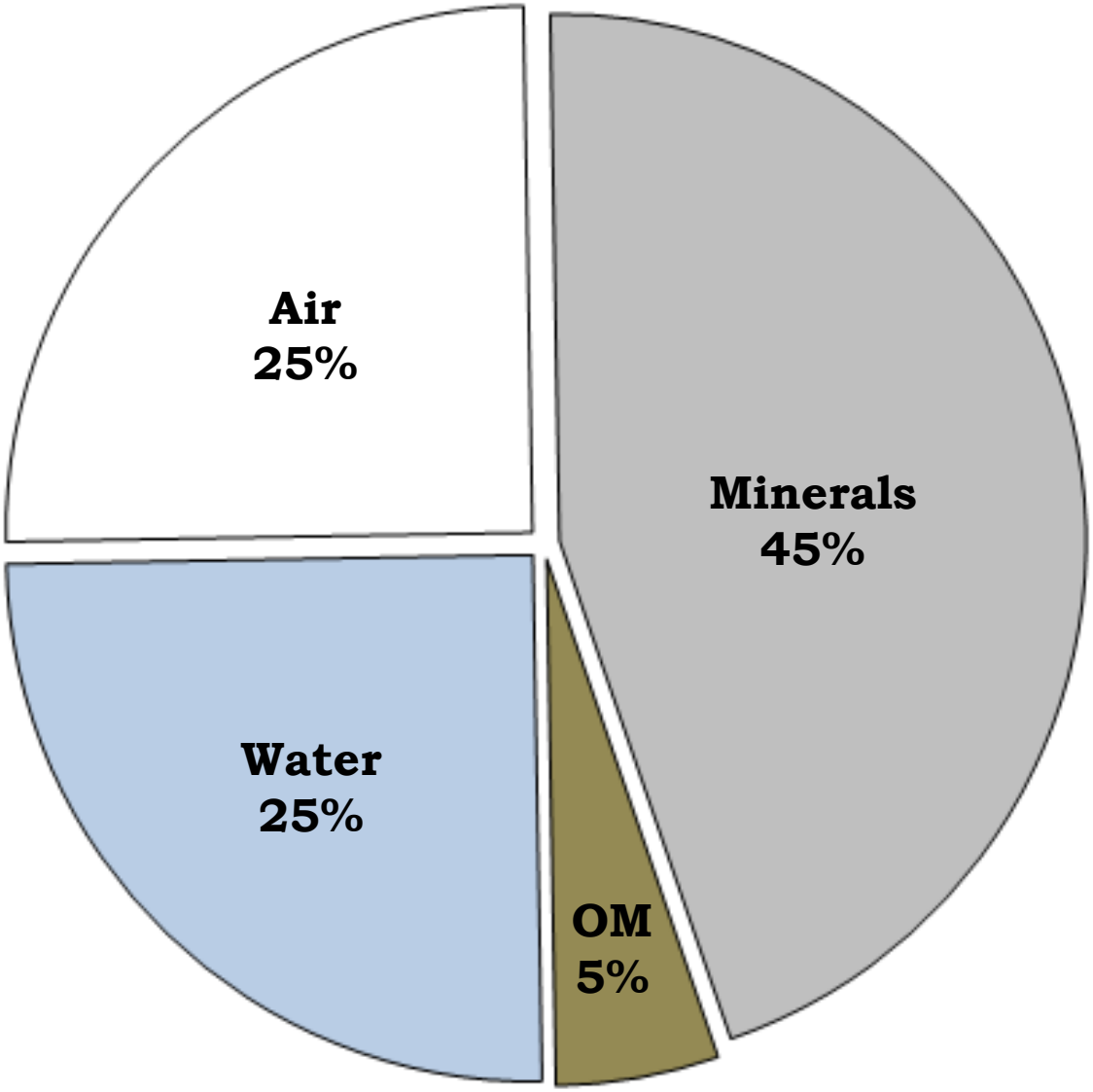
Soils:

Provide elements essential to growth and development

Hold and supply water

As such, soils are physical media and a system

Soil as a Physical Media



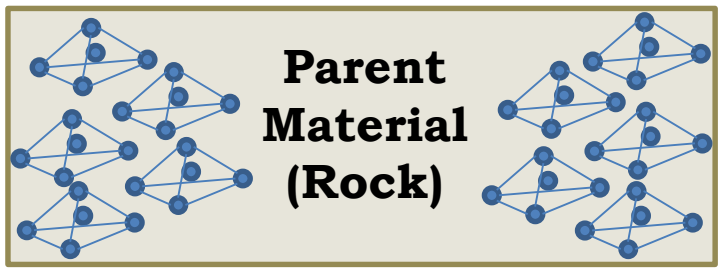
Soil consists of mineral fragments, organic residues, pore spaces, and a multitude of organisms.

Soil develops slowly over time and is always changing

Factors that influence soil development

- **Climate**
- **Parent Material**
- **Biota**
- **Landform**
- **Time**

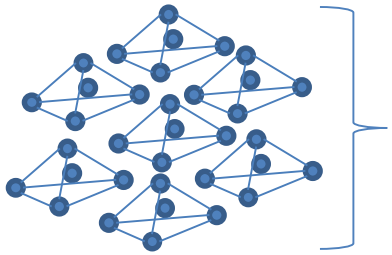
The Mineral Component



Parent materials contain primary minerals

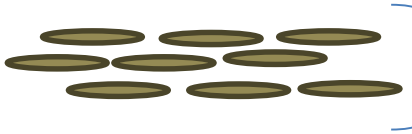
Physical

Weathering



Primary minerals exposed

Chemical Weathering



Secondary Minerals

Clay

Secondary minerals are formed in soil

The Mineral Component

http://geology.fullerton.edu/Faculty/Curtiswilliams/f02miner_files/frame.htm

Weathering of Parent Material

Chemical Weathering

RAIN

Fragments of parent material

Sand/Quartz

Silt

Combine to form Clay

Silica (Si)

Al & Fe Oxides

Available essential elements

Minerals

Fragmented/Fine Parent Material

Bulk Parent Material

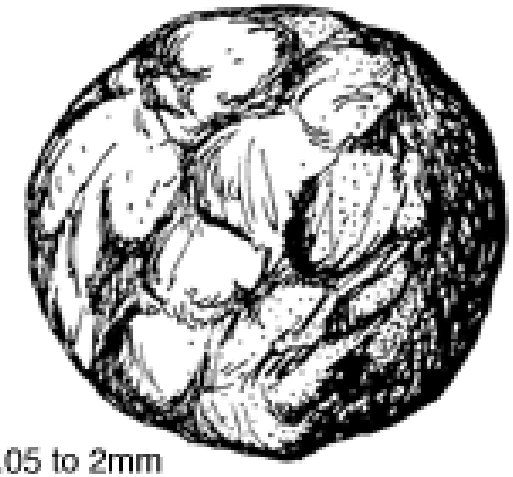
Physical Weathering

Photo: L. Werner, King George Island, Antarctica

Chemical composition of various parent materials

	Igneous Rocks			Sedimentary Rocks		
	Granite	Gabbro	Basalt	Shale	Sandstone	Limestone
SiO_2	73.9	48.4	50.8	58.1	78.3	5.2
Al_2O_3	13.8	16.8	14.1	15.4	4.8	0.8
Fe_2O_3	0.8	2.6	2.9	4.0	1.1	0.5
FeO	1.1	7.9	9.0	2.4	0.3	--
MgO	0.3	8.1	6.3	2.4	1.2	7.9
CaO	0.7	11.1	10.4	3.1	5.5	42.6
Na_2O	3.5	2.3	2.2	1.3	0.4	0.1
K_2O	5.1	0.6	0.8	1.3	0.3	--
P_2O_5	0.1	0.2	0.2	0.2	0.1	0.1
SO_3	--	--	--	0.6	0.1	0.1

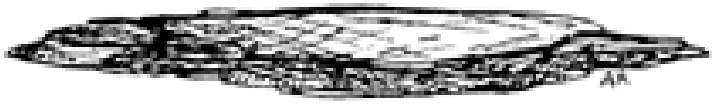
Sources: Bohn et al., 1979; Scheffer et al., 1989



Sand .05 to 2mm
feels gritty

Silt .002 to .05 mm
feels smooth

Clay <.002 mm
feels smooth

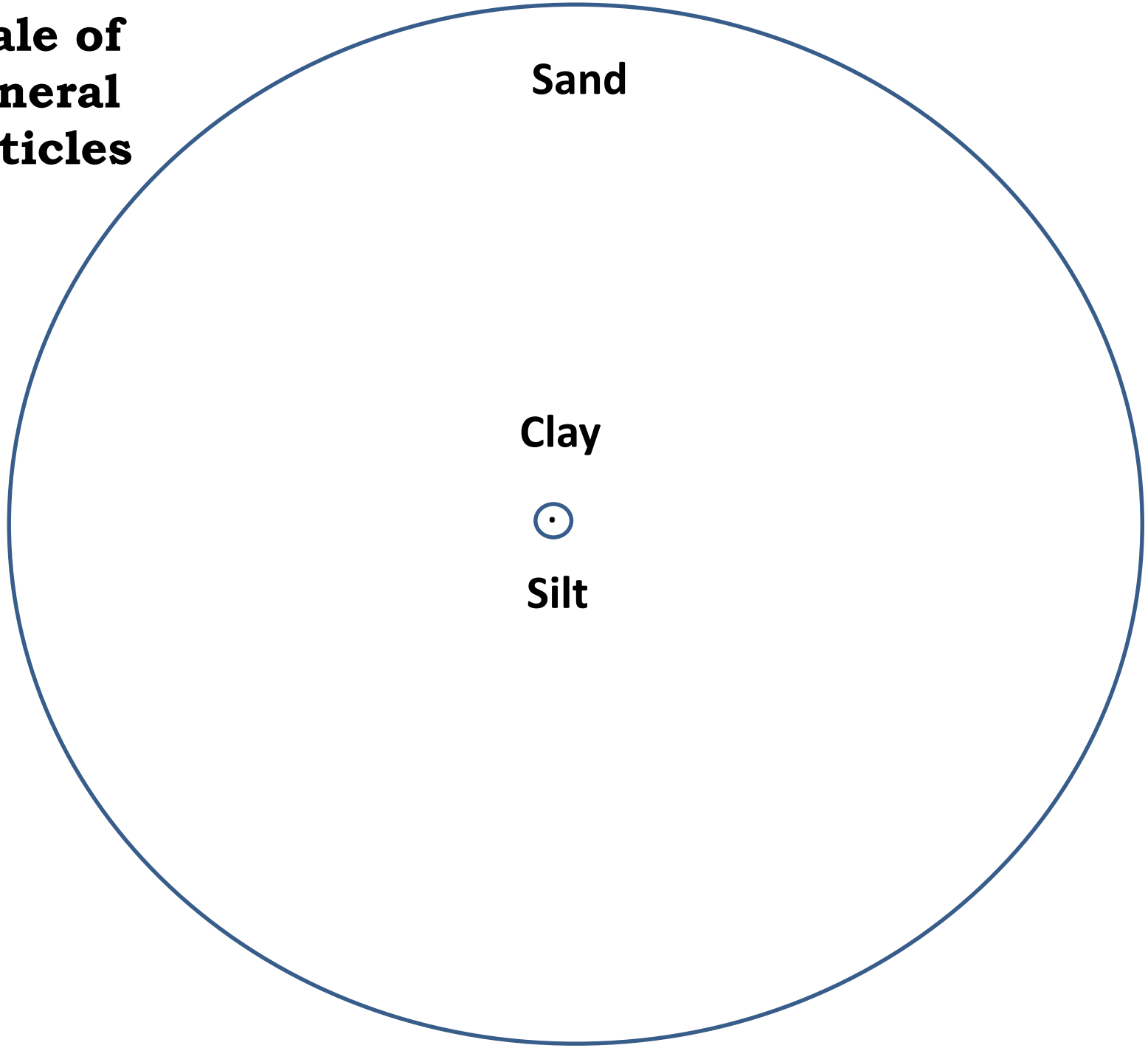


Formed in soil

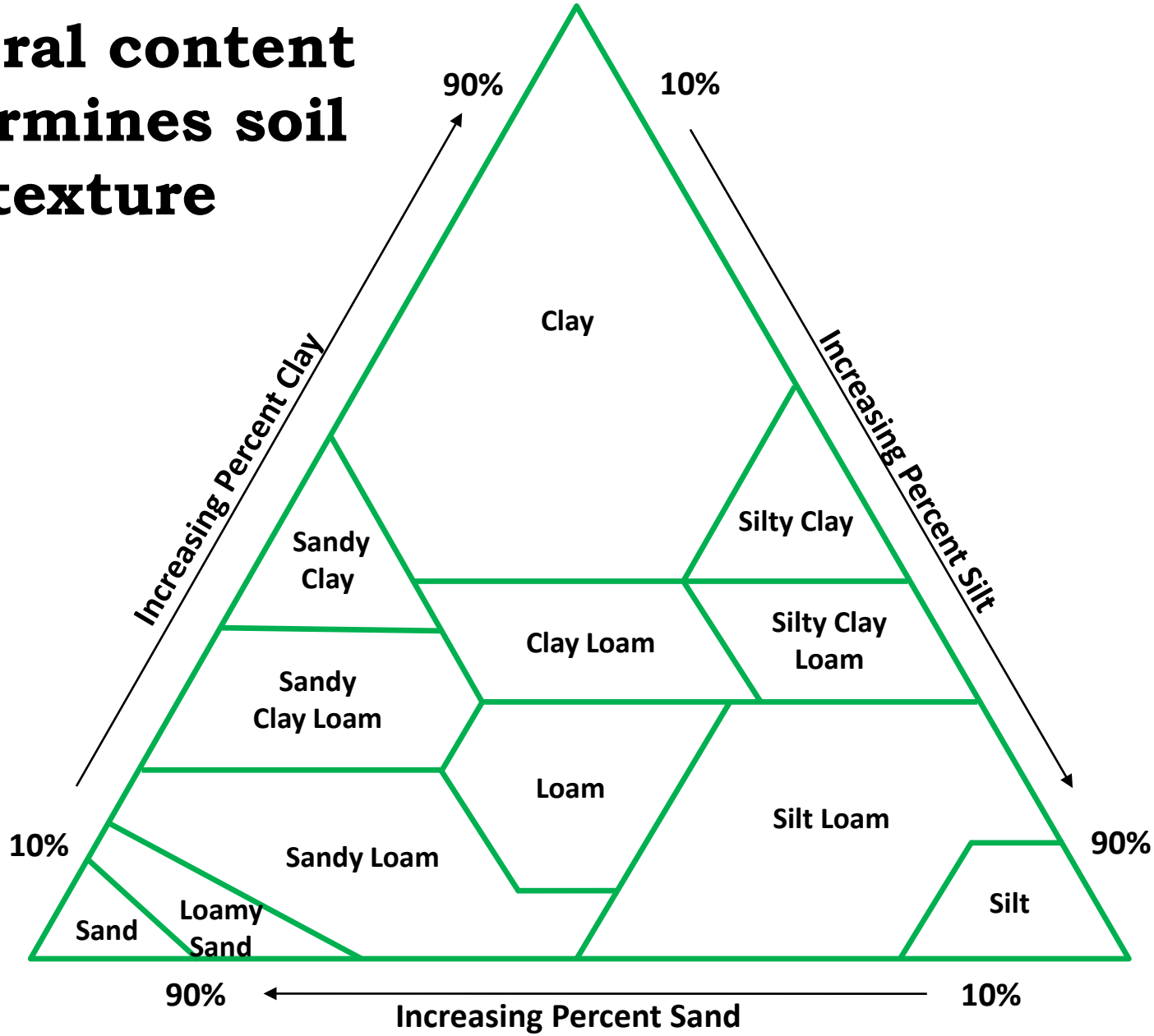
The weathered products of parent materials have different sizes and shapes

The sizes and shapes influence soil texture

Scale of mineral particles



Mineral content determines soil texture



Most soils have a mix of parent materials

Globally, <10% develop in place

Chemical composition reflect the sources of the deposited materials

Loess Deposits, Germany

Glacial Till, Iceland

Glacial Transport, Iceland

Photos by L. Werner

The Pore Space Component

Pore spaces are filled with water or air

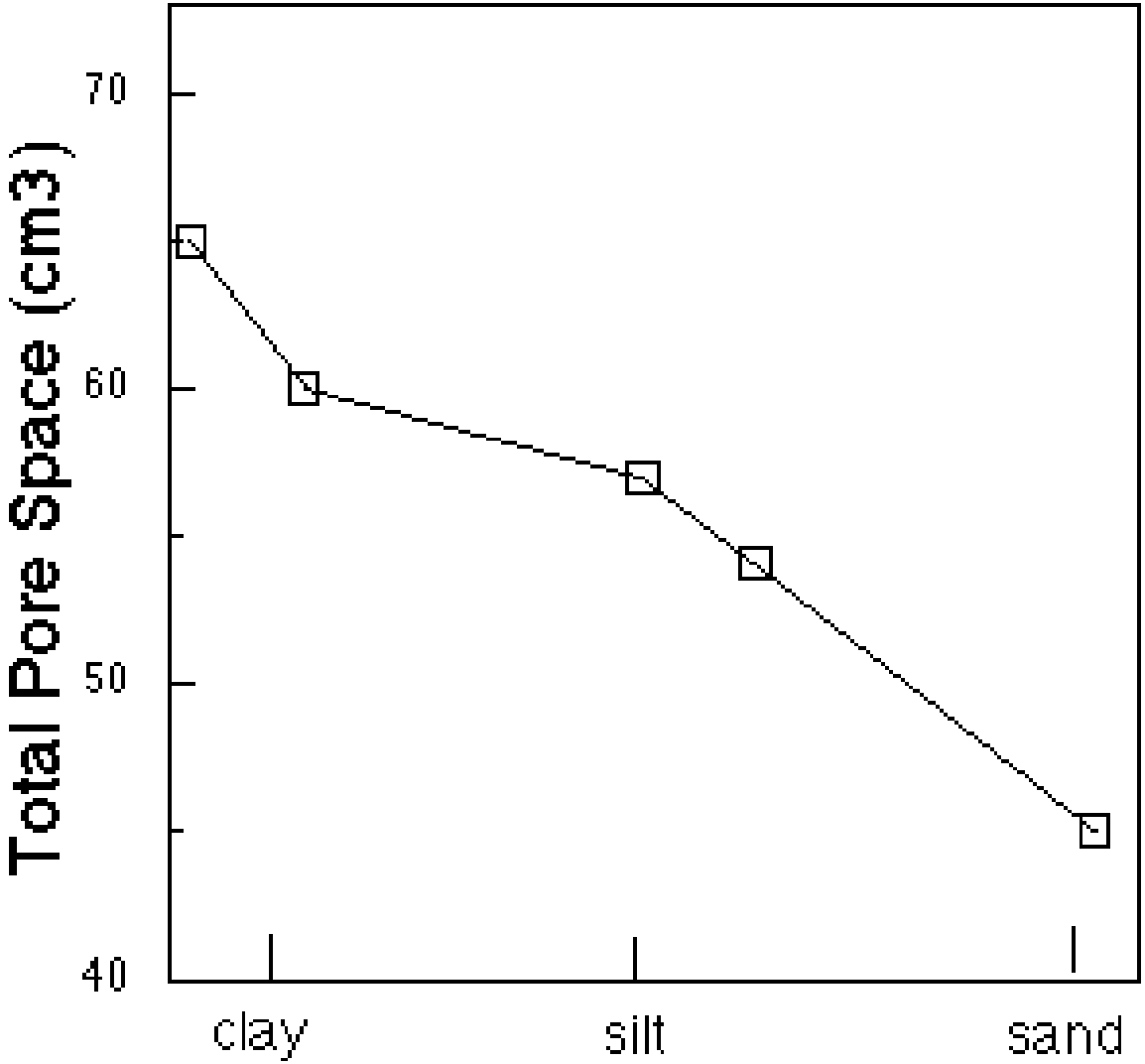
Soil air differs from atmospheric air

	Atmosphere	Soil
Nitrogen	79.0%	79.2%
Oxygen	20.9%	20.6%
Carbon Dioxide	0.03%	0.25%

Increases in CO_2 are the result of root & soil organism respiration

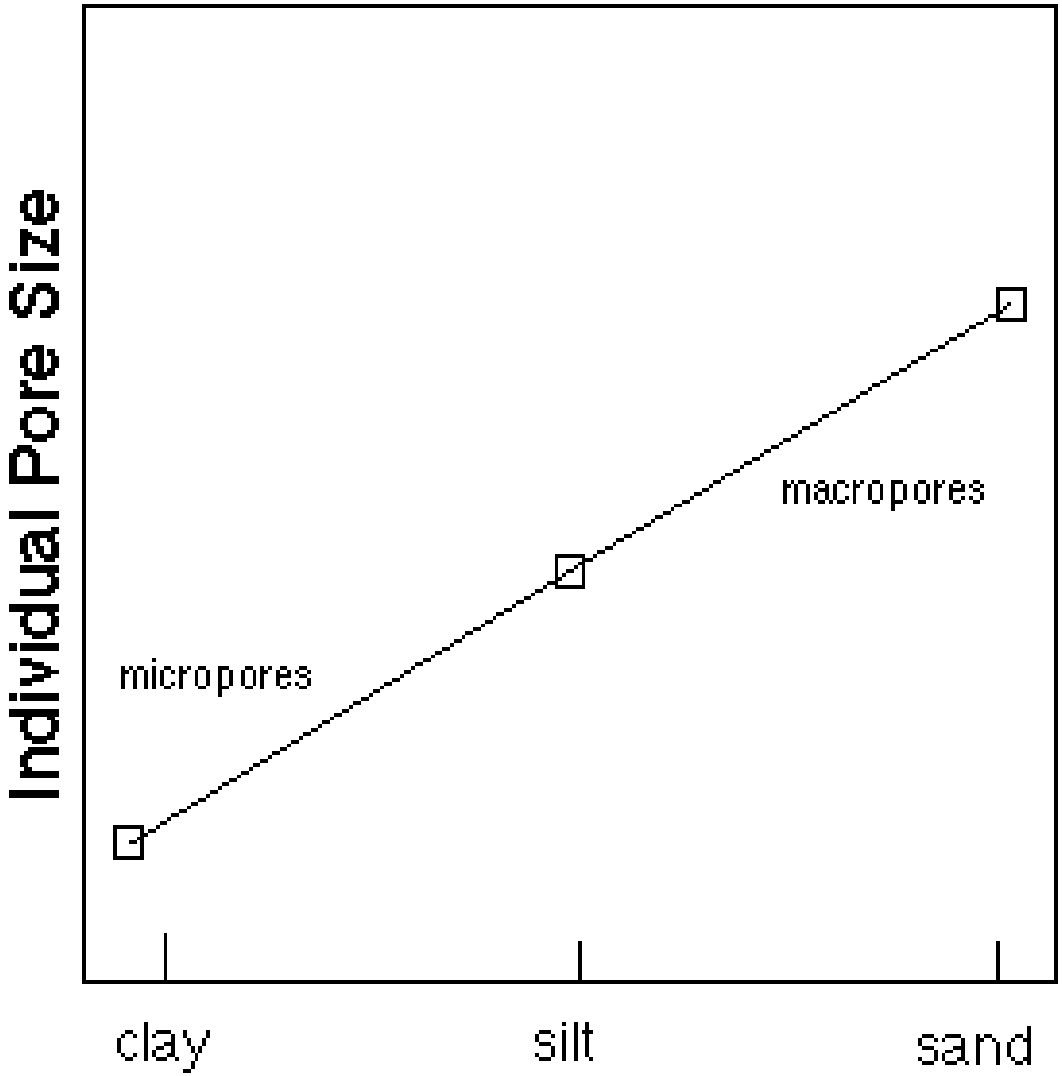
Source: Russell and Appleyard, 1915

Pore space increases as the particles get smaller



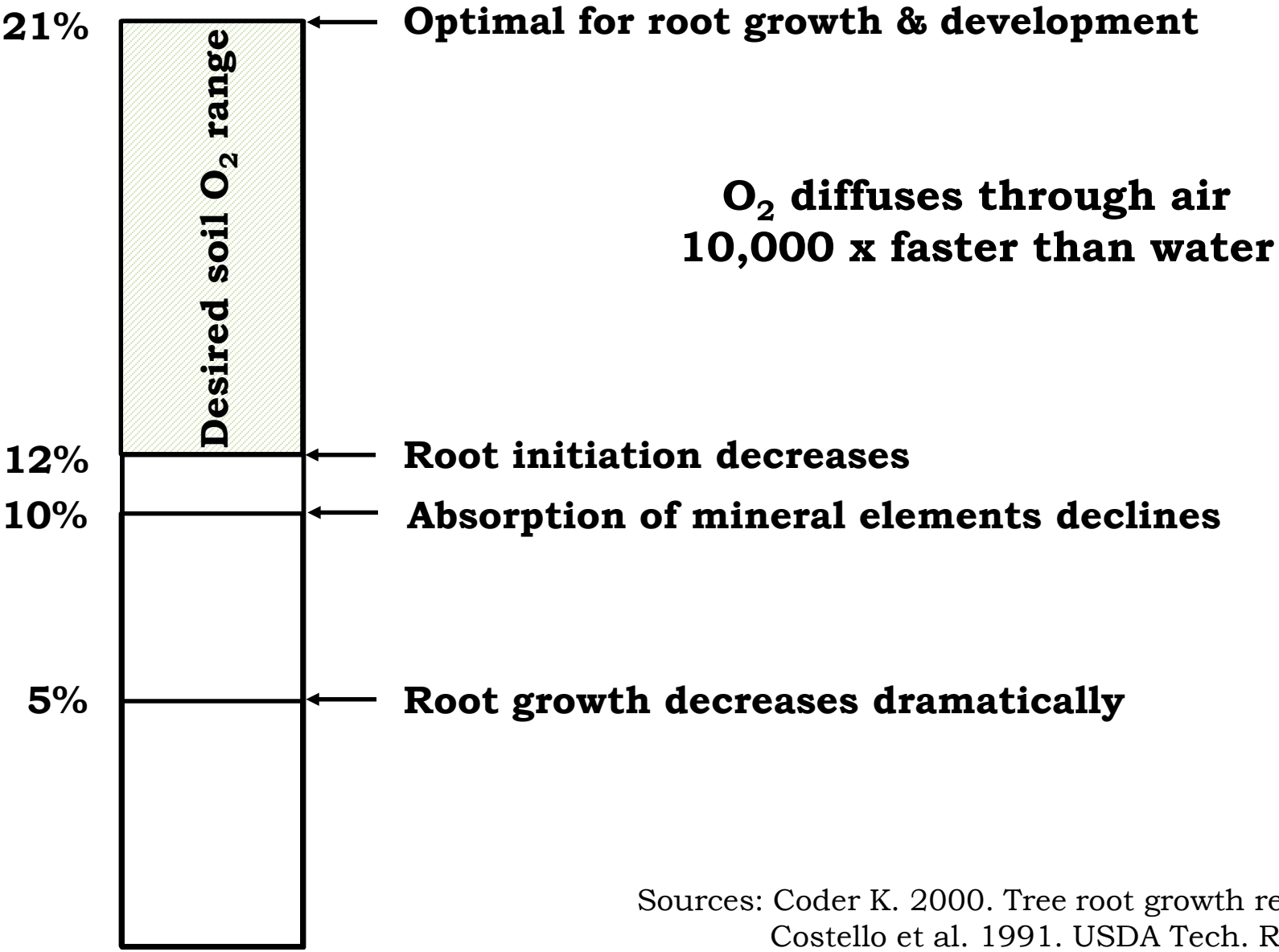
http://soils.cals.uidaho.edu/Soils206/Manual/two.htm

Size of the pore space increases as particles get larger



http://soils.cals.uidaho.edu/Soils206/Manual/two.htm

Increases in water content decrease the air content



Sources: Coder K. 2000. Tree root growth requirements.
Costello et al. 1991. USDA Tech. Rep PSW-126

The Organic Component

Living organisms accumulate carbon and essential mineral elements

Bieszczady Mountains, Poland Photo by L. Werner

> 90% of a trees biomass consists of C, H, and O

Macro-elements make up the bulk of the remainder (e.g. N, Ca, P, and K)

Organic additions differ in their chemical composition

Specifically,

Carbon Content and Nitrogen Content

Type of Organic Input	Carbon : Nitrogen Ratio
Grass Clippings	20:1
<u>Broadleaf Leaves</u> Fresh Dry	 40:1 60:1
Pine Needles	110:1
Sawdust	500-1,000:1
Wood Chips	700-1,250:1
<u>Bark</u> Conifers Hardwoods	 300-725:1 70-250:1
<u>Twigs</u> < 3 mm 3-10 mm > 10 mm	 97:1 104:1 203:1
<u>Roots</u> < 3 mm 3-10 mm > 10 mm	 70:1 81:1 115:1

Generalizations:

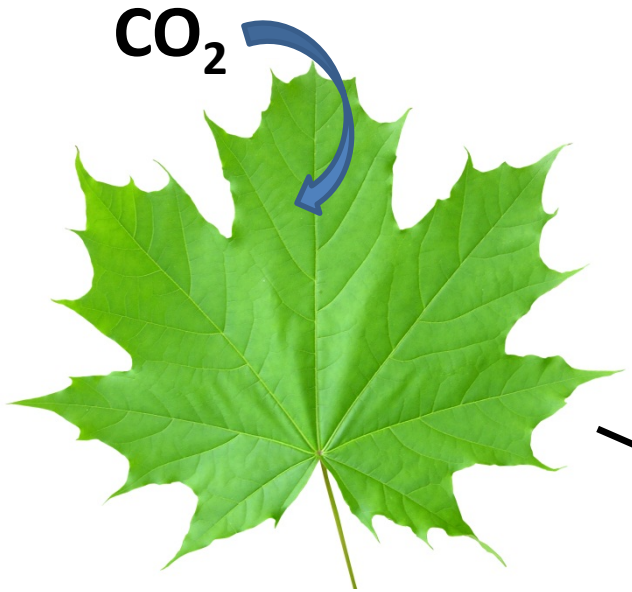
The greener the color, the lower the C: N ratio

Young tissues have lower C:N ratios

Non-structural tissues have lower C:N ratios

Dead biomass is a source of carbon, energy and essential elements for heterotrophic organisms

a.k.a. Decomposers



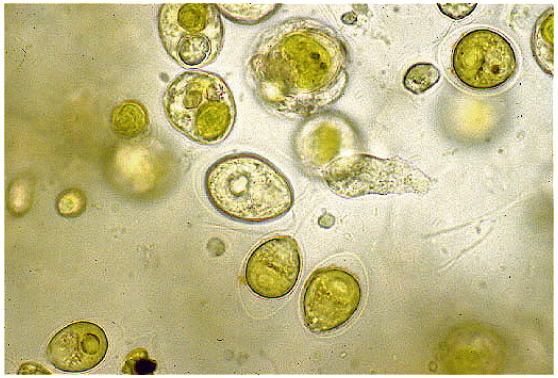
When trees die or shed parts:

Heterotrophic bacteria and fungi attack leaf…

$$CO_2 + H_2O \longleftrightarrow C_6H_{12}O_6 + O_2$$

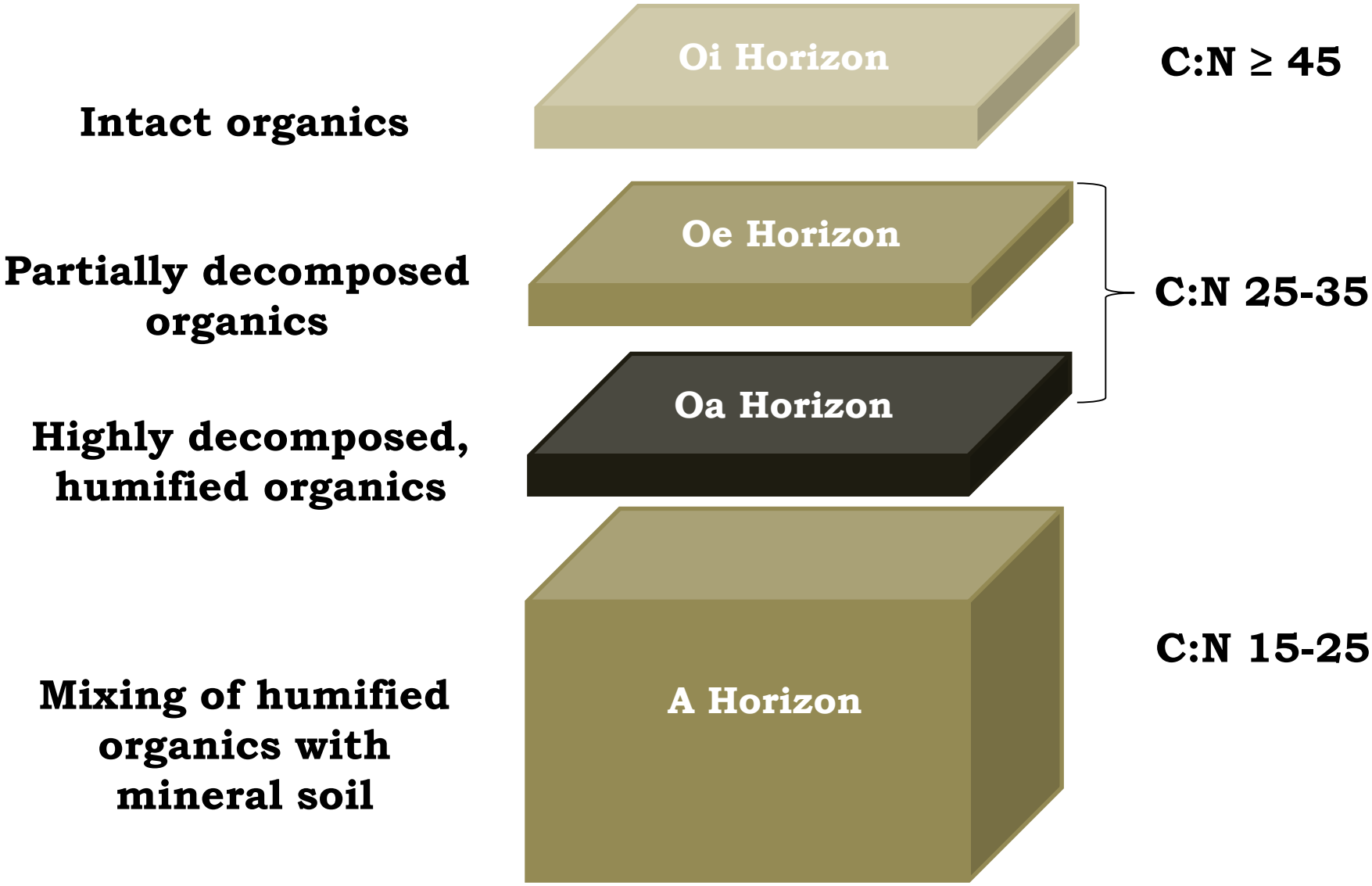
Photosynthesis

Trees are photoautotrophic

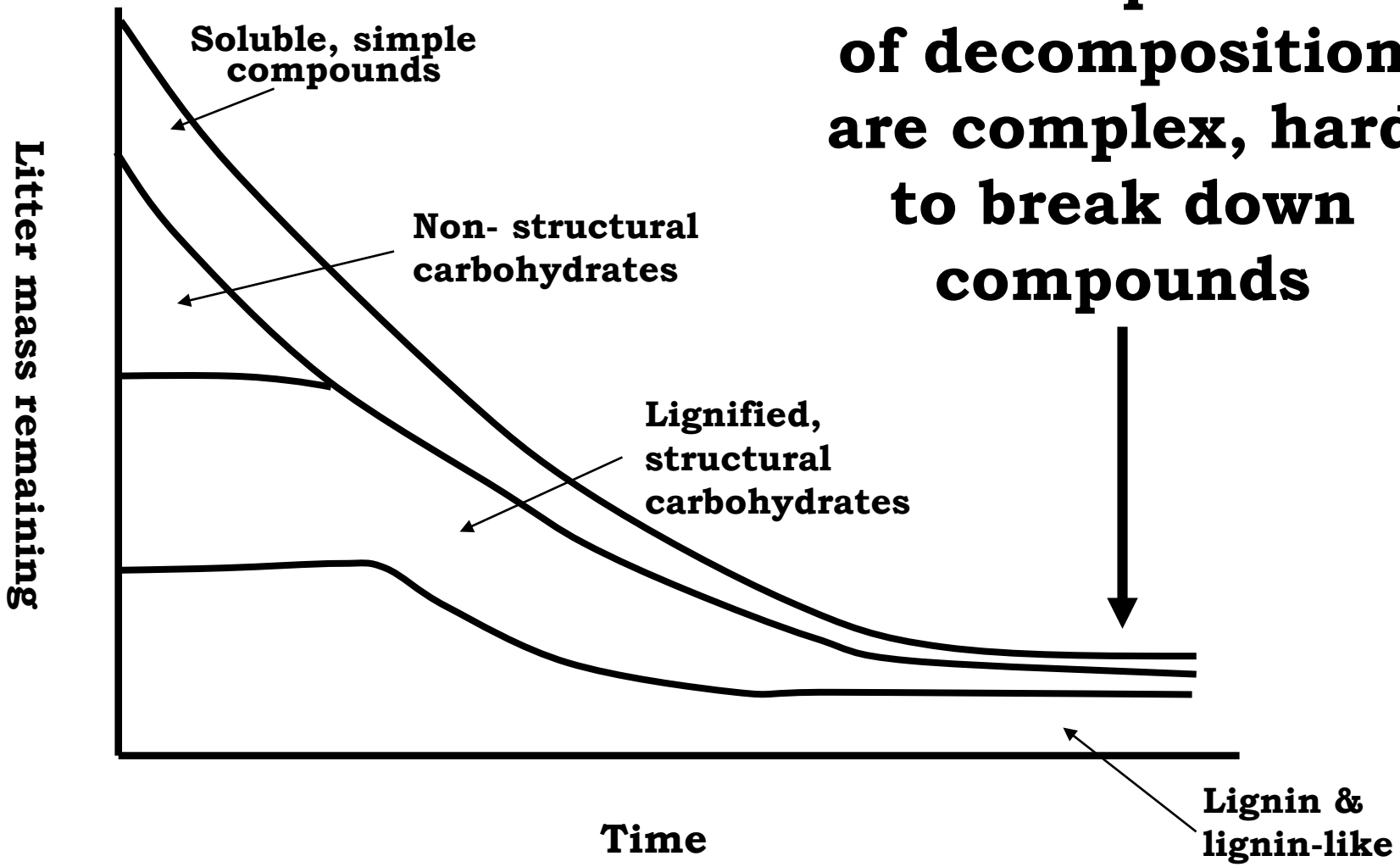


… using carbon from obtained through photosynthesis to build tissues and fuel metabolic processes

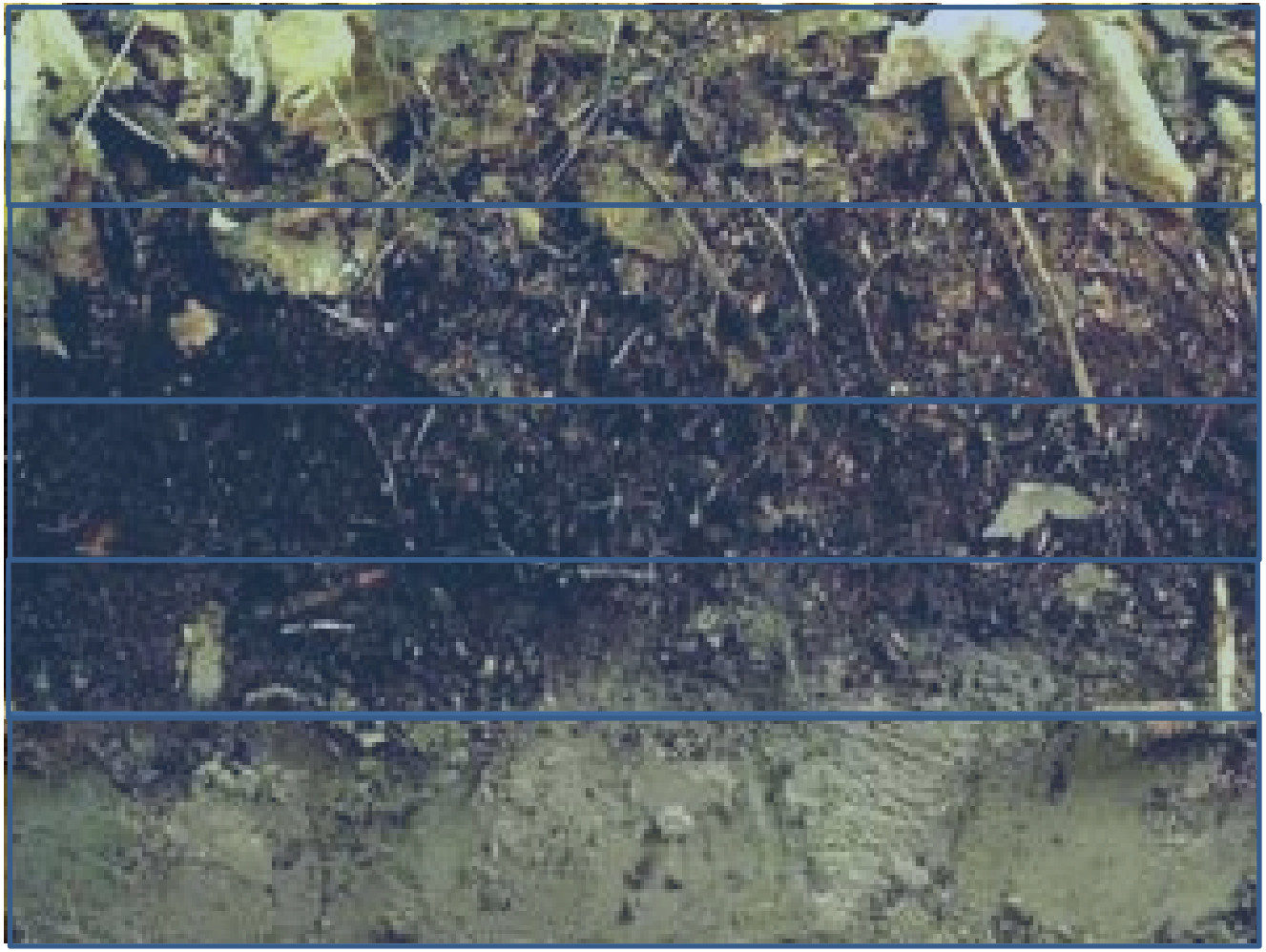
Carbon is transferred/lost from the litter during decomposition



The end products of decomposition are complex, hard to break down compounds



In natural systems organic additions and decomposition are ongoing events



Fresh Organic Addtions

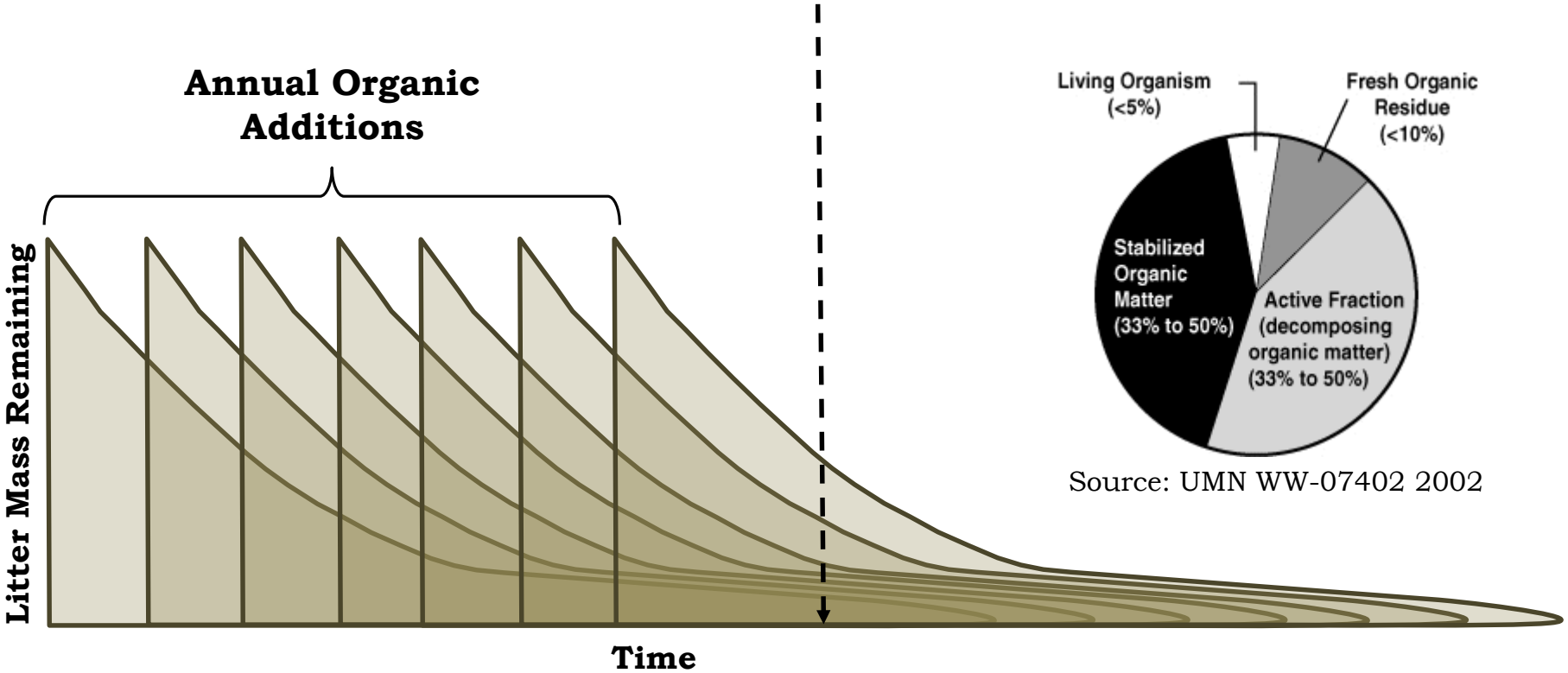
Partially Fragmented

Highly Fragmented

Decomposed OM & Mineral Soil

Mineral Soil

At any point in time, the organic fraction of the soil is a mix of compounds in various stages of decomposition



Source: UMN WW-07402 2002

As a result, there is a diverse soil microbial community

Soil Development

Early soil consists predominantly of minerals

Photos by L. Werner, Mýrdalsjökull, Iceland 2004.

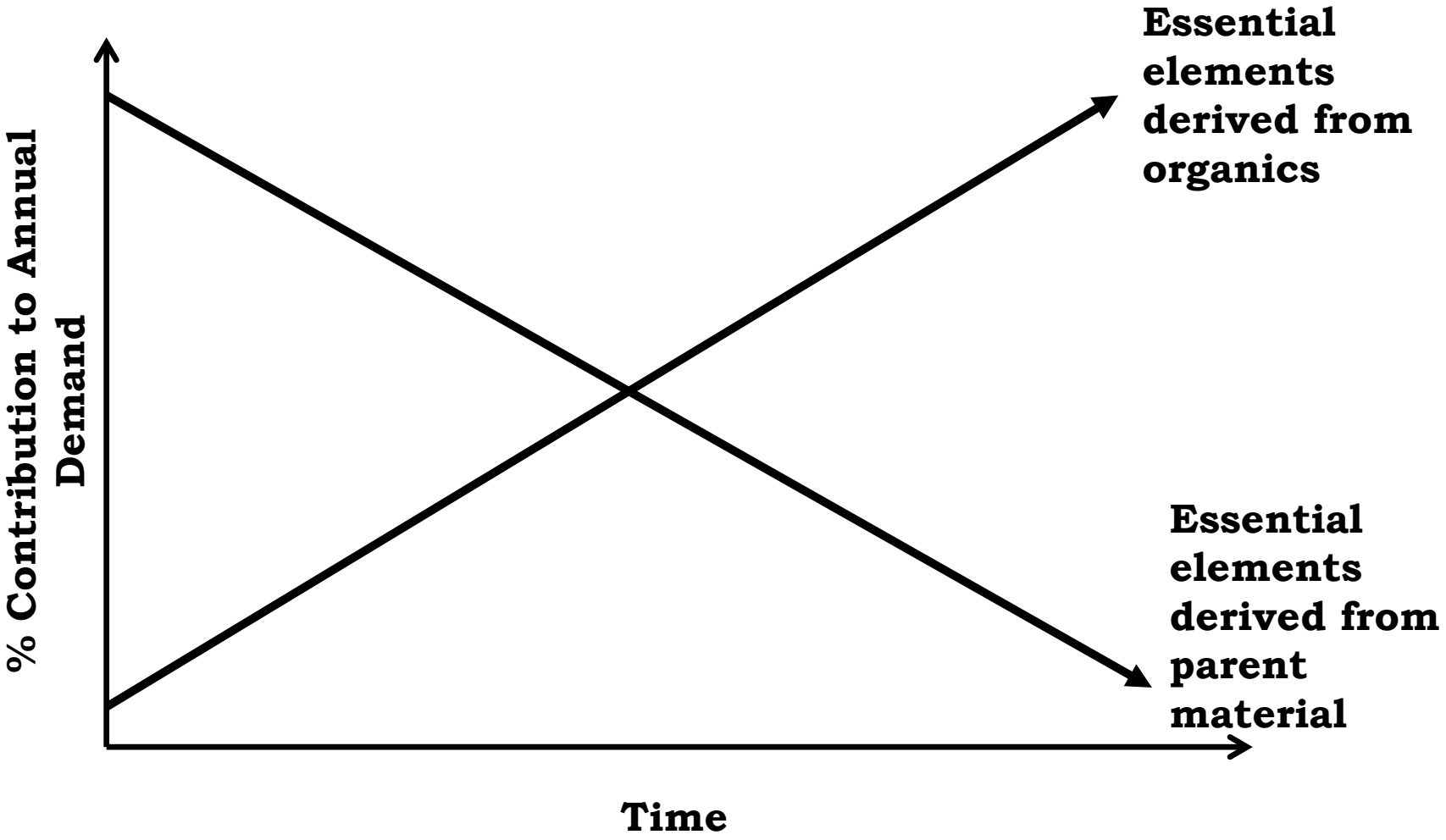
Moss campion (*Silene acaulis*) Photo: L. Werner, Iceland

Over time,…

Lichen – King George Island, Antarctica, 2010
Photo: L. Werner

…micro-organisms and plant-like organisms develop on these minerals

As organics accumulate and primary minerals weather, the availability of EE increases

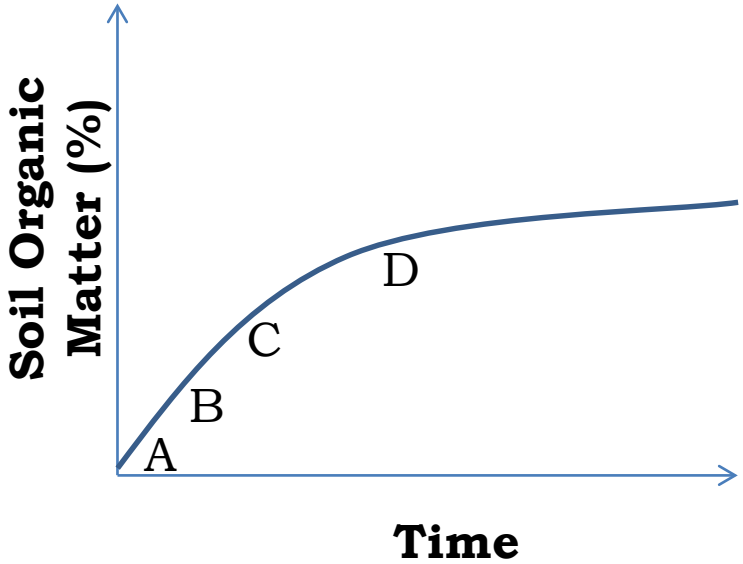


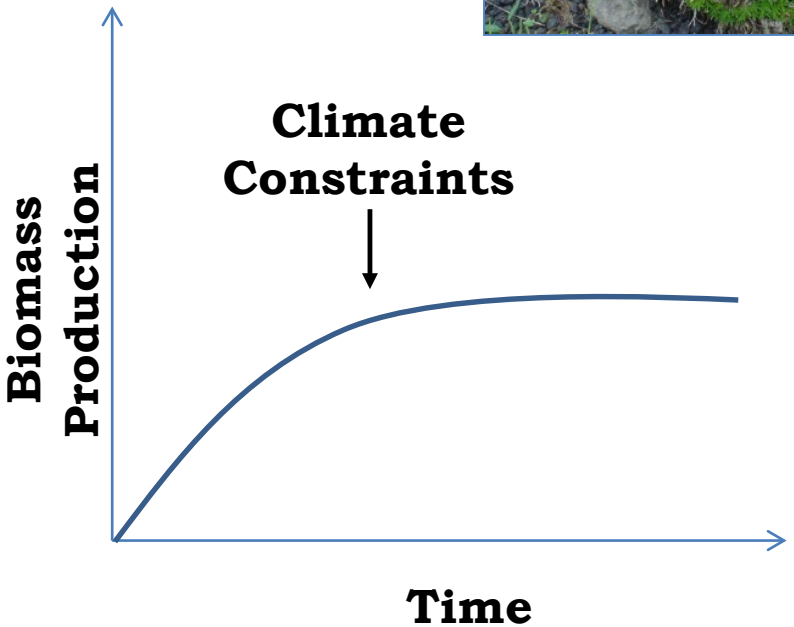
A

B

C

D

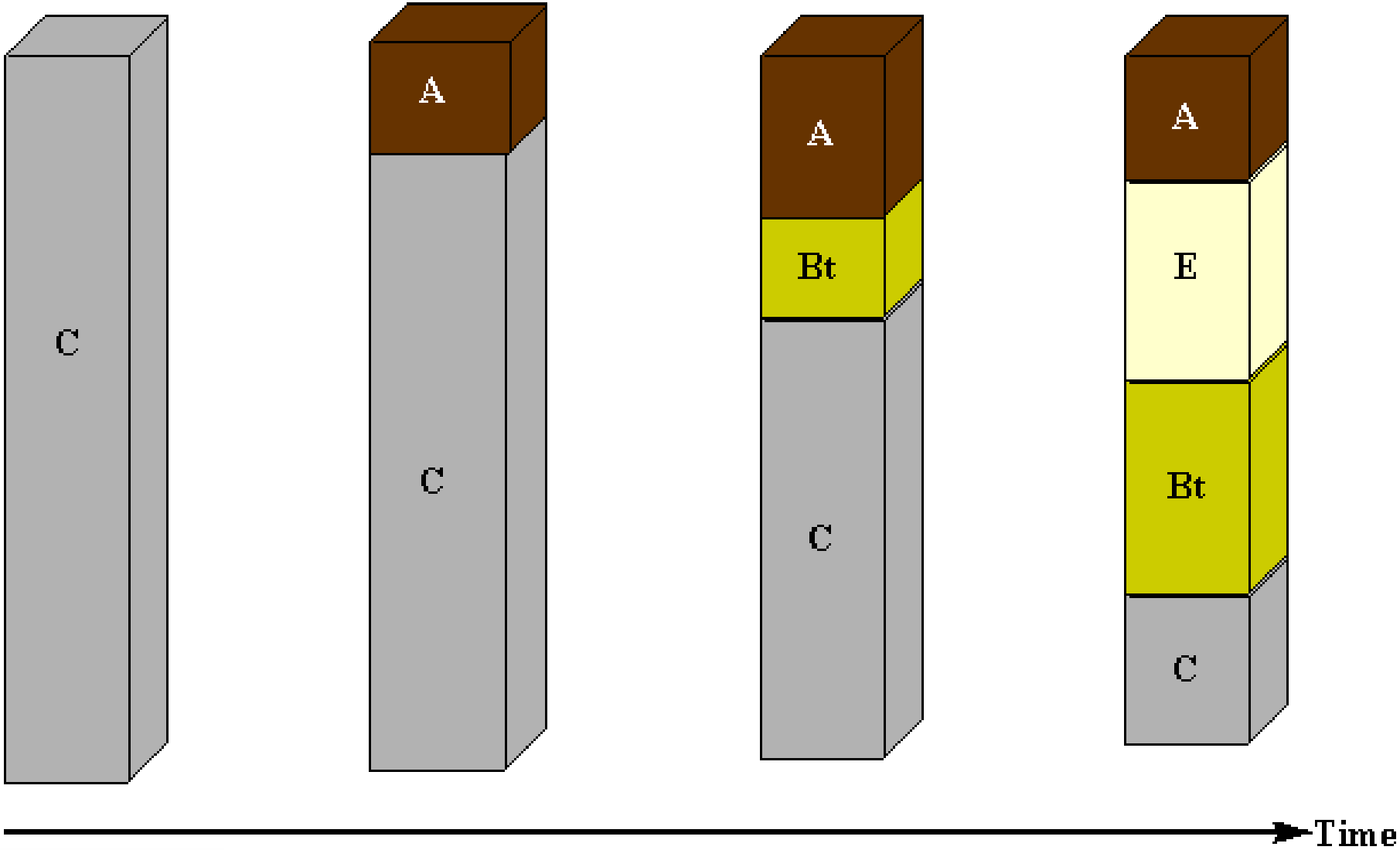




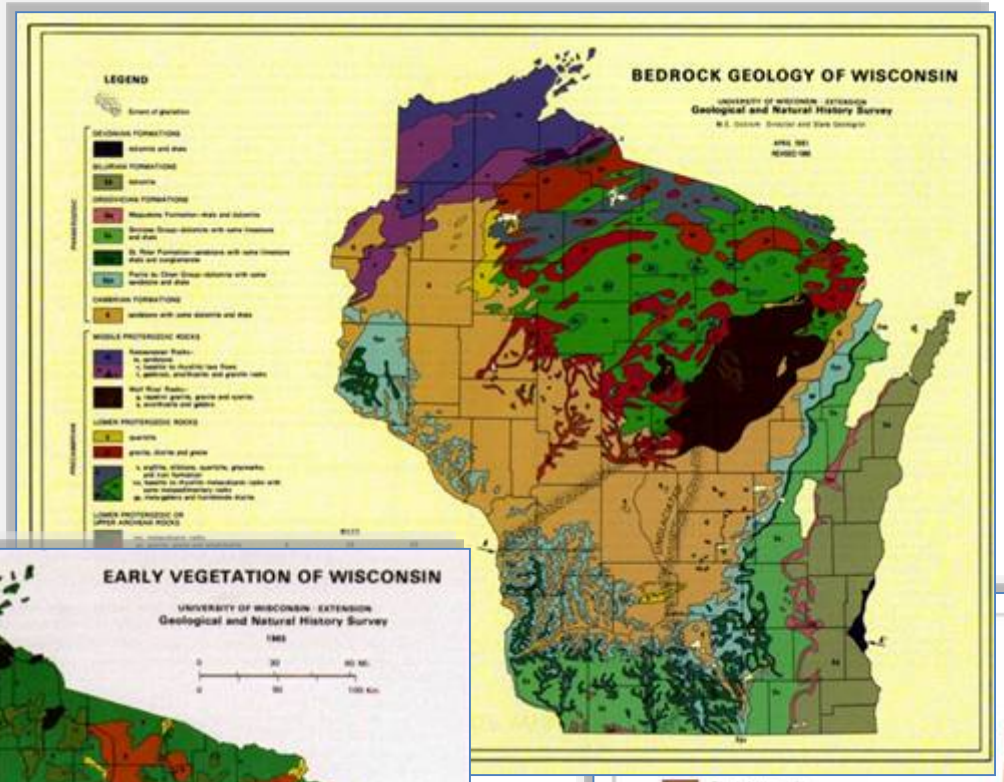
Photos by L. Werner, Iceland

Over time, soils;

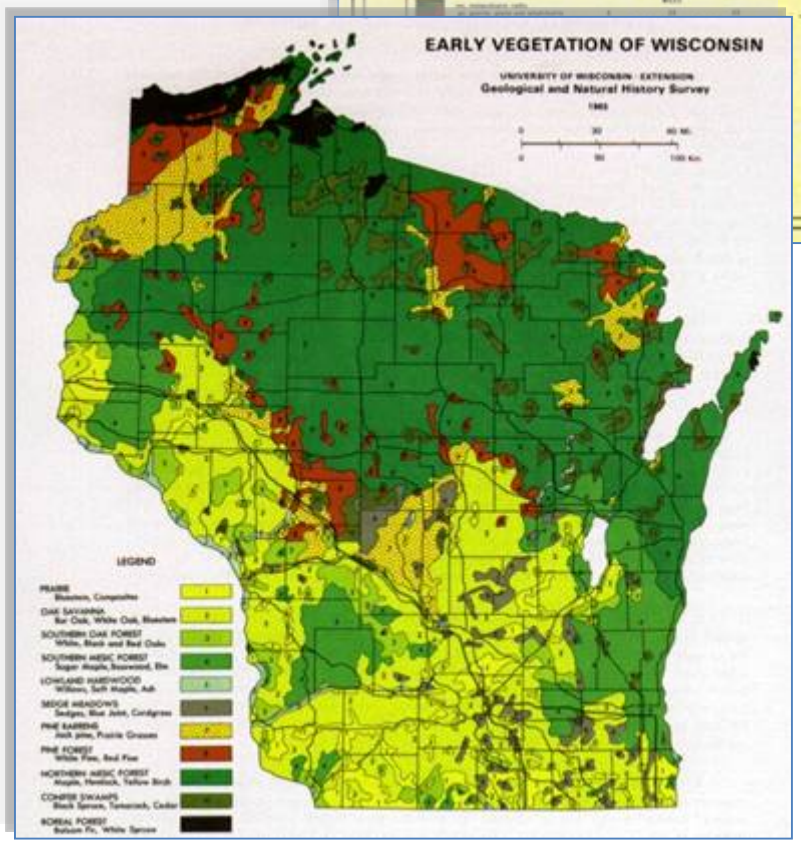
1. **Accumulate organic matter**
2. **Accumulate more clay**
3. **Become more acidic**
4. **Develop horizons**


C
A
C
A
Bt
C
A
E
Bt
C
Time

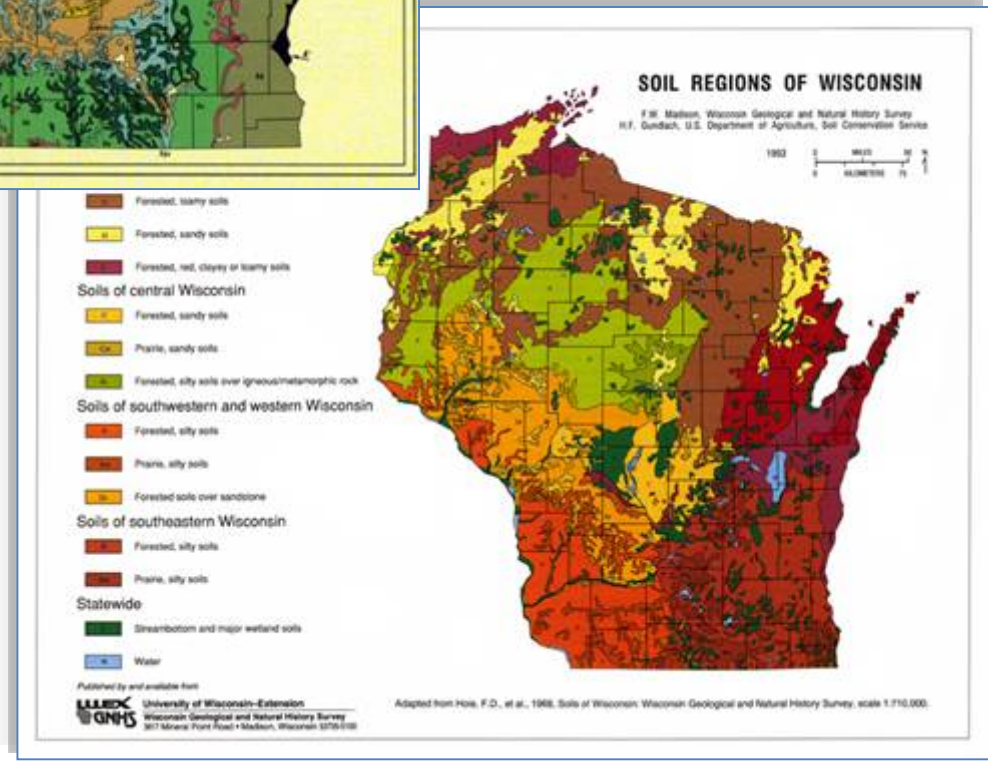
Bedrock



Vegetation



Soils



Soil as a System:

Soils are evaluated on their ability to hold and supply water

3 Types of Water in Soil

Hygroscopic water

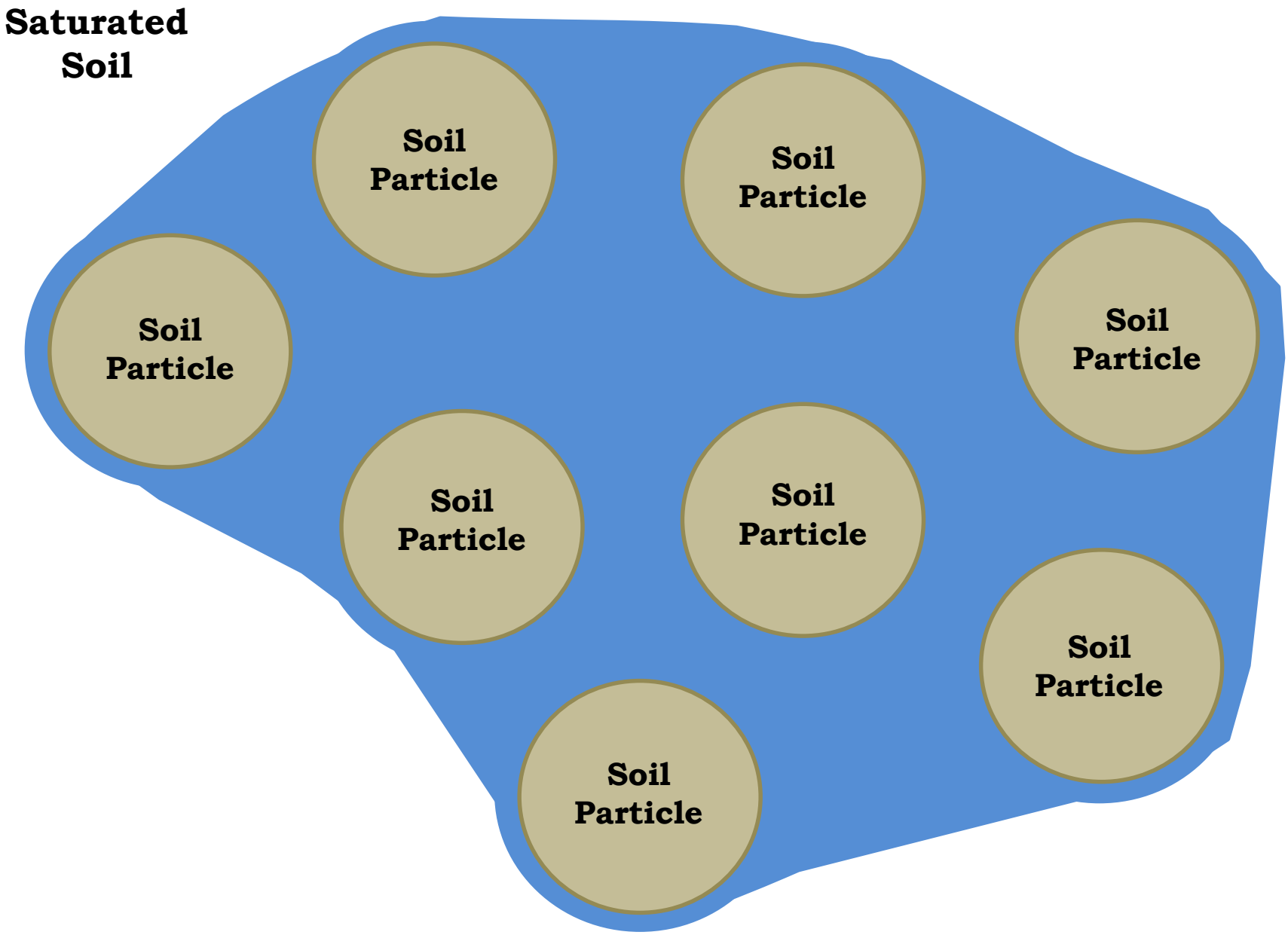
- water attached to soil particles
- not available to plants

Micro-pore water

- water held in small pores
- most of it is available to plants

Macro-pore water

- water temporarily held in large pores
- water that moves downward in response to gravity
- not available to plants



Sponge Demonstration

Volumetric Water Content:

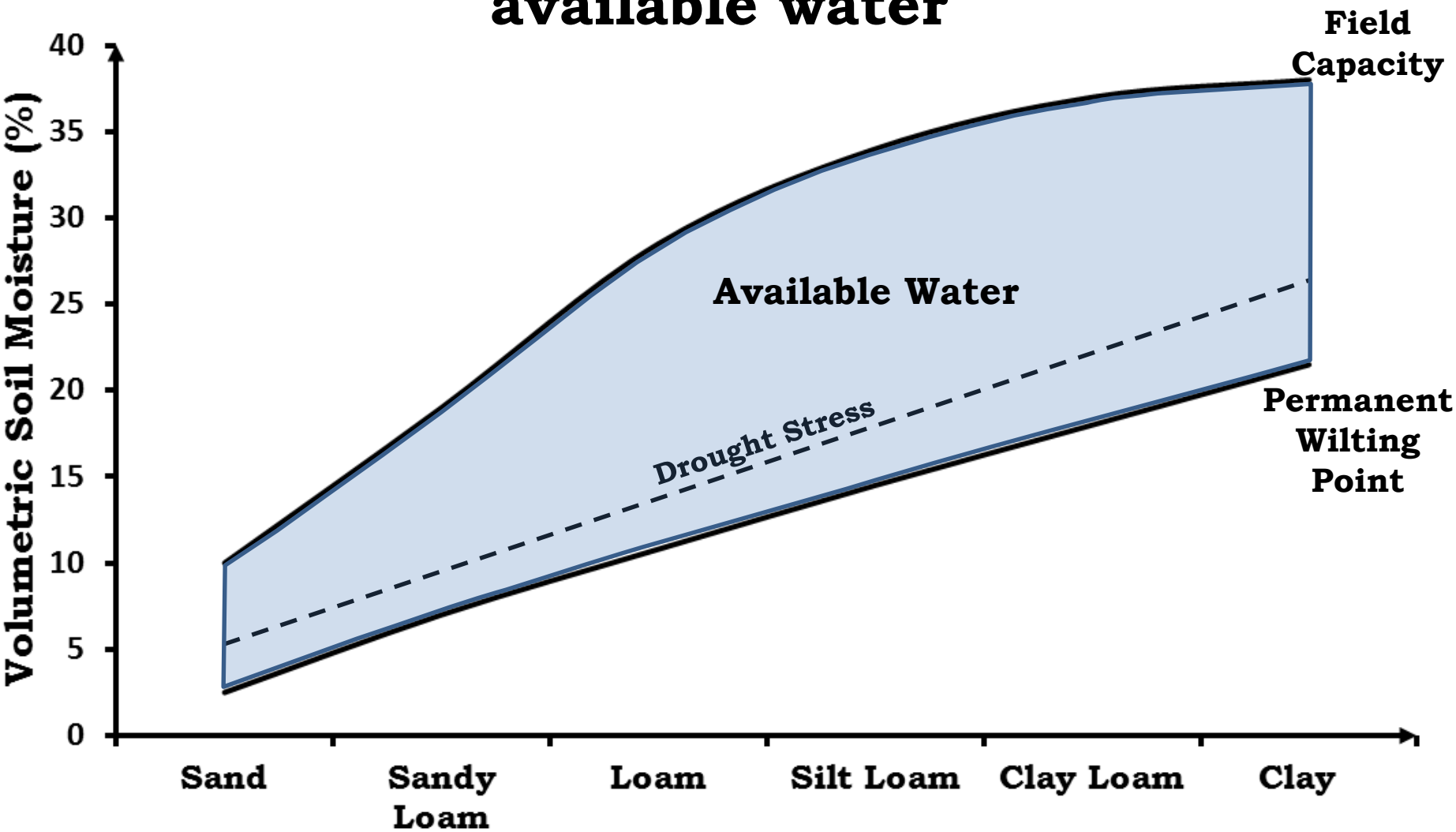
% of a soil volume occupied by water

$$\Theta_v = \frac{Volume\ of\ Water}{Volume\ of\ Soil} \times 100$$

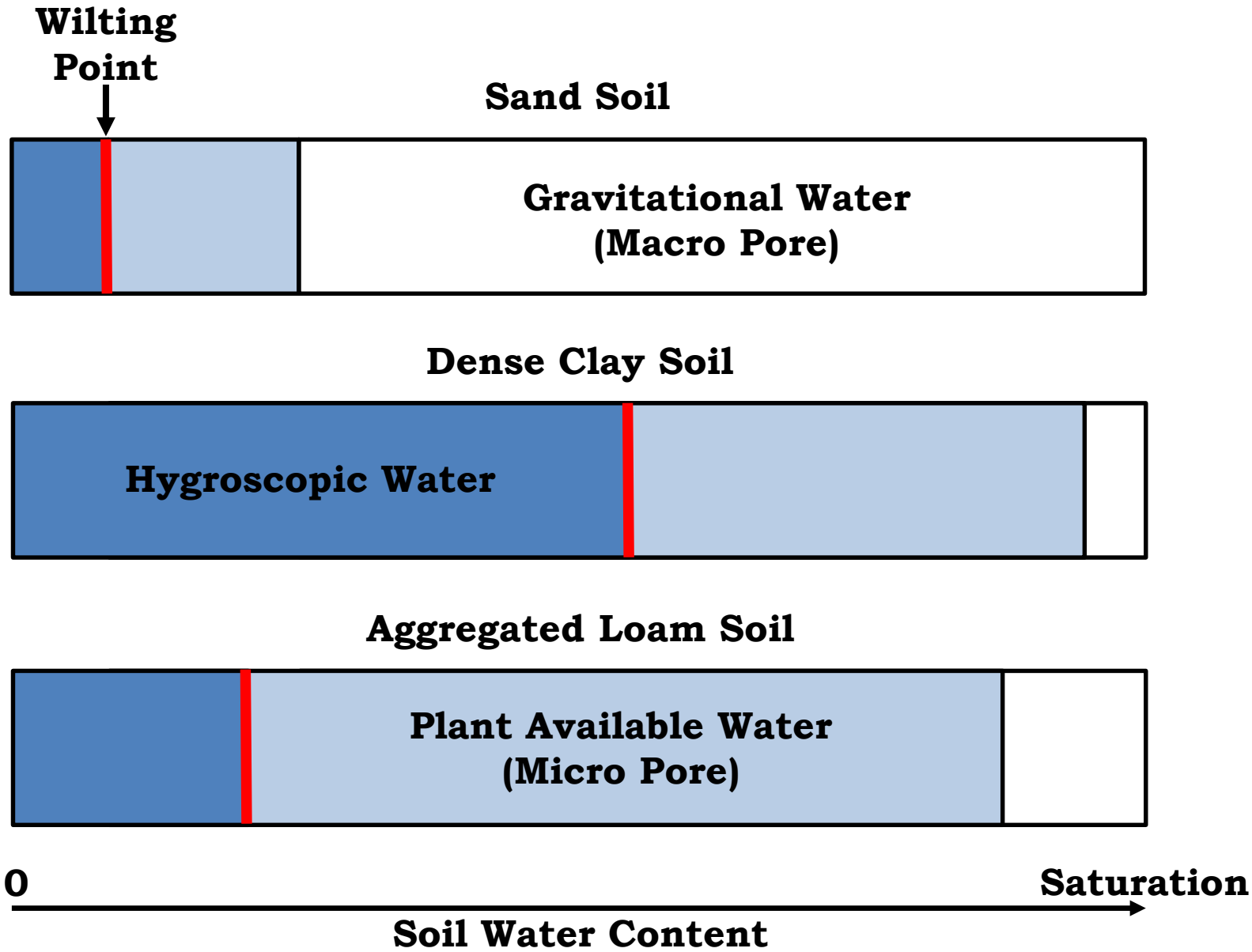
	θ_v @ Field Capacity	θ_v @ Permanent Wilting Point
Sandy Soils	10%	3%
Loam Soils	29%	11%
Clay Soils	40%	21%

Demonstration – TDR Probe

Soil texture influences water holding capacity and plant available water

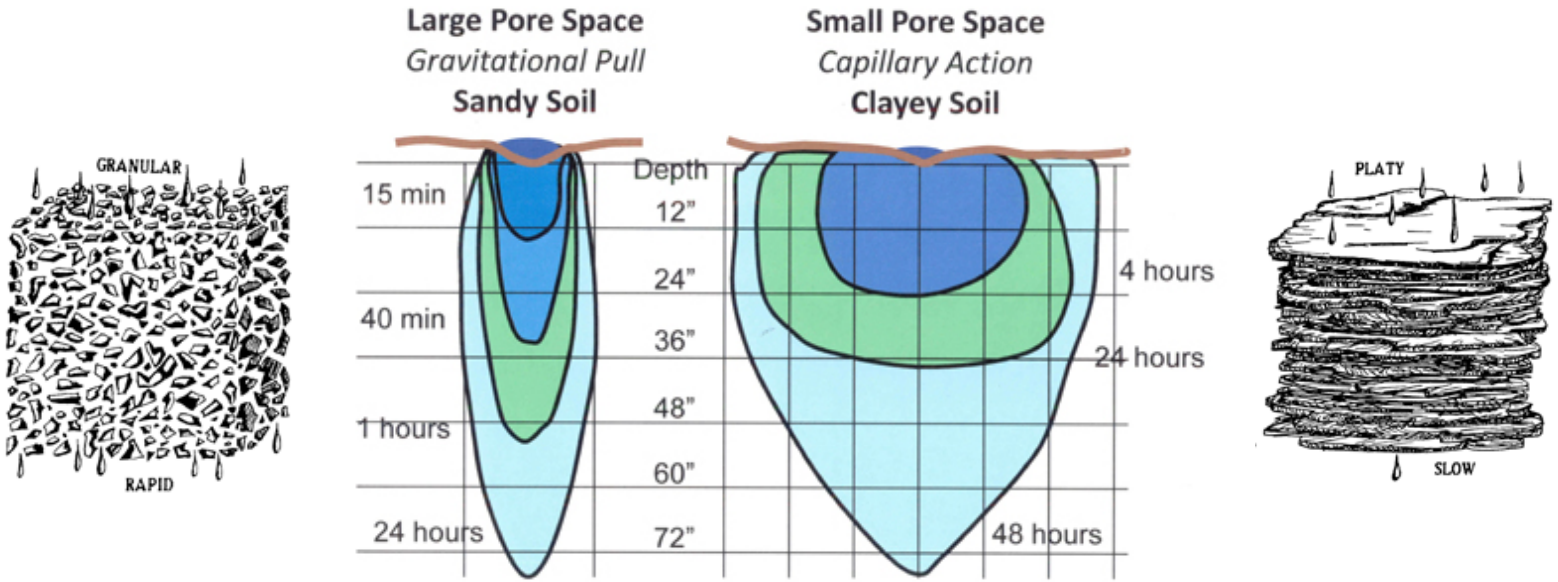


Redrawn from Brady, 10th Edition



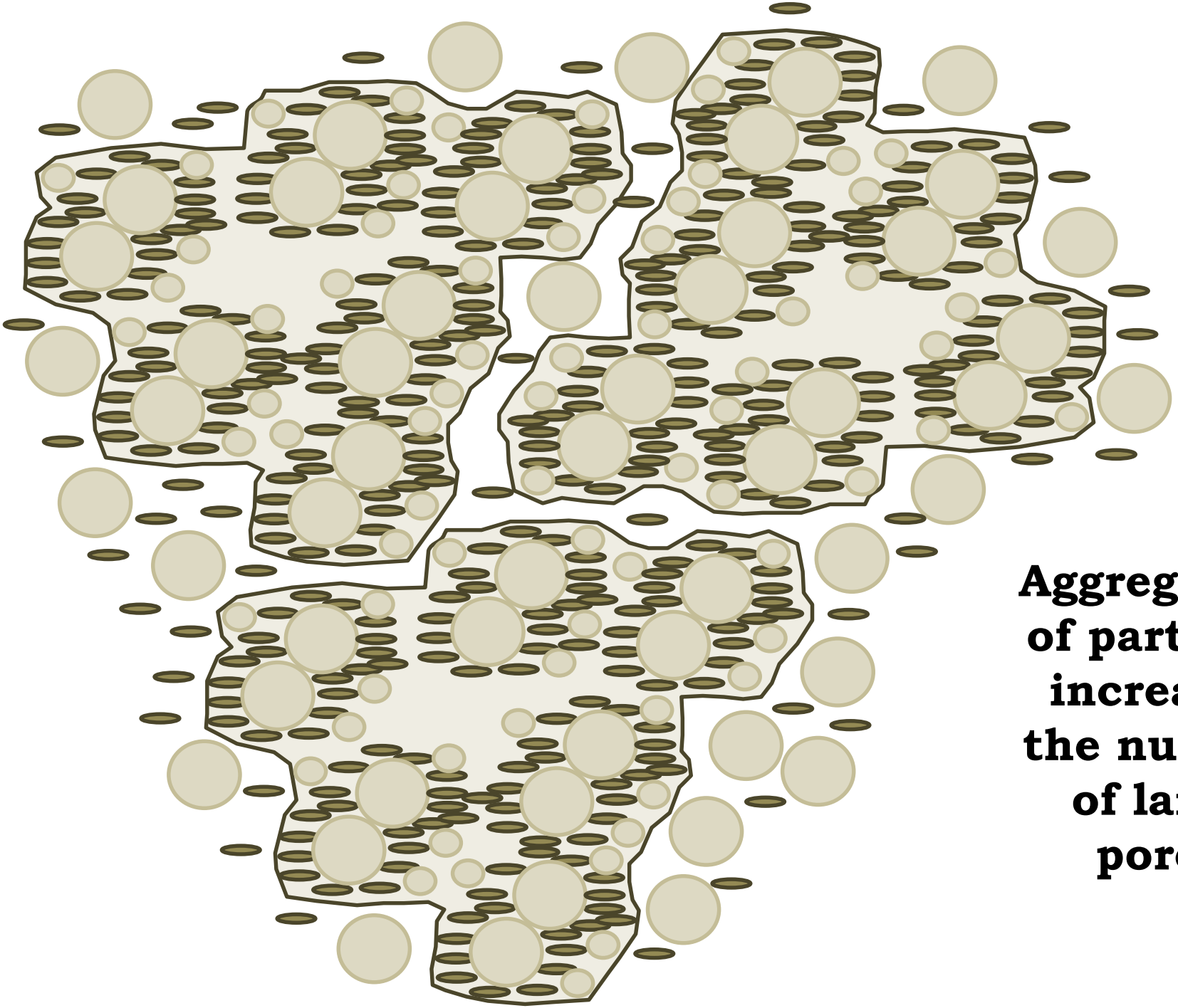
Source: Sustainable Agriculture Research and Education (SARE)

Size of the pore spaces influences how quickly water drains from soil

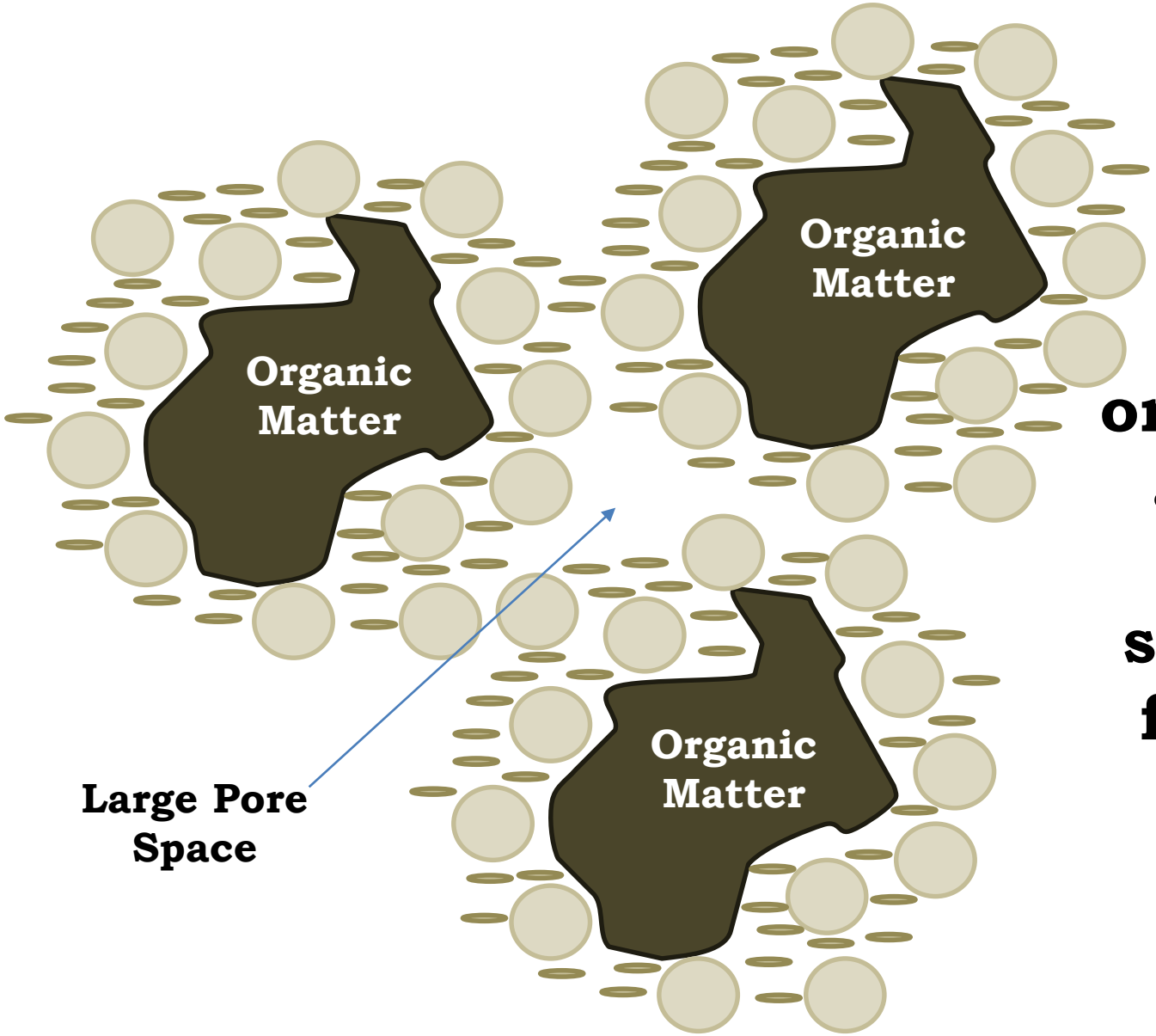


Demonstration

Whiting et al.. 2009. Managing Soil Tilth: Texture, Structure, and Pore Space

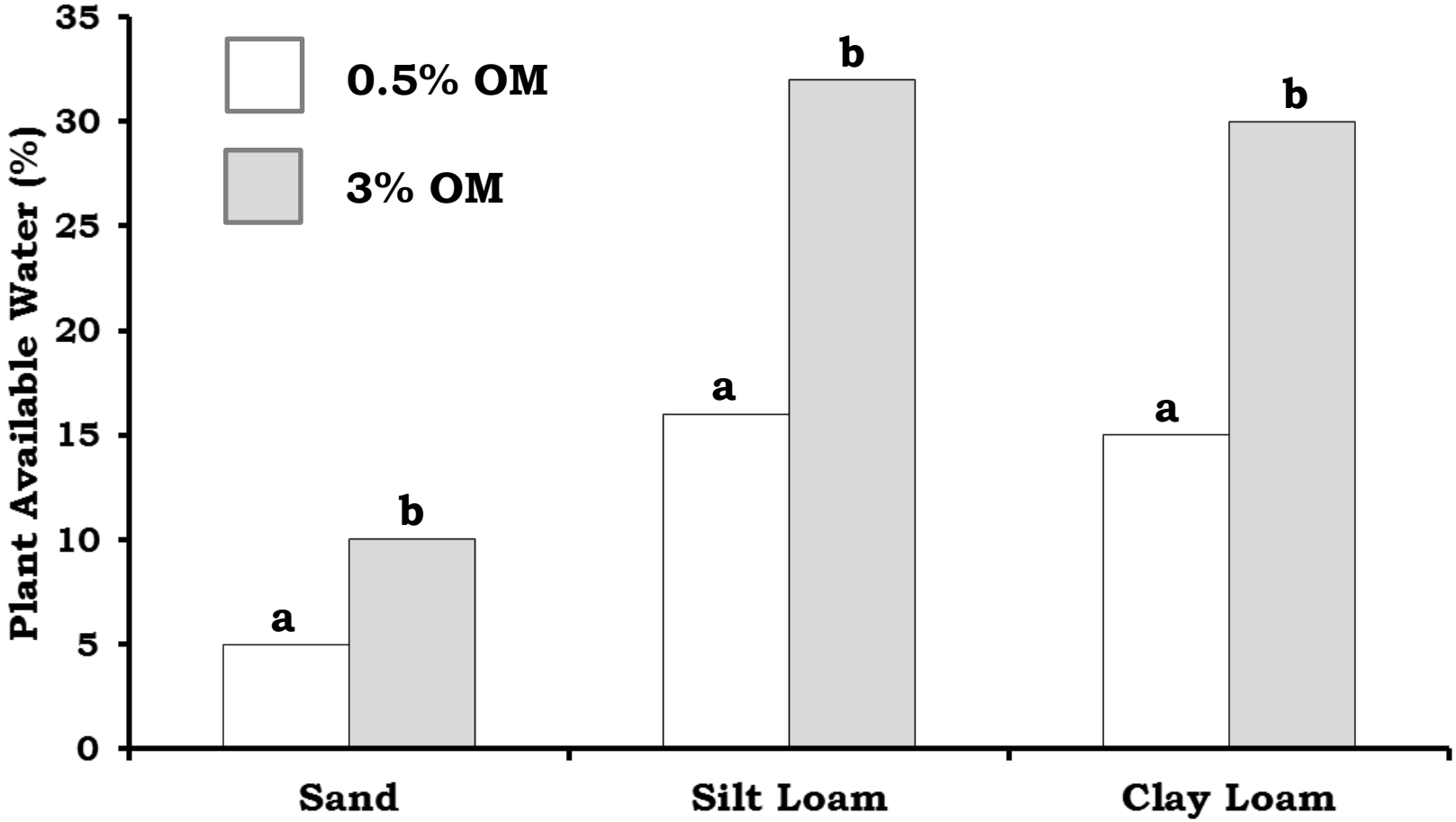


Aggregation of particles increases the number of large pores



Clay, soil organic matter and organic residues stimulate the formation of aggregates

Increases in soil organic matter tend to increase plant available water (to a point)



Drawn from: Hudson, B.D. 1994. J. Soil Water Conservation

Soil as a System:

Soils are evaluated on their ability to hold and supply essential elements

Terminology

Essential elements

Nitrogen (N)
Phosphorus (P)
Potassium (K)
Calcium (Ca)

Macro elements - %
- Accumulate in great amounts

Sulfur (S)
Magnesium (Mg)

Secondary elements - %
- Accumulate in great amounts

Iron (Fe)
Manganese (Mn)
Boron (B)
Copper (Cu)
Molybdenum (Mo)
Zinc (Zn)
Chlorine (Cl)

Micro elements - ppm
- Accumulate in small amounts

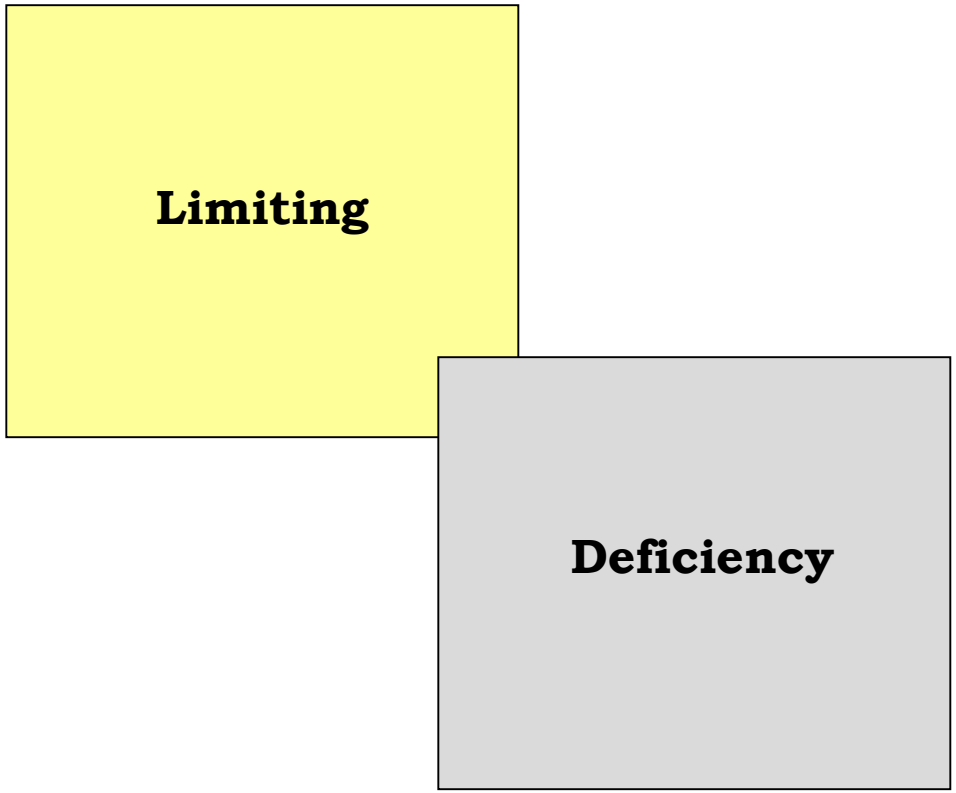
Definition of Essentiality

1. In the absence of a sufficient quantity, the plant dies

2. The element is directly involved in metabolic processes

3. The element cannot be replaced by another element

Terminology



<u>Nutrient Limiting</u>

- Reduced growth

<u>Nutrient Deficient</u>

-Dysfunction
-Death

Not all parent materials are created equally!

	Igneous Rocks			Sedimentary Rocks		
	Granite	Gabbro	Basalt	Shale	Sandstone	Limestone
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MgO	0.3	8.1	6.3	2.4	1.2	7.9
CaO	0.7	11.1	10.4	3.1	5.5	42.6
Na_2O	3.5	2.3	2.2	1.3	0.4	0.1
K_2O	5.1	0.6	0.8	1.3	0.3	--
P_2O_5	0.1	0.2	0.2	0.2	0.1	0.1
SO_3	--	--	--	0.6	0.1	0.1

Sources: Bohn et al., 1979; Scheffer et al., 1989

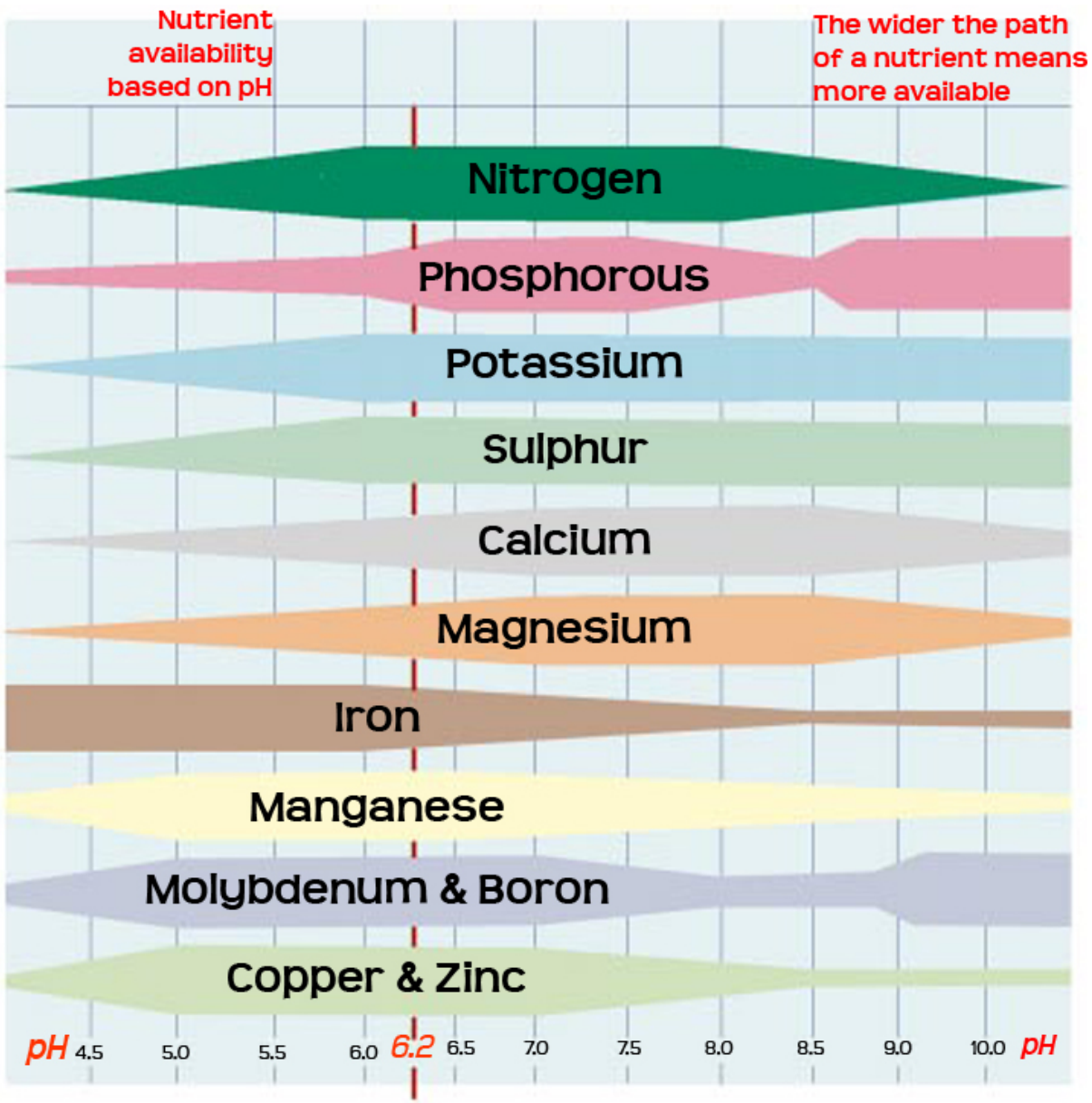
Generally, soils that develop from parent materials with:

High Silica Content	High Calcium Content
Coarse texture	Fine texture
Low pH	High pH
Low EE	High EE

EE = Essential mineral elements

Essential elements are taken up by trees as ions dissolved in water (i.e. they have a charge)

Positive Charge (Cations)	Negative Charge (Anions)
Nitrogen (NH_4^+)	Nitrogen (NO_3^-)
Potassium (K^+)	Phosphorus (HPO_3^{2-}, $H_2PO_4^-$)
Calcium (Ca^{2+})	Sulfur (SO_4^{2-})
Magnesium (Mg^{2+})	Chlorine (Cl^-)
Iron (Fe^{2+})	
Manganese (Mn^{2+})	
Zinc (Zn^+)	
Molybdenum (Mo^+)	
Copper (Cu^+)	



pH influences the solubility of essential elements

Acidic Soils

P, K, S, Mg, Mo

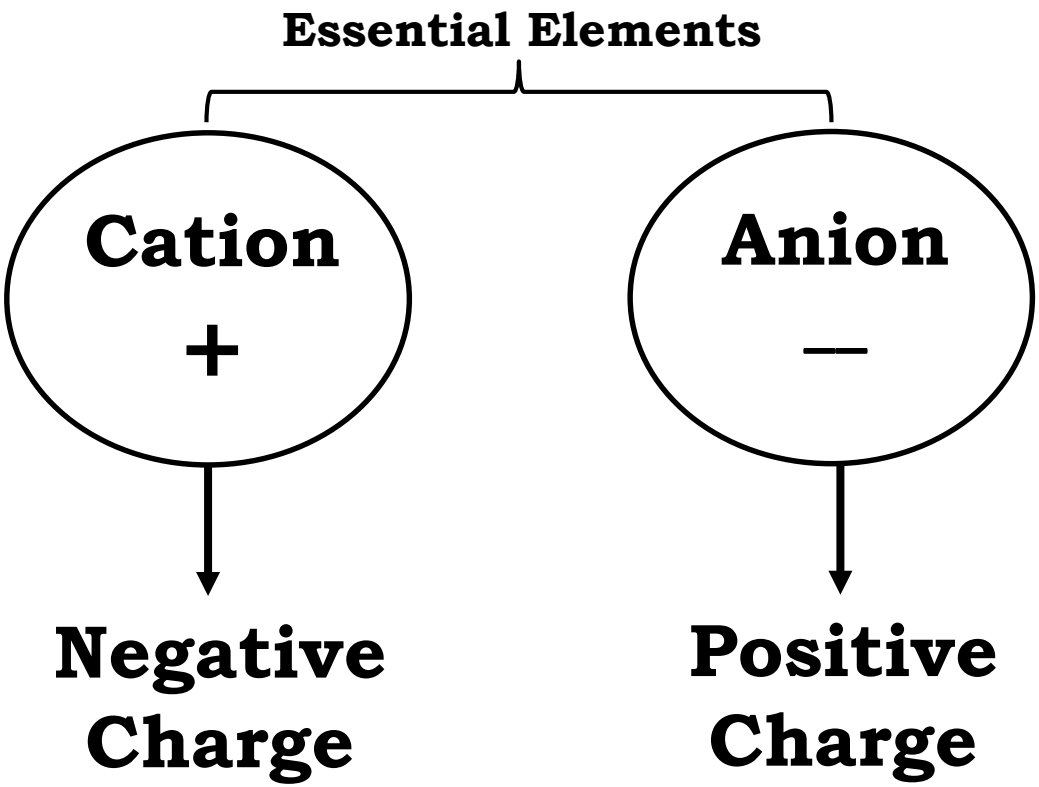
Alkaline Soils

P, Fe, Mn, Cu, Zn

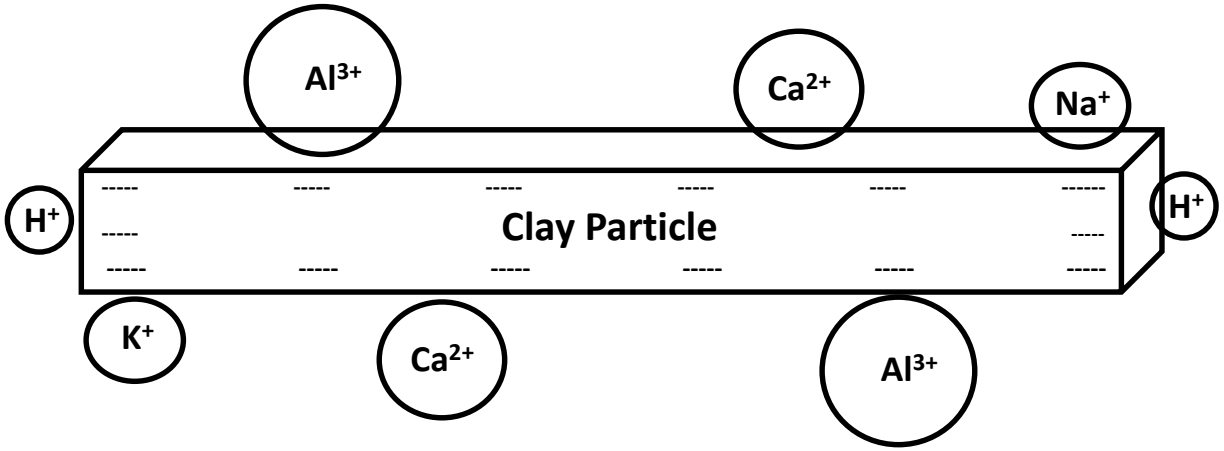
The ability of the soil to hold onto and release essential elements is called:

Cation Exchange Capacity

Anion Exchange Capacity



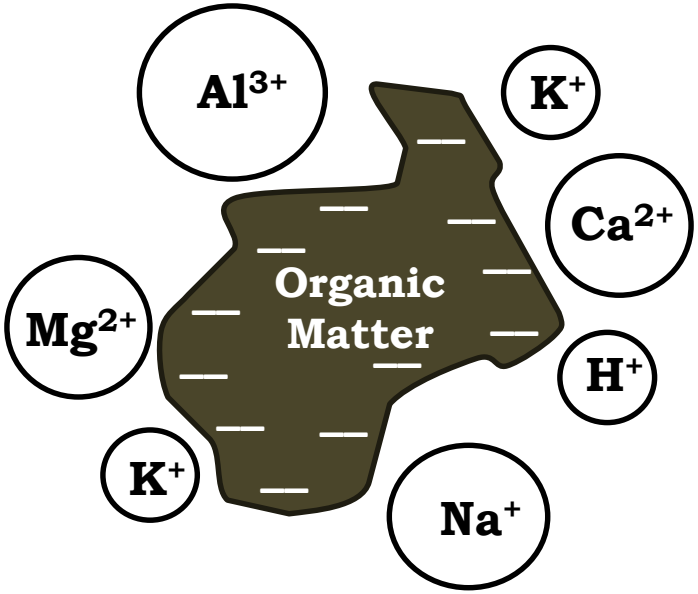
Negative charges develop on clays that attract positively charged essential elements



The negative charges are not influenced by pH

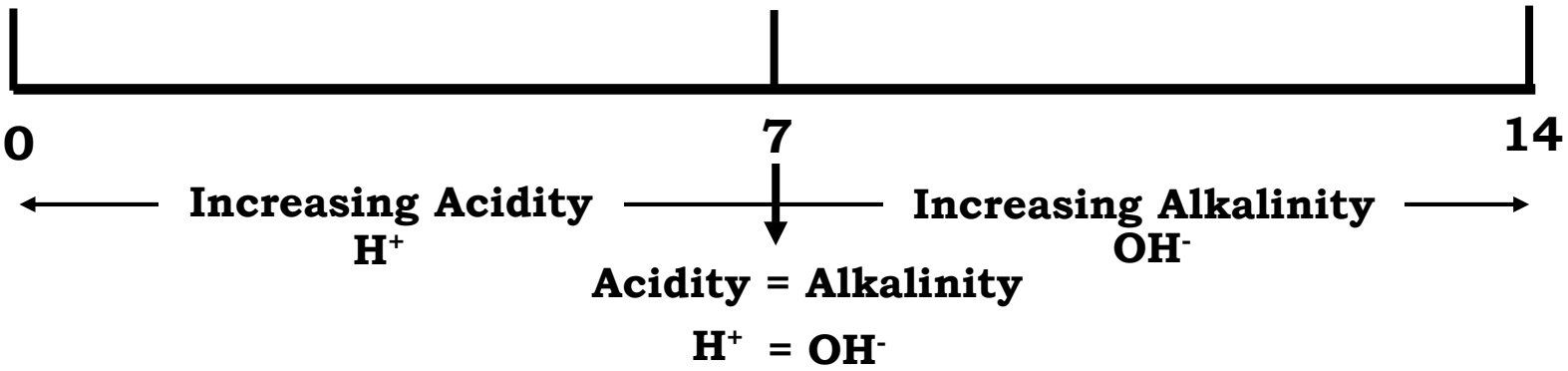
Demonstration

Negative charges develop on organic matter that attract positively charged essential elements



The amount of negative charge on OM is pH dependent

Understanding pH



pH = negative log of the H concentration

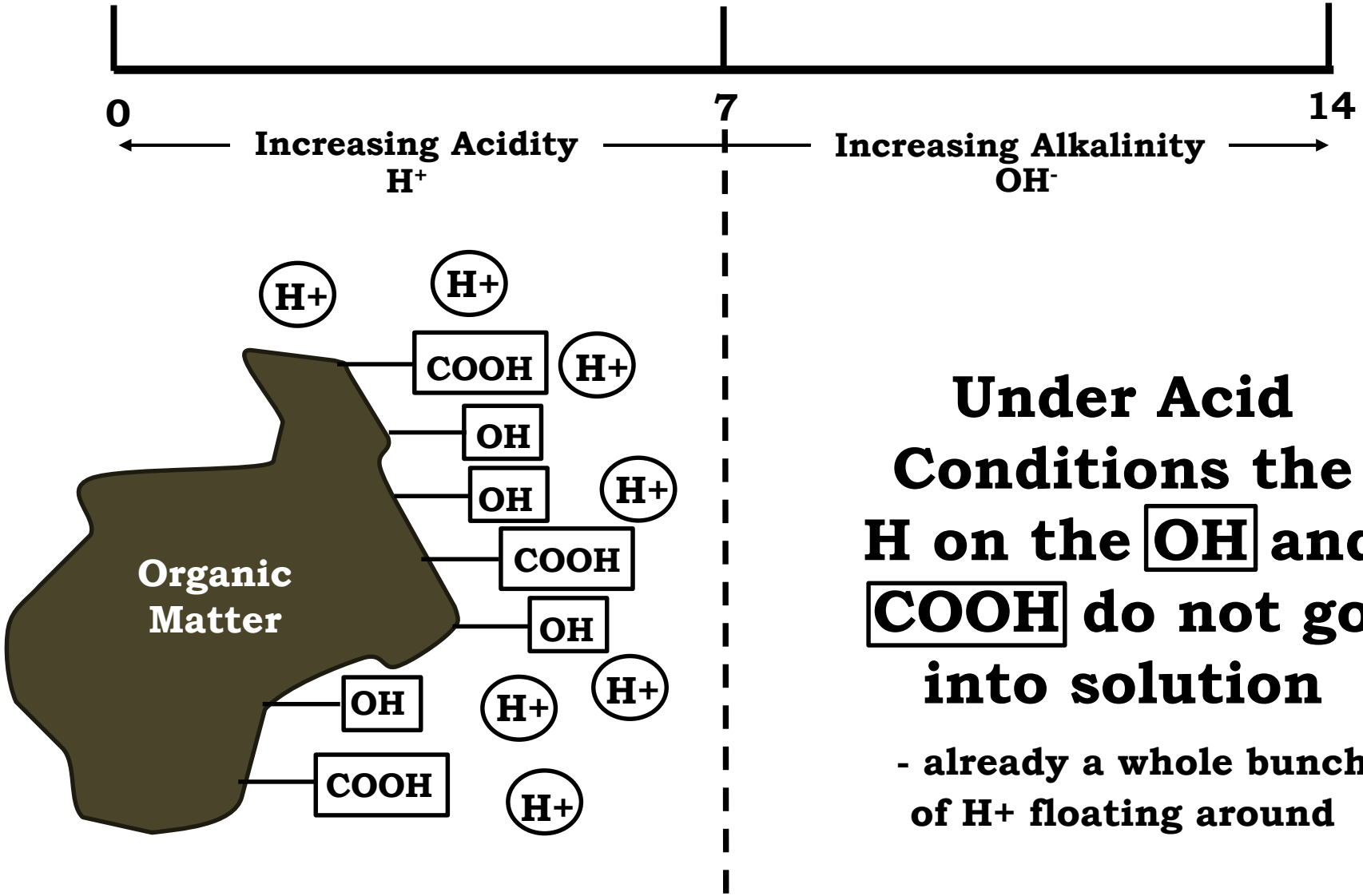
-log of 0.0000001 H = 7

(10^x = 0.0000001, x = -7)

-log of 0.000001 = 6

-log of 0.00001 = 5

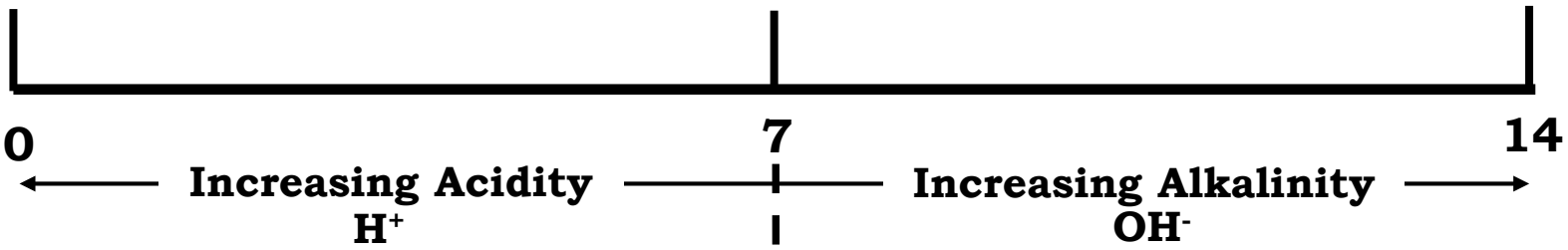
A pH of 5 is 10 times more acidic than a pH of 6



Under Acid Conditions the H on the OH and COOH do not go into solution

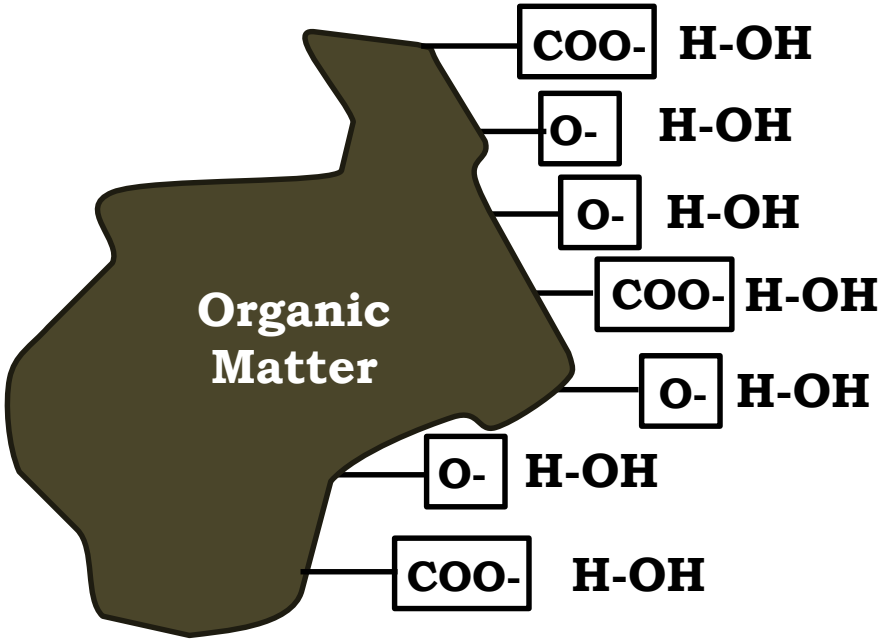
- already a whole bunch of H+ floating around

OH and COOH are abundant on OM

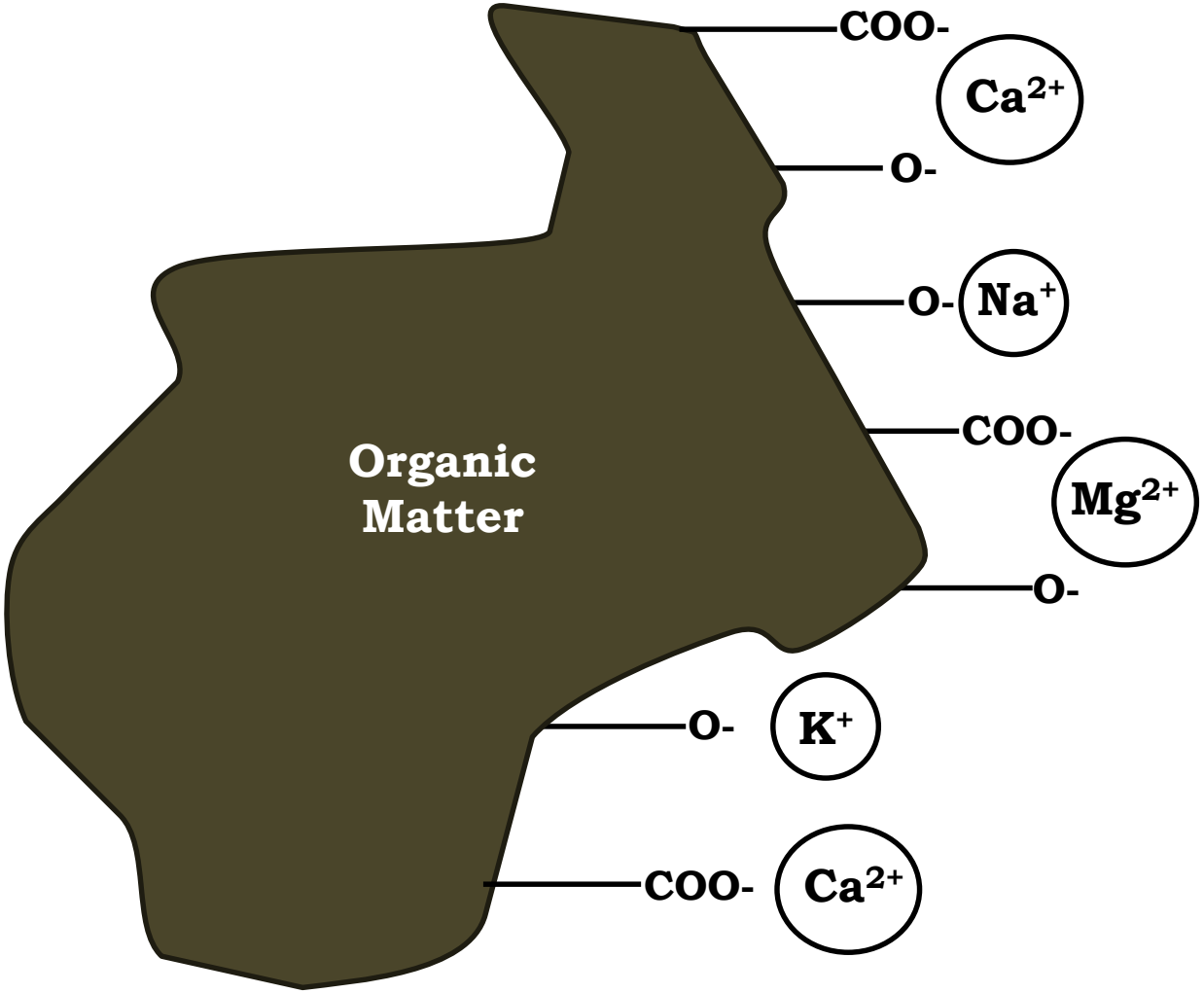


Under alkaline conditions (high OH^-), the H on OH and COOH react with the OH- in solution

This creates a negative charge on the OM



Essential element cations balance the negative charge



CEC is a measure of the soils ability to hold and supply essential elements

CEC = pH Dependent + pH Independent

(organic matter) (clay fraction)

cmol +/kg$_{soil}$

meq /100 g$_{soil}$

CEC Increases with:

OM content

Clay content

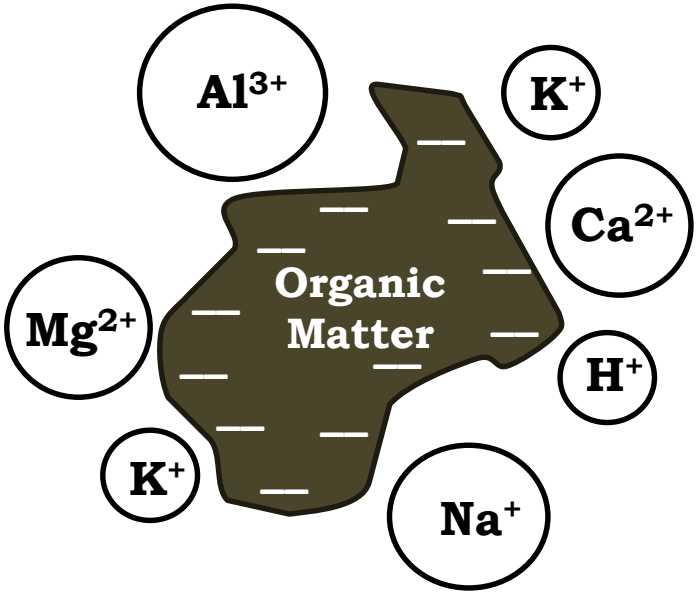
Increased pH

How many charges are we talking about?

1 cmol has 6 x 10^{20} negative charges

600,000,000,000,000,000,000 charges

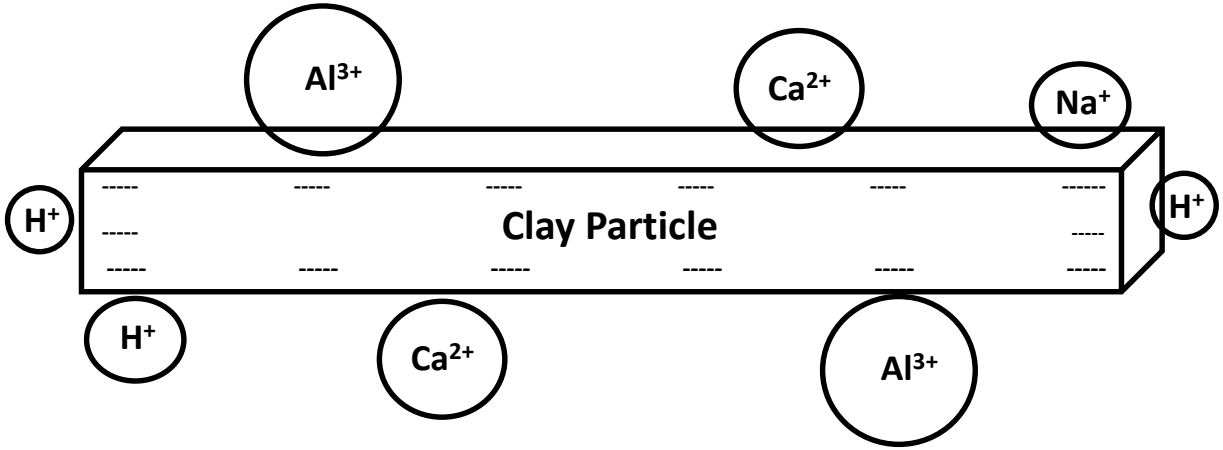
CEC	Charges
1	600,000,000,000,000,000,000
5	3,000,000,000,000,000,000,000
10	6,000,000,000,000,000,000,000
15	9,000,000,000,000,000,000,000
20	12,000,000,000,000,000,000,000
25	15,000,000,000,000,000,000,000



BS = 5/7 = 71%

Base Saturation reflects how many of the exchange sites are occupied by:

K, Ca, Mg, and Na (non-acidic = base)



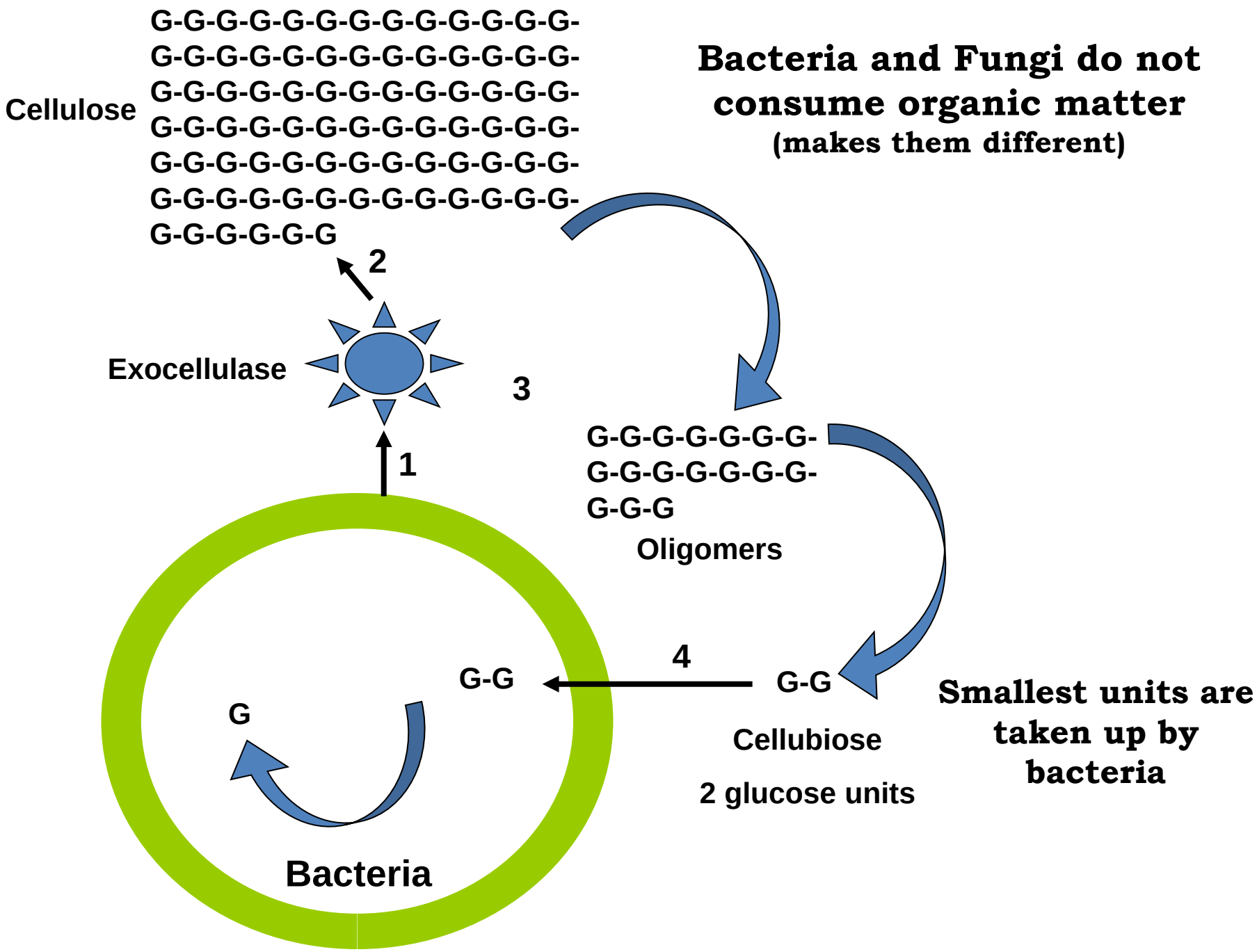
BS = 3/8 = 37.5%

Essential mineral elements are released through decomposition

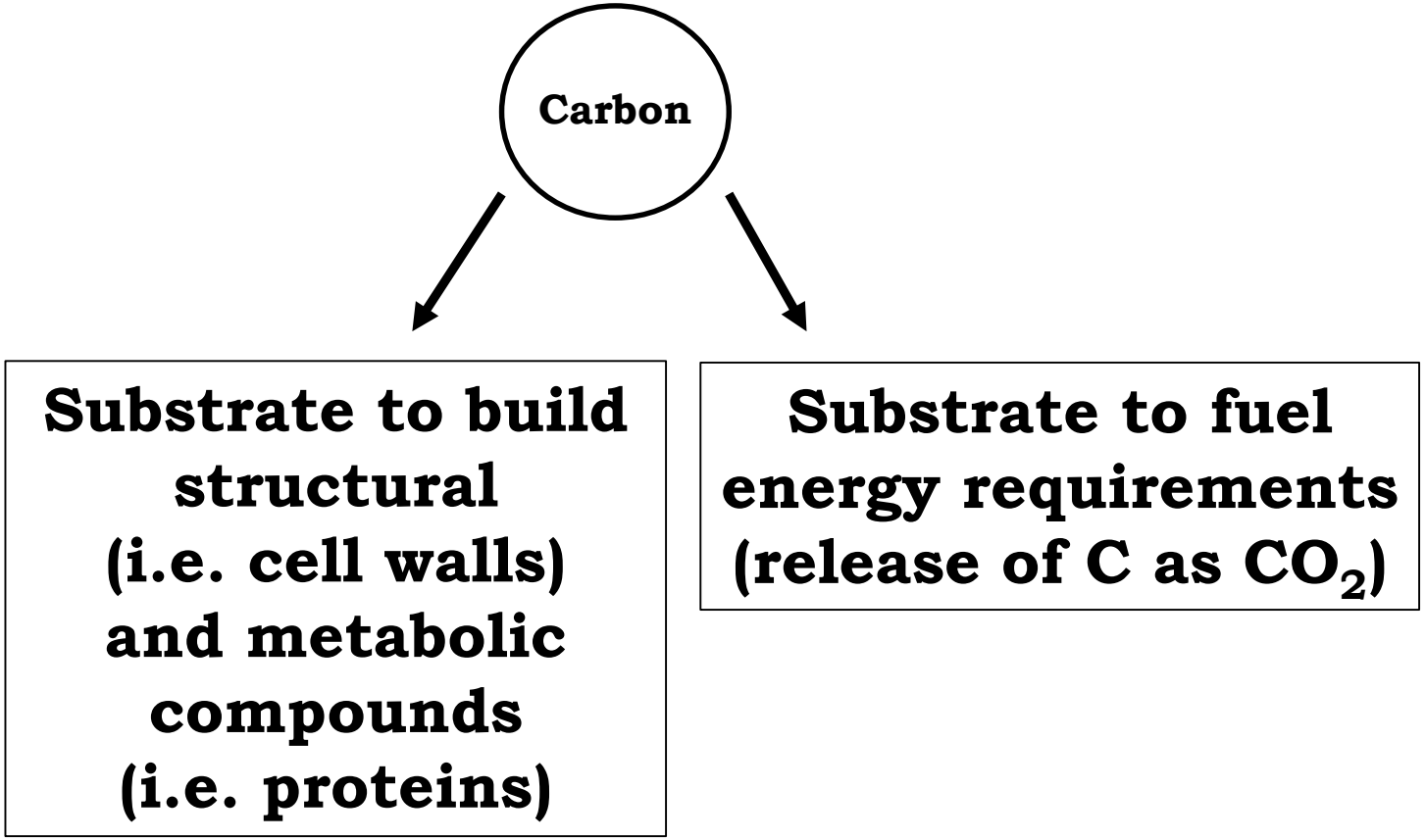
Decomposition is a process involving multiple species of organisms

Each wave alters the substrate, making it a target for another group of organisms

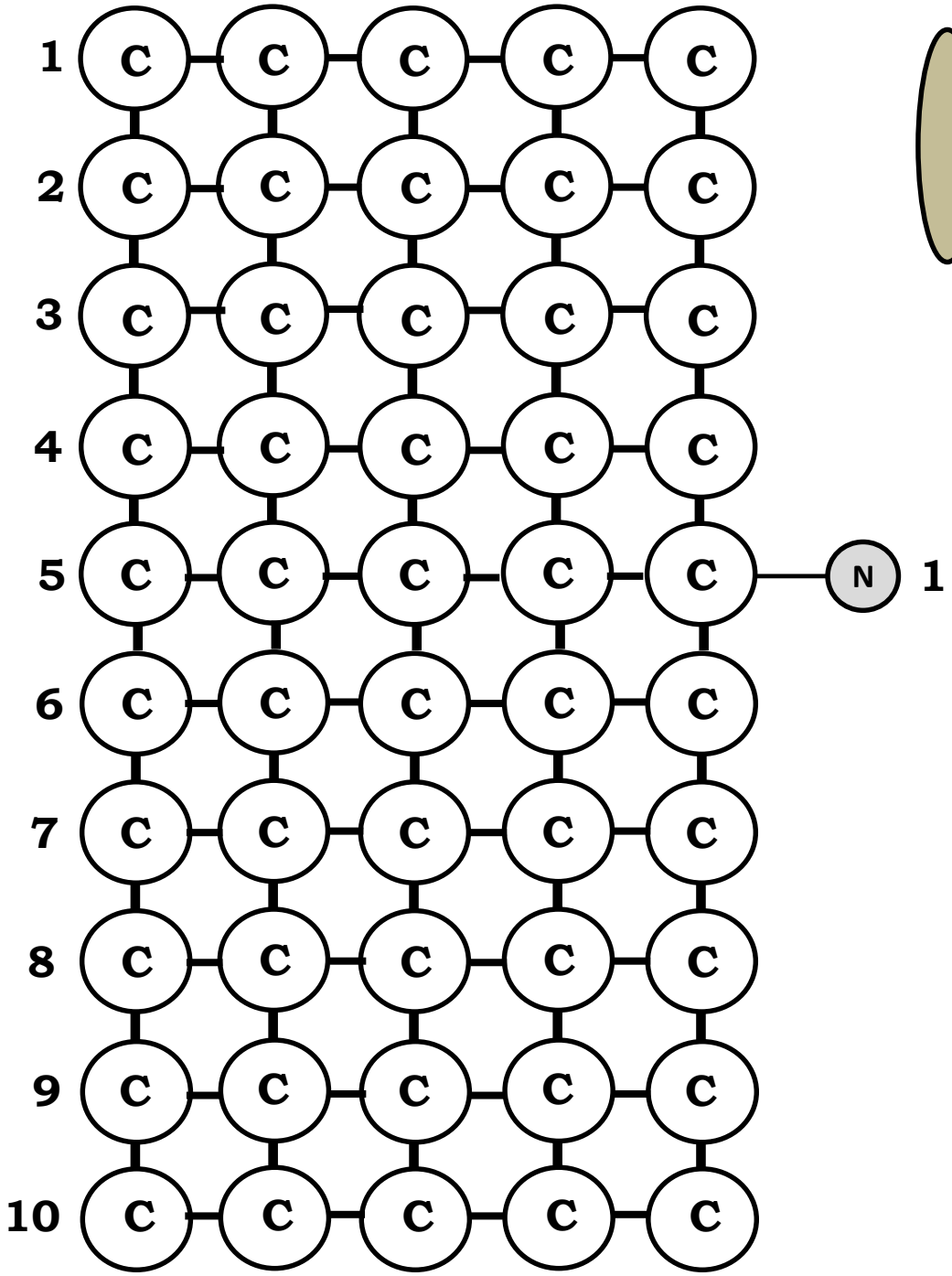
Photos by L. Werner

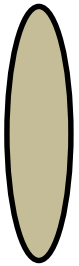

Bacteria and Fungi do not consume organic matter
(makes them different)
Cellulose
G-G-G-G-G-G-G-G-G-G-G-G-G-
G-G-G-G-G-G-G-G-G-G-G-G-G-
G-G-G-G-G-G-G-G-G-G-G-G-G-
G-G-G-G-G-G-G-G-G-G-G-G-G-
G-G-G-G-G-G-G-G-G-G-G-G-G-
G-G-G-G-G-G-G-G-G-G-G-G-G-
G-G-G-G-G-G
2
Exocellulase
3
1
G-G-G-G-G-G-G-
G-G-G-G-G-G-G-
G-G-G
Oligomers
4
G-G
G-G
G
Cellubiose
2 glucose units
Smallest units are taken up by bacteria
Bacteria

Soil microbes (bacteria, fungi) breakdown litter to obtain C and essential elements to support growth and metabolic functioning



Only a fraction of the Carbon is used for growth





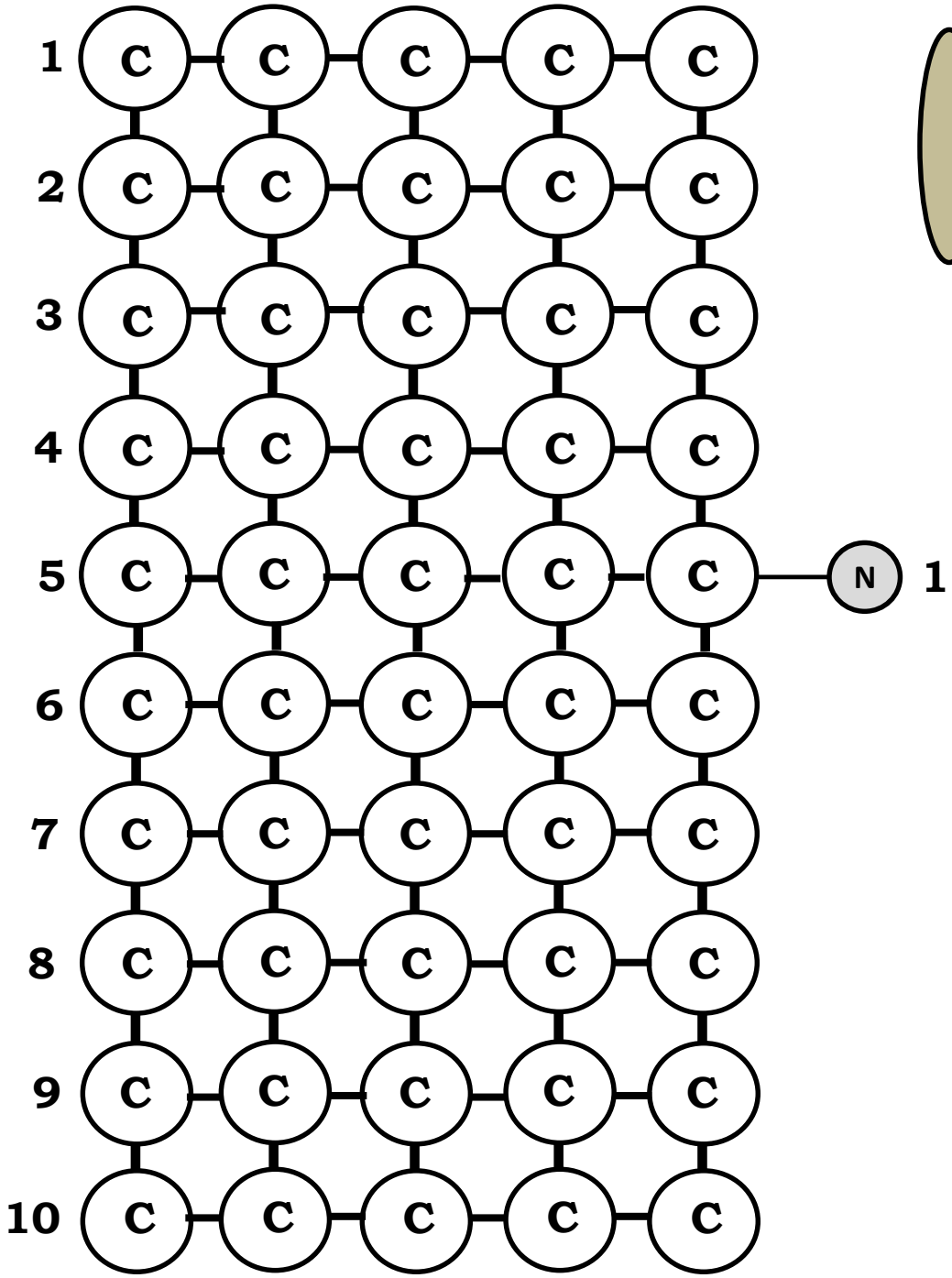
Soil Bacteria

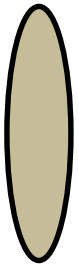
The organic matter has a 50 carbons and 1 N

C:N = 50

The soil bacteria has 10 carbons for every 1 N

C:N = 10





Soil Bacteria

The bacteria is 40% efficient:

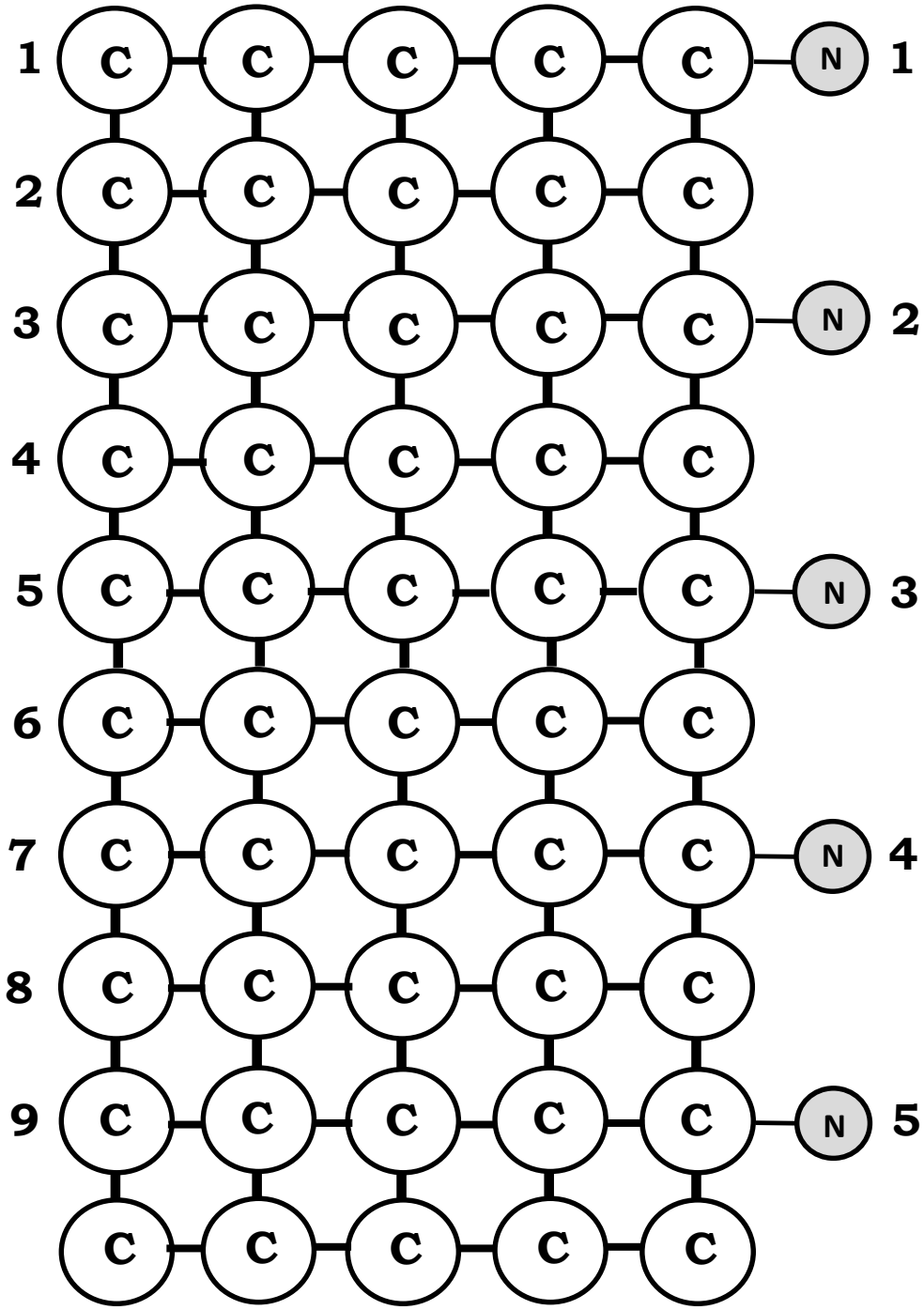
20 carbons for growth

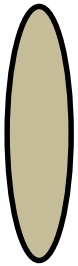
30 carbons respired as CO_2

Bacterial C:N of 10:1

20 C requires 2 N

1 additional EE is needed





Soil Bacteria C:N = 10

The organic matter has a 50 carbons and 5 N
C:N = 10

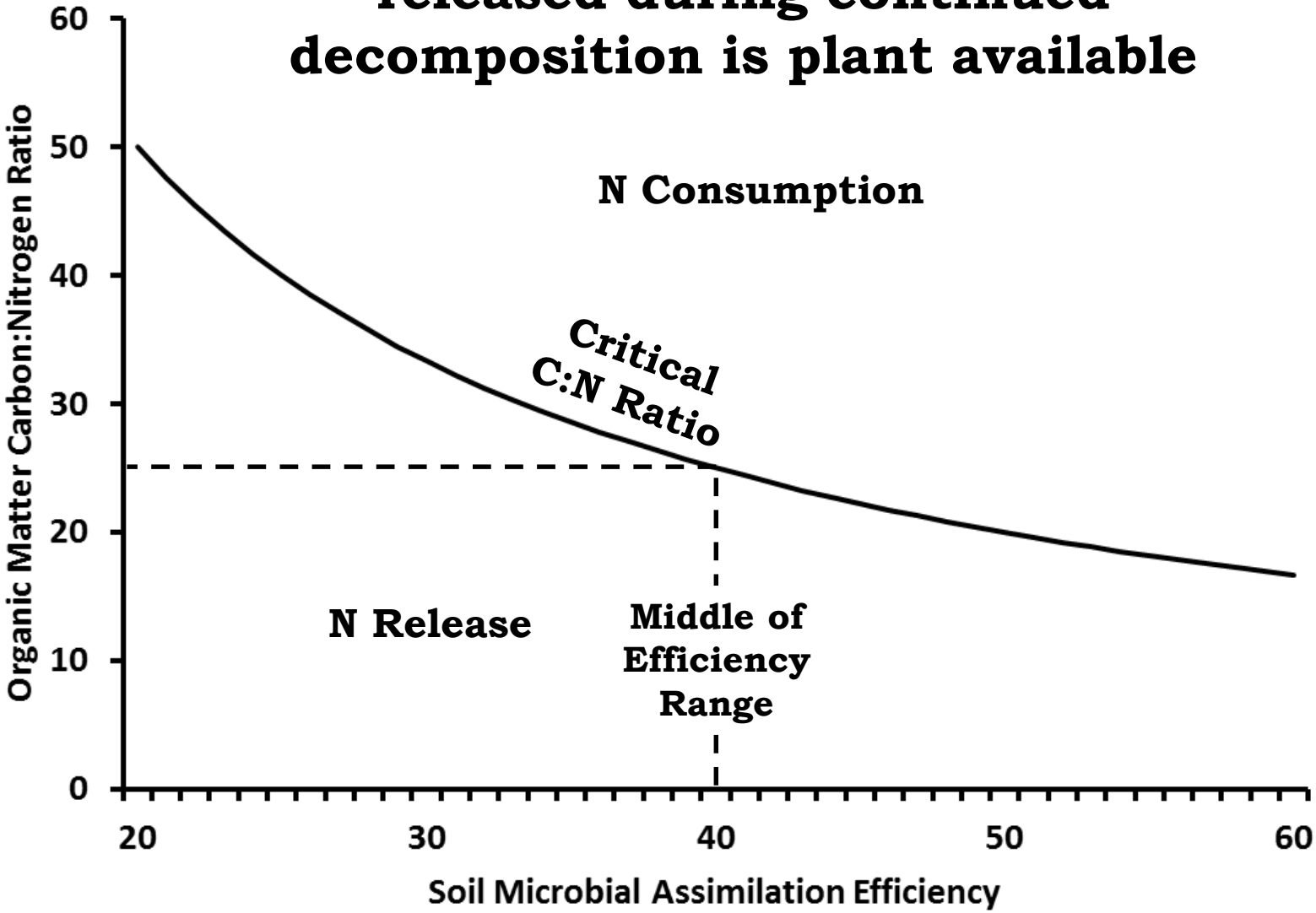
Based on the same efficiency:

3 N are available to the tree

Carbon efficiency varies between 20-60%

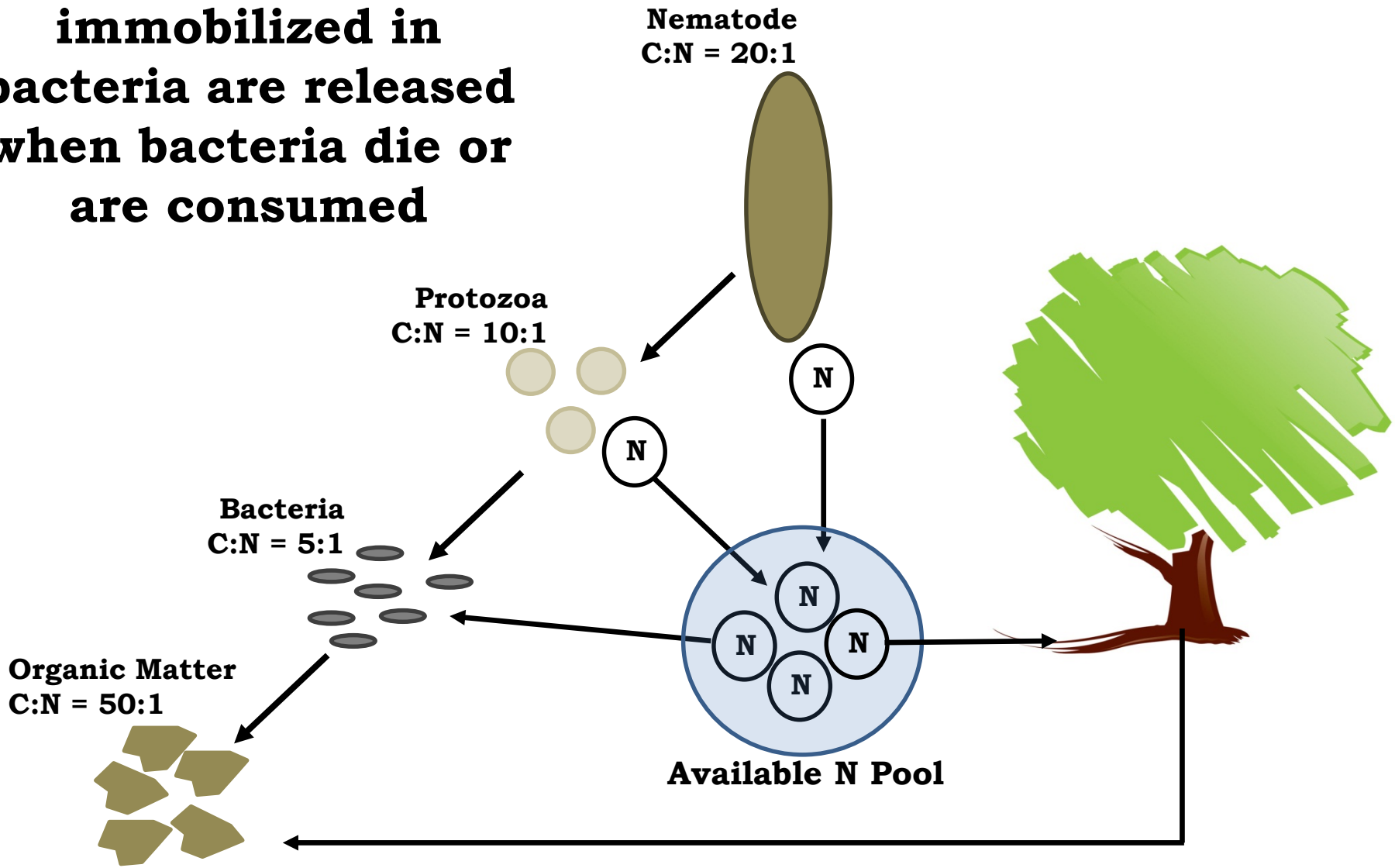
Source: Gupta and Roget, 2003, Chapin et al, 3rd Edition

Organic inputs with C:N <25 means N released during continued decomposition is plant available



Essential Elements immobilized in bacteria are released when bacteria die or are consumed

Soil Food Web



Soil factors that influence microbial activity and litter decomposition

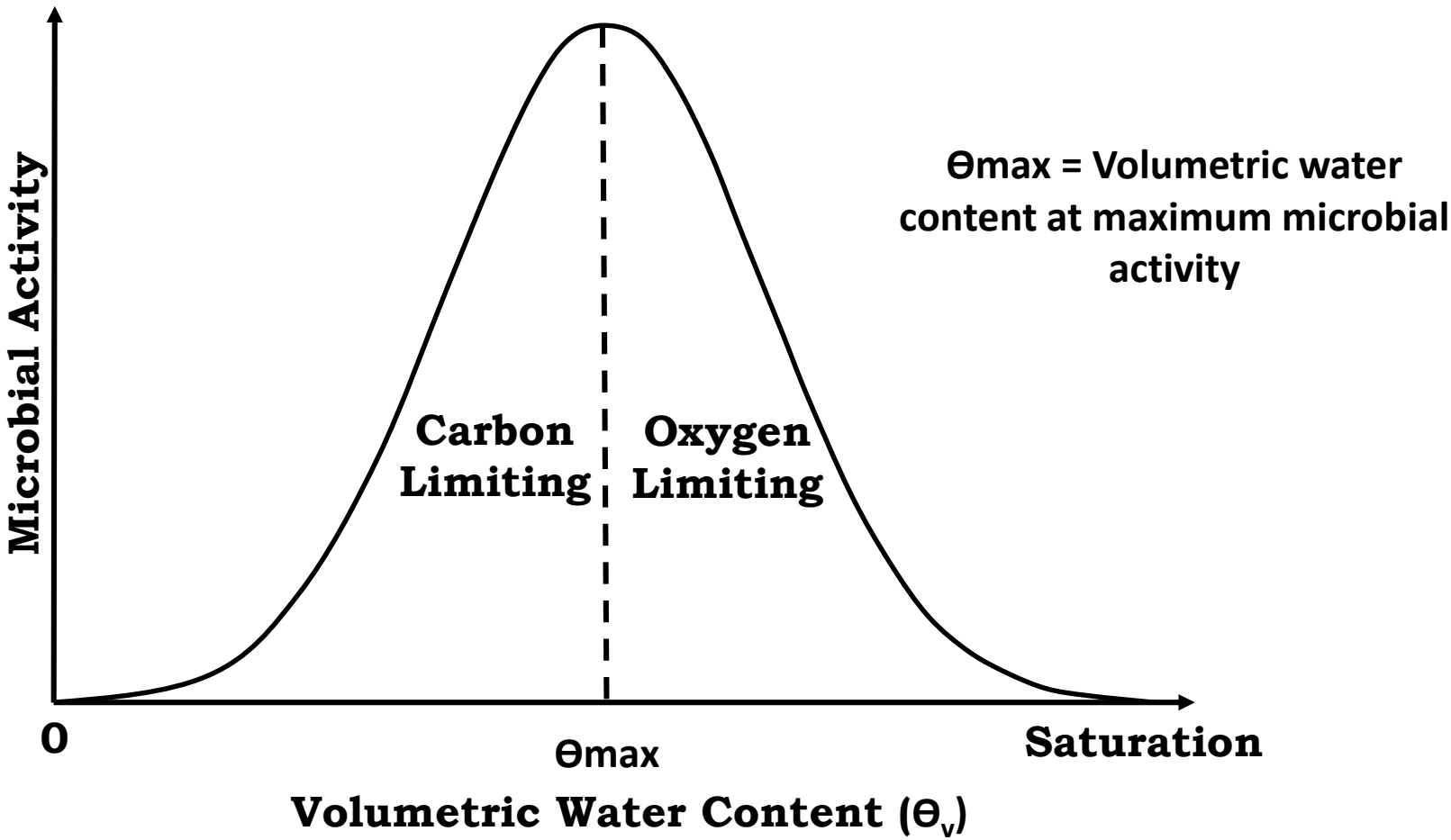
Soil Oxygen

Soil Water

Soil Temperature

Type of Organic Matter

Microbial activity is influenced by water content



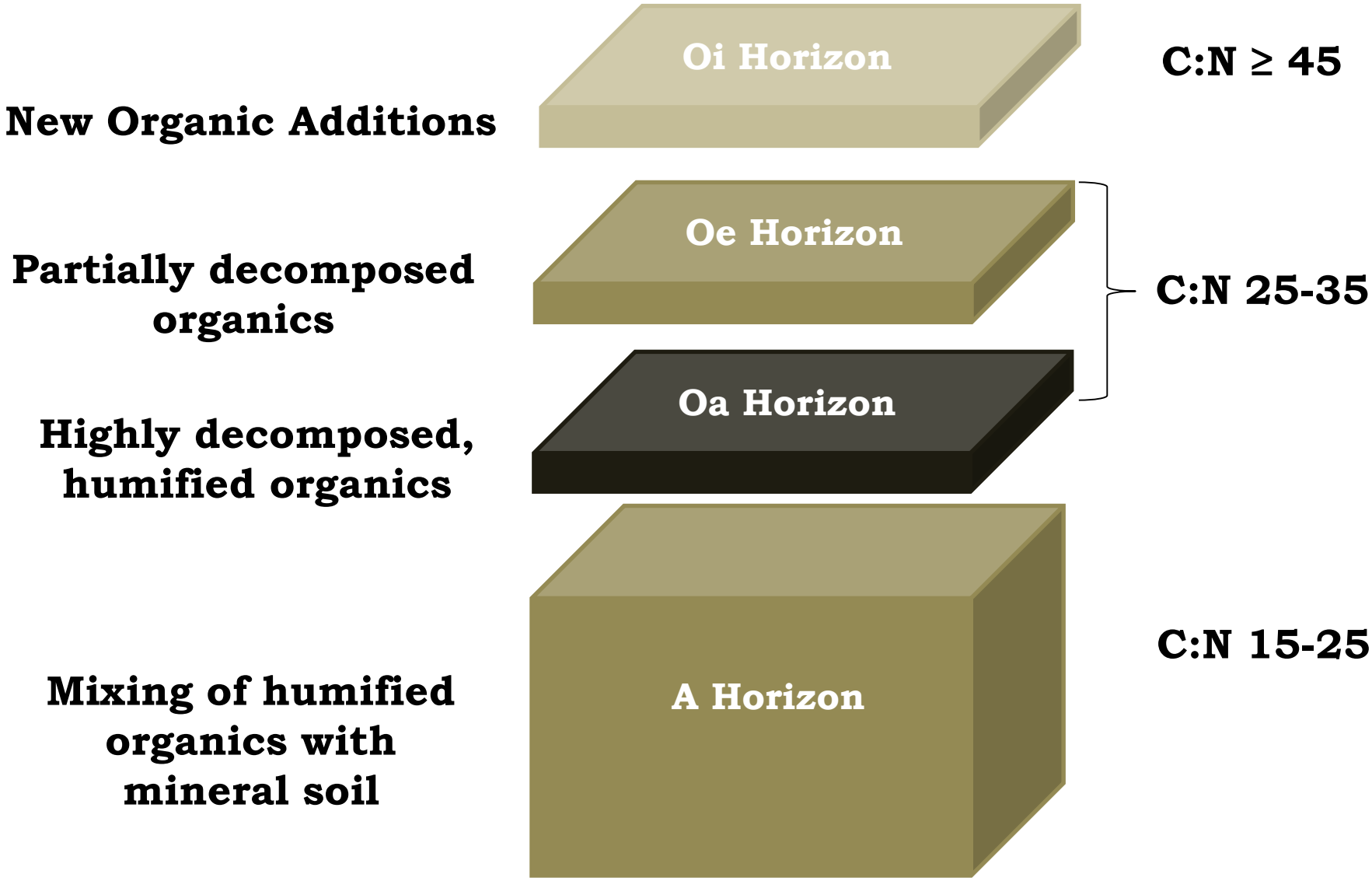
Drawn from: Skopp et al. 1990. SSSA 54:1619-1625.

Type of Organic Input	C:N Ratio
Grass Clippings	20:1
<u>Broadleaf Leaves</u> Fresh Dry	 40:1 60:1
Pine Needles	110:1
Sawdust	500-1,000:1
Wood Chips	700-1,250:1
<u>Bark</u> Conifers Hardwoods	 300-725:1 70-250:1
<u>Twigs</u> < 3 mm 3-10 mm > 10 mm	 97:1 104:1 203:1
<u>Roots</u> < 3 mm 3-10 mm > 10 mm	 70:1 81:1 115:1

In natural systems, the organic additions are varied:

Leaves, twigs, fruit, branches, trunks, roots, etc.

Decomposition creates a C:N gradient that maintains a supply of N and other EE's



Homework:

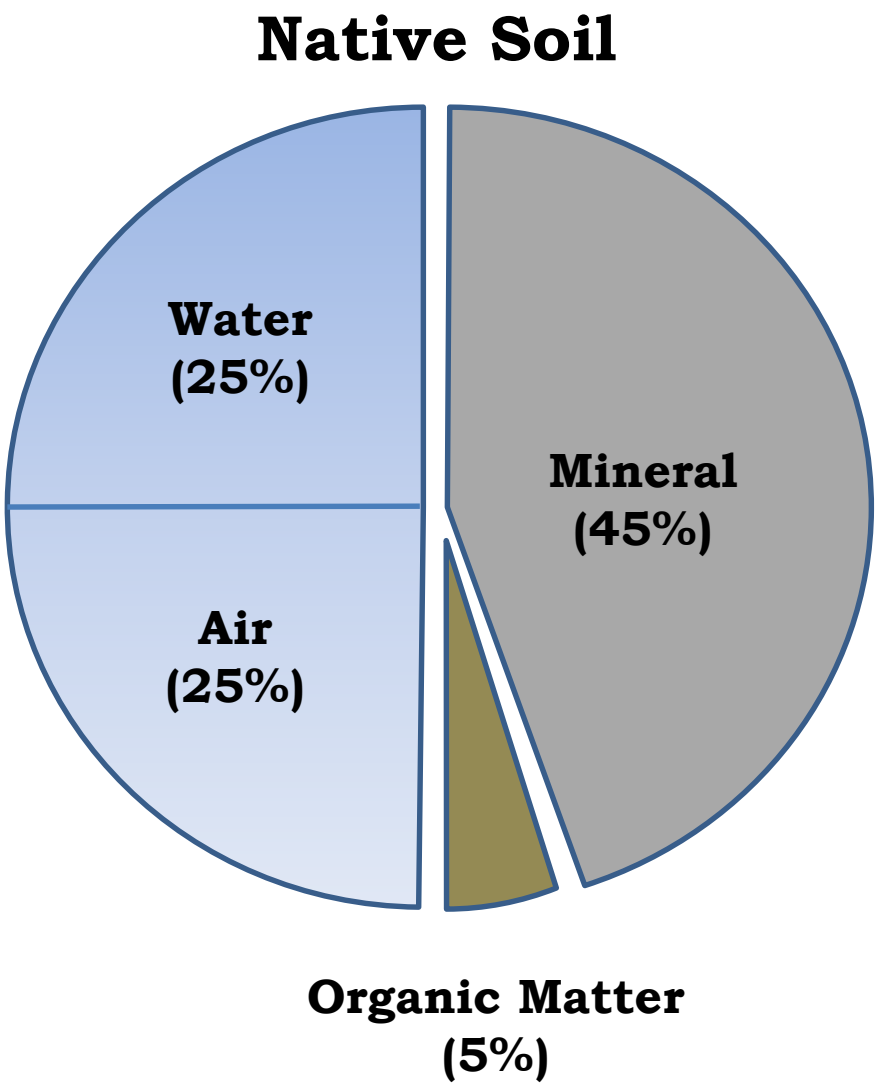
Describe an ideal soil using the characteristics just talked about.

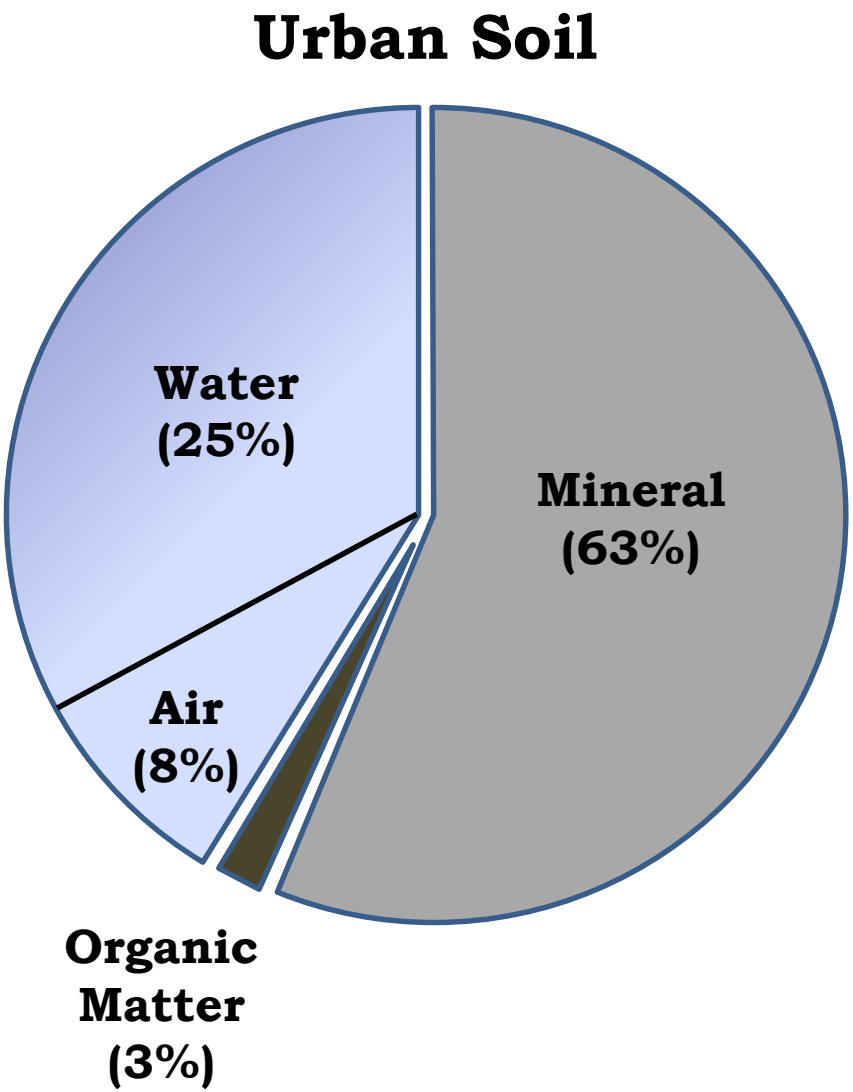
Urban Soils Differ from Natural Soils

Natural Soil

Urban Soil

Photo by L. Werner


Native Soil
Water
(25%)
Mineral
(45%)
Air
(25%)
Organic Matter
(5%)


Urban Soil
Water
(25%)
Mineral
(63%)
Air
(8%)
Organic
Matter
(3%)

From a Trees Perspective:

Critical Soil Factors

(a.k.a. the things that are most often wrong with urban soils)

- **Reduced Soil Fertility**
- **Compromised Soil Structure**
- **Reduced Soil Volume**

Causes for Reduced Soil Fertility

Mineral sub-soils lack the organic content of the topsoil (A horizon)

Photos from web

Causes for Reduced Soil Fertility

Organics removed from the site are a net loss to the nutrient cycle

1-1.5 lbs N/1000 ft^2

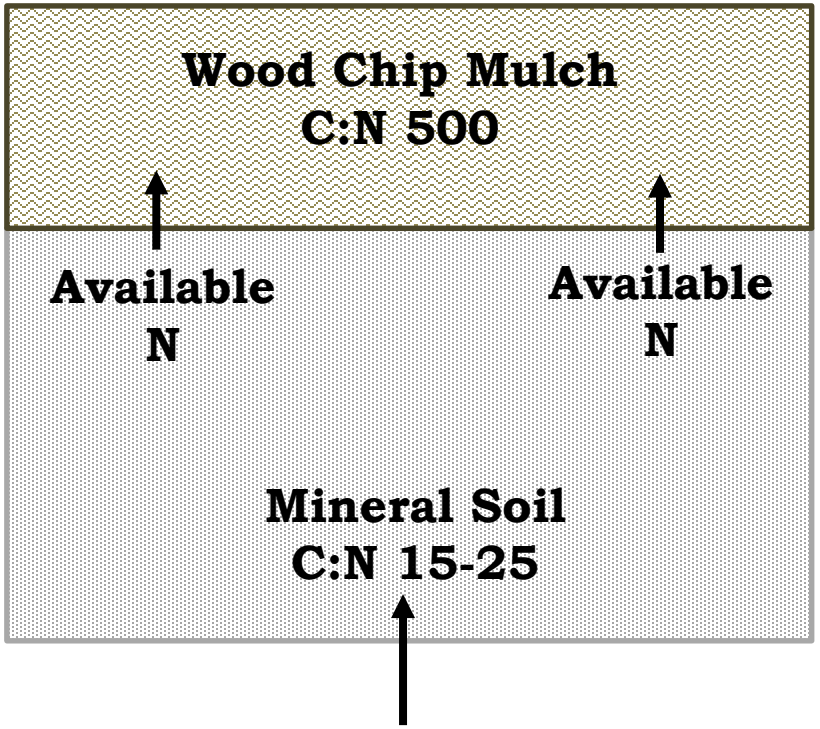
Source: Werner and Miller, 2000, Photos from Web

Causes for Reduced Soil Fertility

The composition and density of plants differs from surrounding forest

Causes for Reduced Soil Fertility

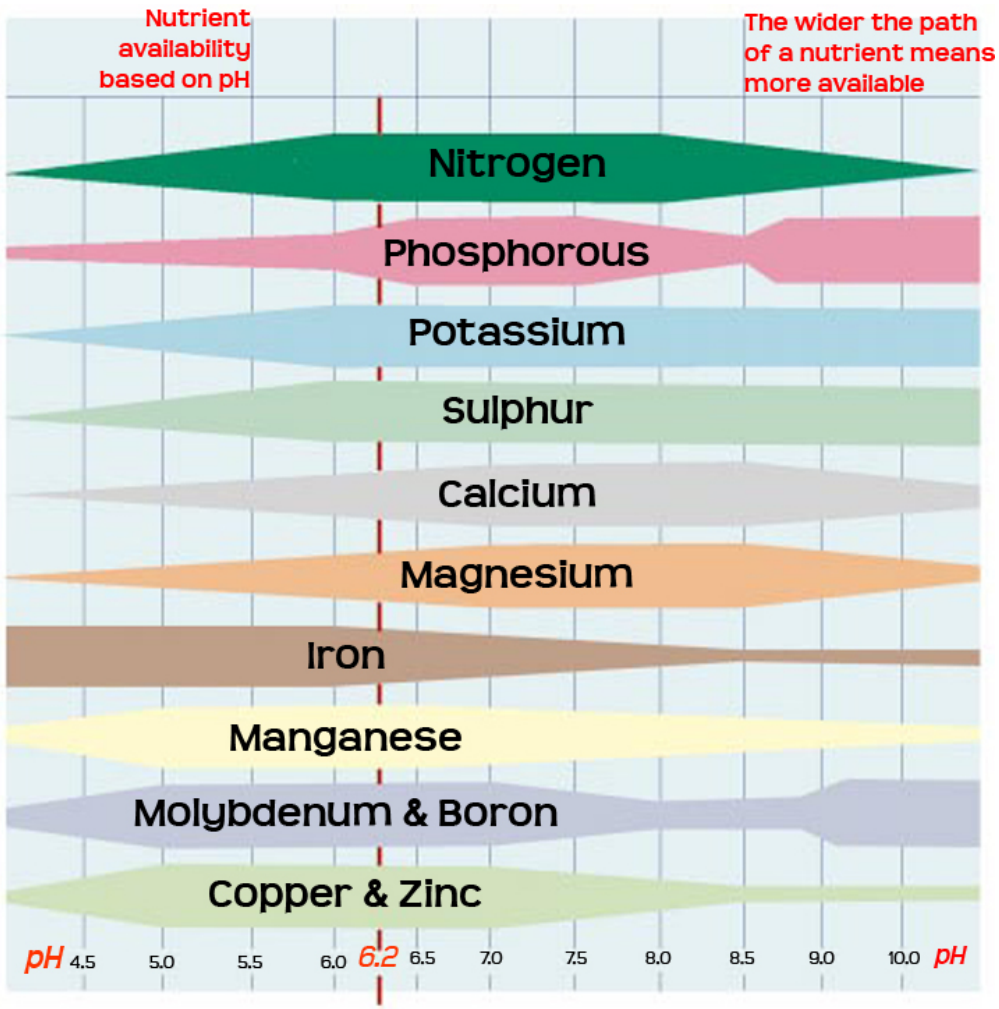
Uniform mulches can alter nutrient dynamics



Below the critical C:N ratio

Photo: L. Werner

Causes for Reduced Soil Fertility



Urban environments tend to be more alkaline

pH affects the availability of essential elements

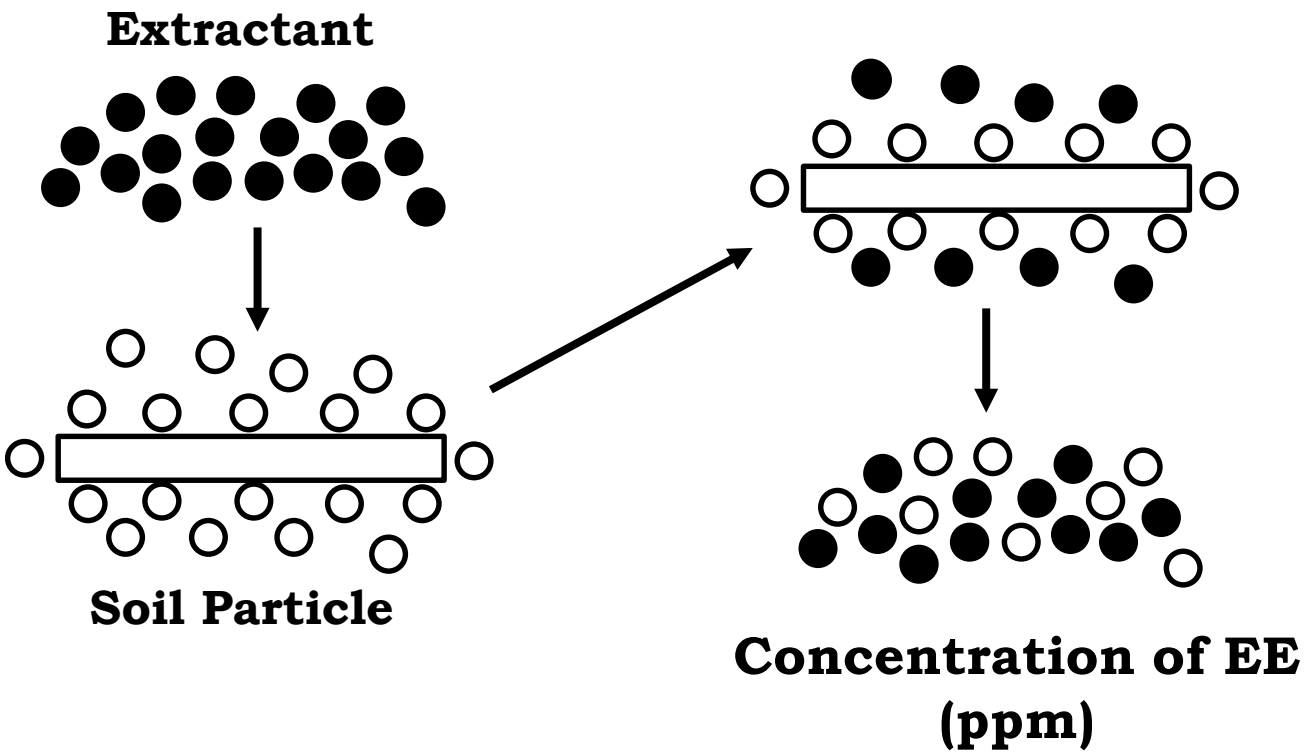
Activity of bacteria/fungi

pH induced Iron Chlorosis

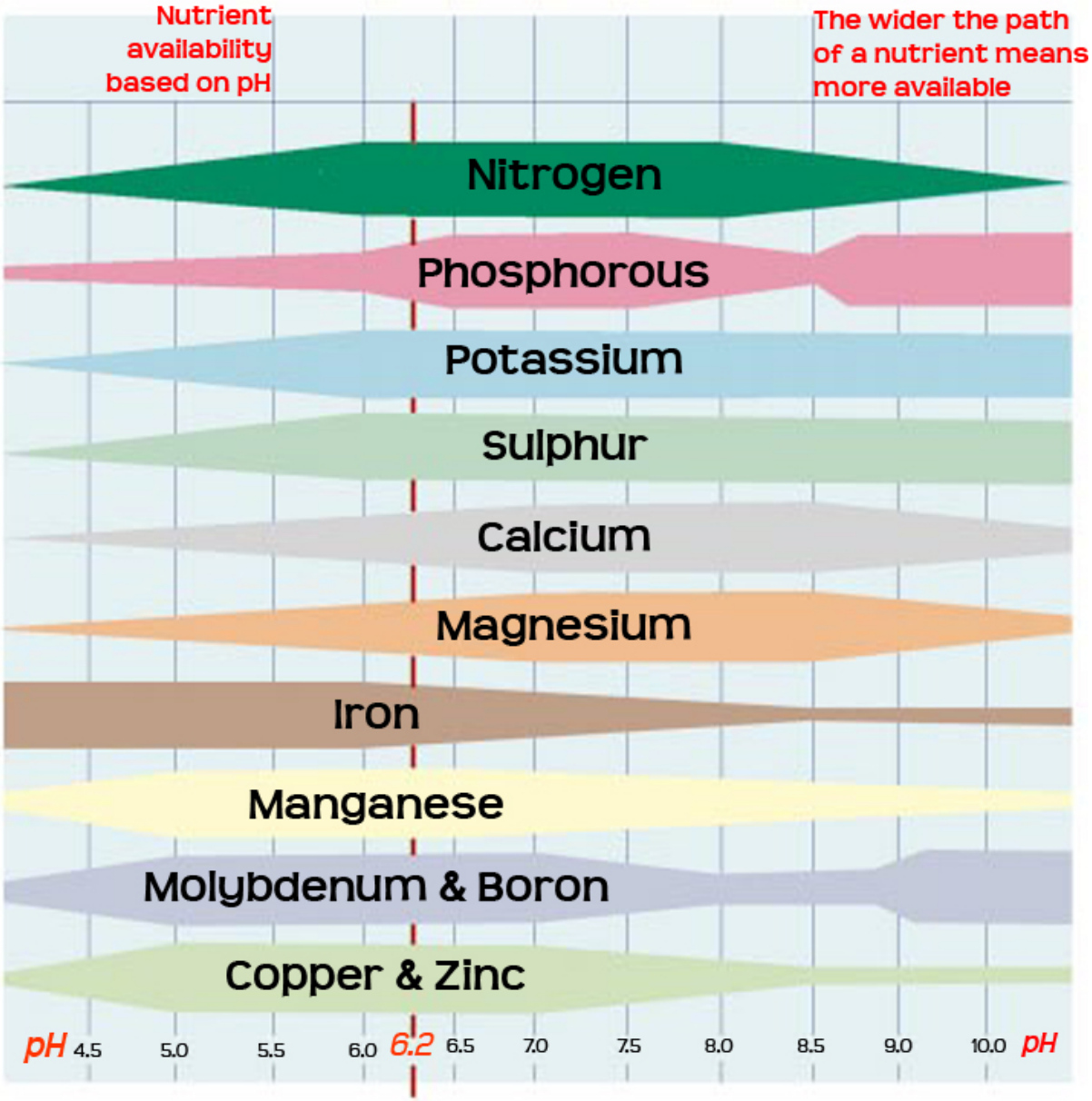
Photos by Purdue Plant & Pest Diagnostic Lab

Common Chemical Tests to Evaluate Soil Fertility

pH, Cation Exchange Capacity (CEC), Base Saturation (BS), Soil OM, Phosphorous



Essential elements are most available between pH 6.2-6.9



Values and Interpretations Vary

Essential Element	Concentration (ppm)
Phosphorus (P)	10 -30
Potassium (K)	75
Calcium (Ca)	300/1000+
Magnesium (Mg)	60/250
Sodium (Na)	< 92
Copper (Cu)	2
Iron (Fe)	10
Manganese (Mn)	5
Zinc (Zn)	1.5

Note: Ca and Mg recommendations are for sandy/clay soils
Na value is a maximum concentration

Source: Griffin, J. 2006. Interpreting a K-State soil test for tree and shrub beds

<u>Nitrogen was not part of the test:</u>

Exchangeable N is not an effective evaluation parameter

Remember: N is derived from decomposing OM and is quickly consumed by soil micro-organisms or plants

Point-in-time analyses do not provide an estimate of long-term N availability

Soil's N supplying power can be determined through OM mineralization tests

or

Estimated based on soil OM content (%)

2,000,000	lbs soil/A
5%	Soil organic matter content
100,000	lbs soil OM/A
5%	N content in soil organic matter
5,000	lbs N /A
2%	N made available per year (mineralization)
100	lbs N /A

Cation Exchange Capacity (CEC) and Base Saturation (BS)

**** Always ask for it when submitting a sample**
- It can be calculated from ppm-

Soil Type	CEC Range
Sand (light color)	1-5
Sand (dark color)	5-8
Loams	10-15
Silt Loams	15-25
Clay/Clay Loam	20-50

Base Saturation rates > 75% are desirable

Evaluating Soil Structure

The type (texture) and arrangement (vertical/horizontal) of soil particles influences:

Water Movement & Holding Capacity

Air Content

Rooting Depth

Soil biology

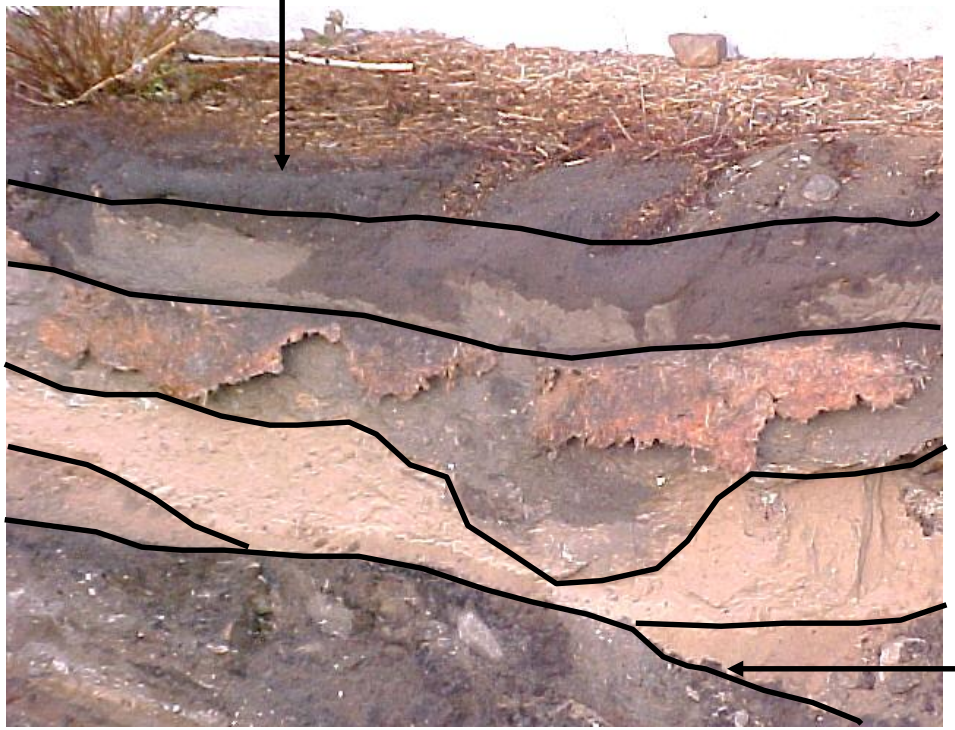
Causes for Compromised Soil Structure
Urban Soils are Highly Disturbed

Mineral sub-soils lack the organic content of the topsoil (A horizon)

Photos from web

Causes for Compromised Soil Structure

Note: Saturated Surface Soil



Vertical discontinuities can impede water drainage

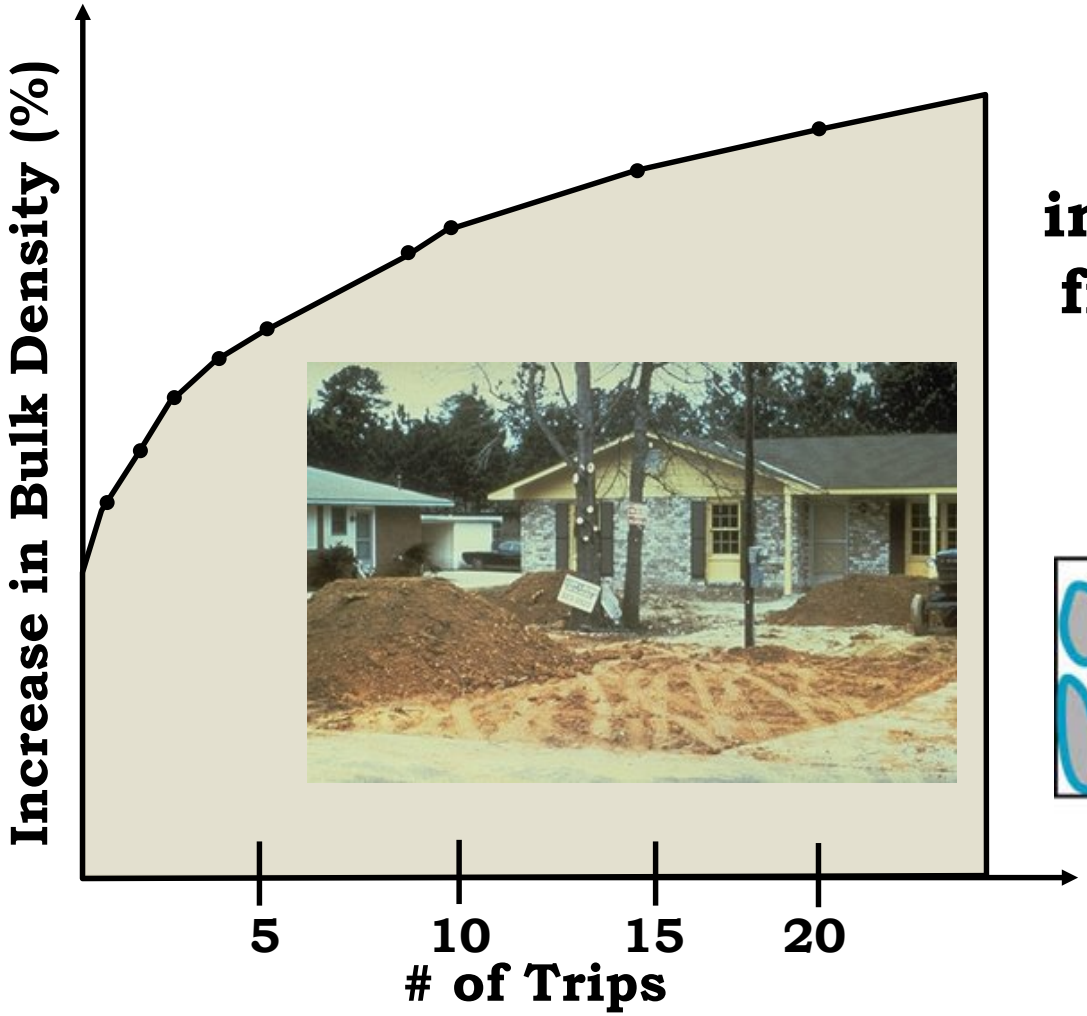
Original Soil Grade

Demonstration

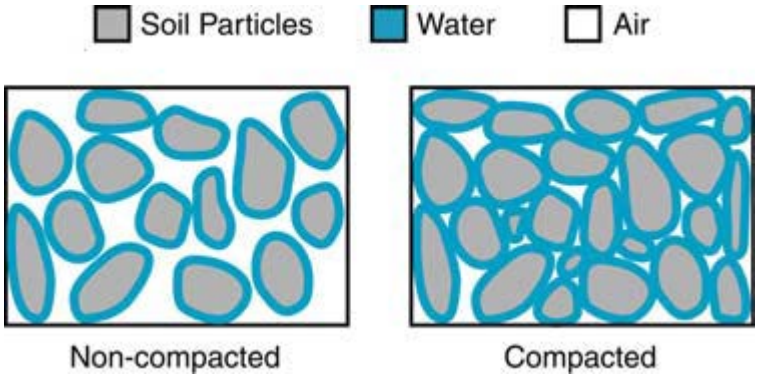
Photo: L. Werner

Causes for Compromised Soil Structure

Urban soils tend to be highly compacted



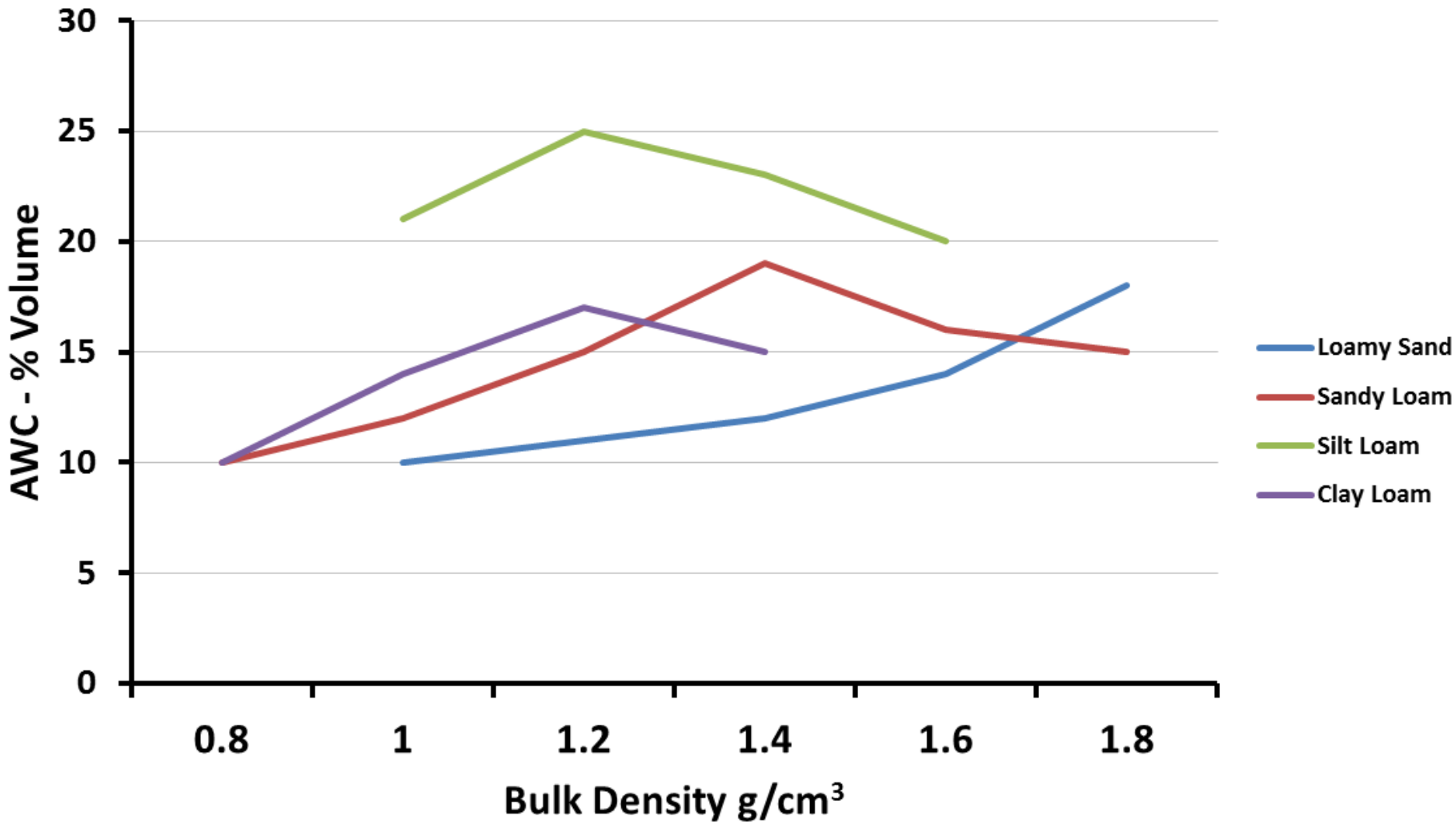
Compaction increases the mineral fraction and reduces pore space



Source: NRCS Urban Soil Primer

Source: WI DNR, Forest Management Guidelines

Compaction (a.k.a. bulk density) affects plant available water



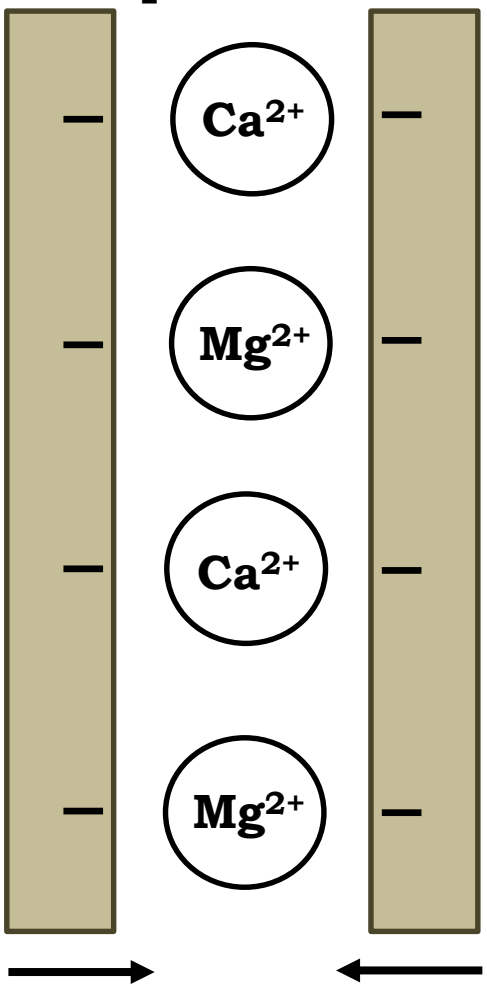
Drawn from data in Archer and Smith, 1972

Demonstration

Causes for Compromised Soil Structure

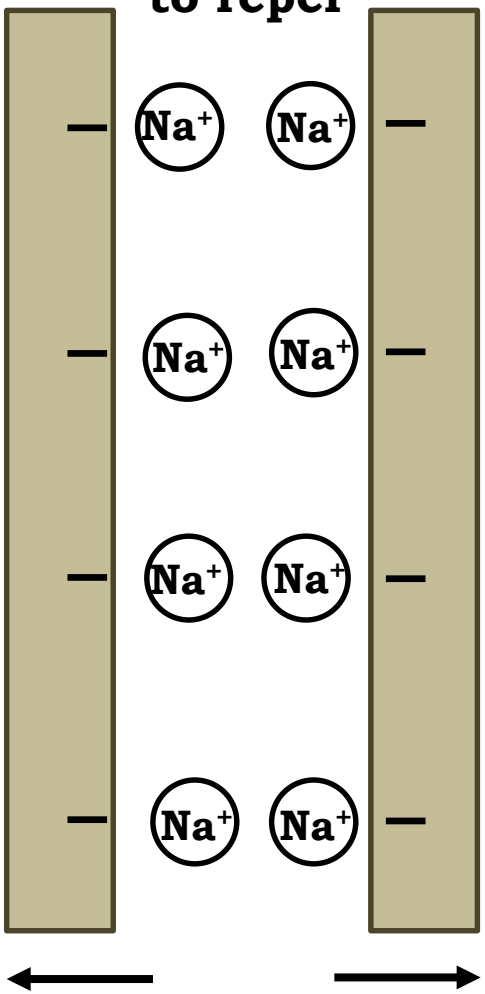
High sodium levels can destroy soil aggregates and increase compaction

Divalent Ca^{2+} and Mg^{2+} form bridges between particles



Deicing salts high in sodium are common in northern cities

Monovalent Na+ causes the particles to repel



Common Physical Tests to Evaluate Soil Structure

Bulk Density

Soil Organic Matter Content

Thickness of Organic Layer & A Horizon

Depth to Restrictive Layers

Soil Aggregation

Bulk Density is a measure of the amount of solids and pore space

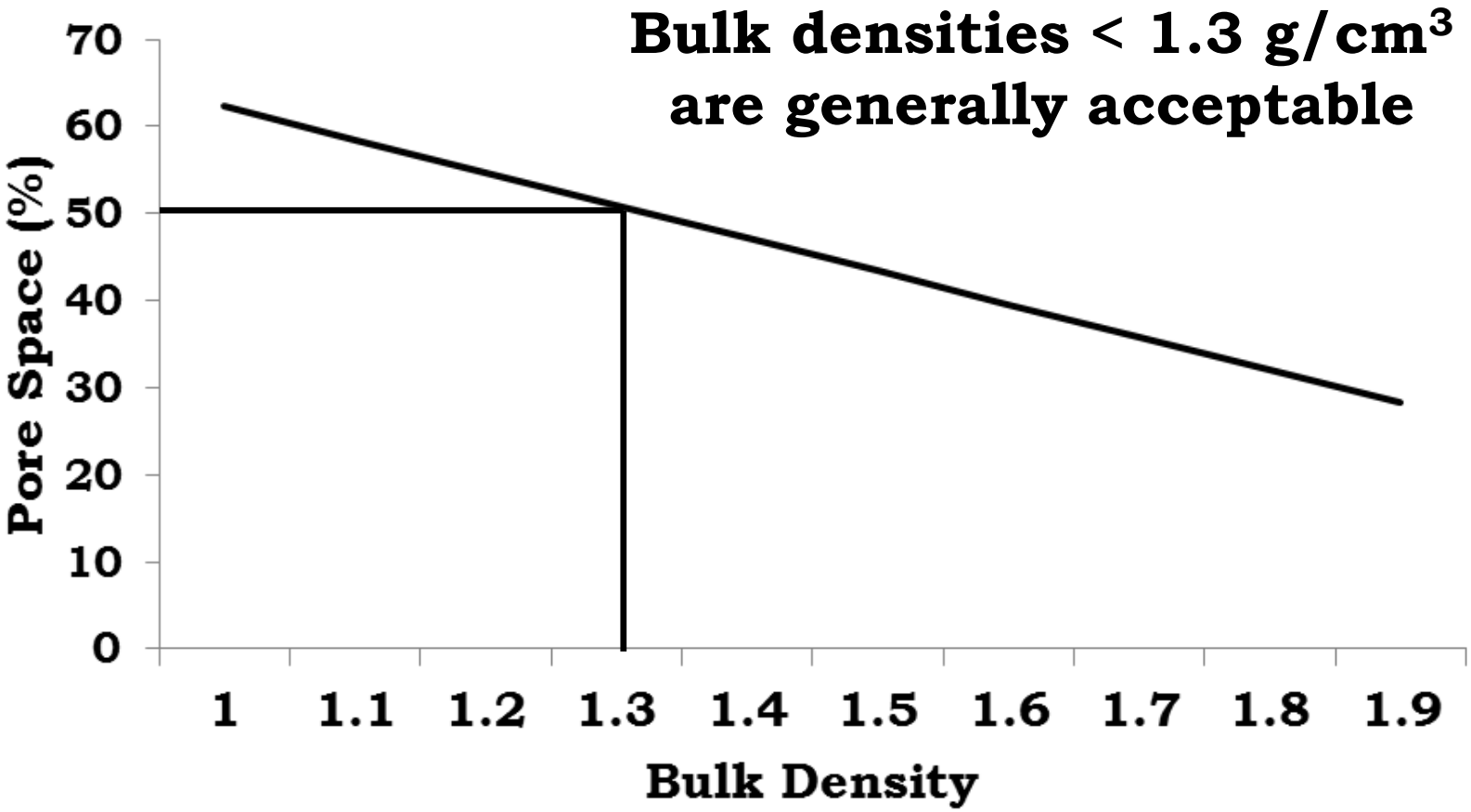
Bulk density = dry weight (g) / volume (cm^3)

% solids = 100 x (bulk density ÷ particle density)

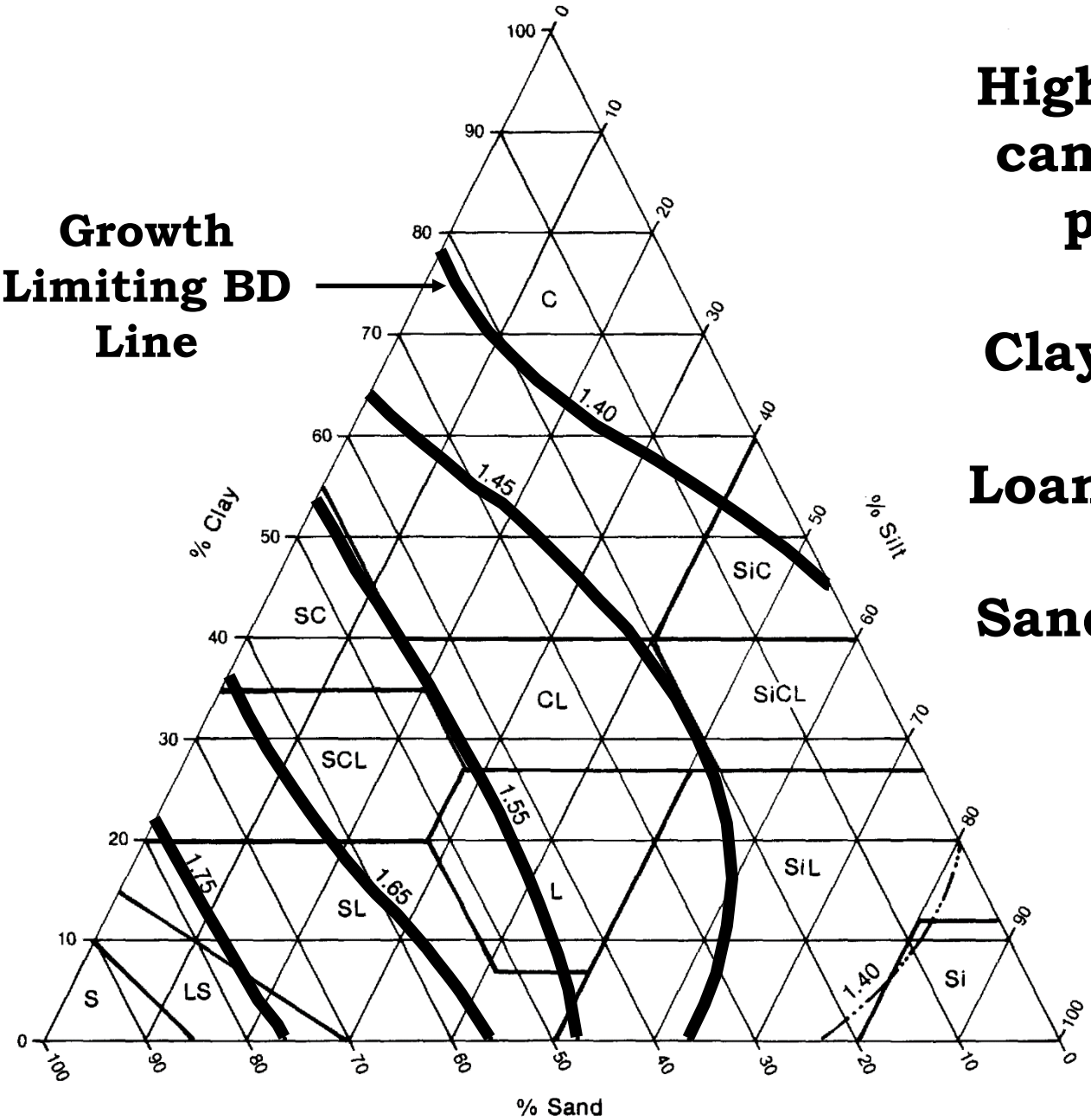
Note: Particle density = 2.65 g/cm^3 = quartz

% pore space = 100 - % solids

Ideal soil is 50% solid, 50% pore space



Growth Limiting BD Line



High bulk density can restrict root penetration

Clay ~ 1.4 g/cm3

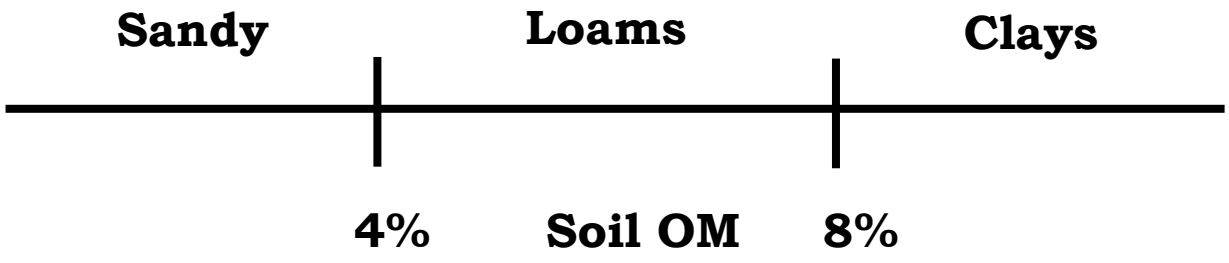
Loam ~ 1.5 g/cm3

Sand ~ 1.7 g/cm3

Dadow and Warrington, WSDG-TN 00005 1985

5% Organic is commonly depicted as being desirable

Range of soil OM contents typically observed in soils varies with soil texture



Digging out a soil profile in problem areas can be of great assistance in diagnosing soil structure

*** Thickness of Organic Layer**
*** Rooting depth**
*** Depth of soil**
*** Depth to restrictive layers**
*** Potential contaminants**

Evaluating Soil Volume

Plant available water and EE increase with increasing soil volume

120 ft³ of Soil

500 ft³ of Soil

1000 ft³ of Soil

Tree Space Design - Courtesy of Casey Tree

Evaluating Soil Volume

Photo courtesy of Casey Tree

Trees planted at the same time

How Much Soil Does a Tree Need?

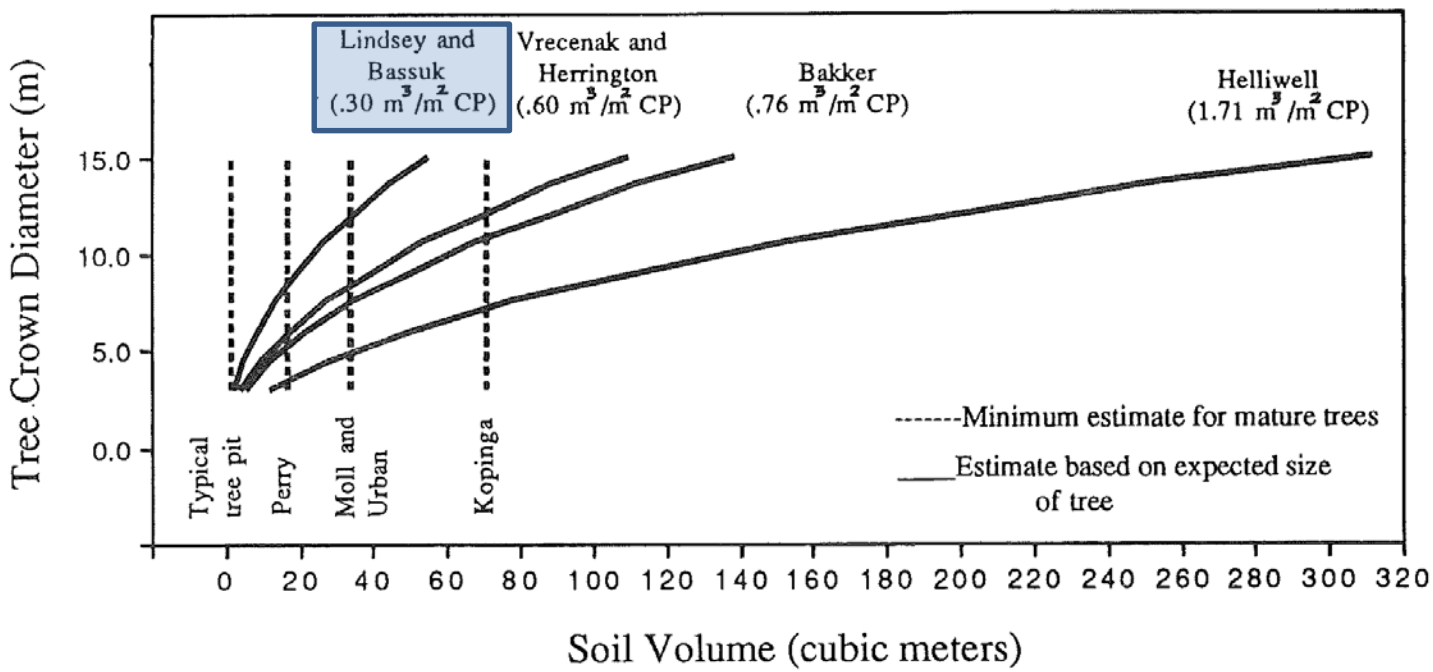
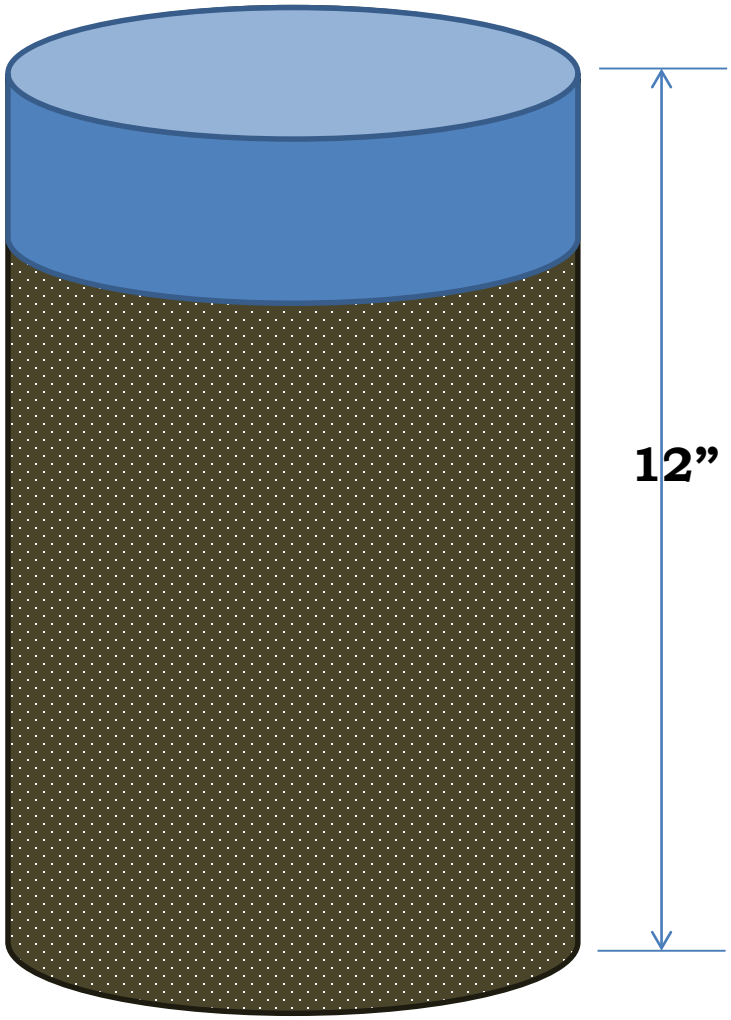


FIGURE 1. A comparison of recommended soil volume estimates. A typical tree pit is 1.8 m^3. HELLIWELL (1986) and VRECENAK and HERRINGTON (1984) estimates were re-interpreted by authors to relate to crown projection (CP). Crown projection is defined as the total surface area of the ground area under the dripline of a canopy. It is easy to measure and is frequently used as a way to quantitatively describe the canopy relative to some other measurement of plant growth or development.

0.3 m^3 / m^2 Canopy

Managing Soil Water



$$\theta_v = \frac{Volume\ of\ Water}{Volume\ of\ Soil}$$

Volume = Area x Depth

Area of Soil = Area of Water

Therefore:

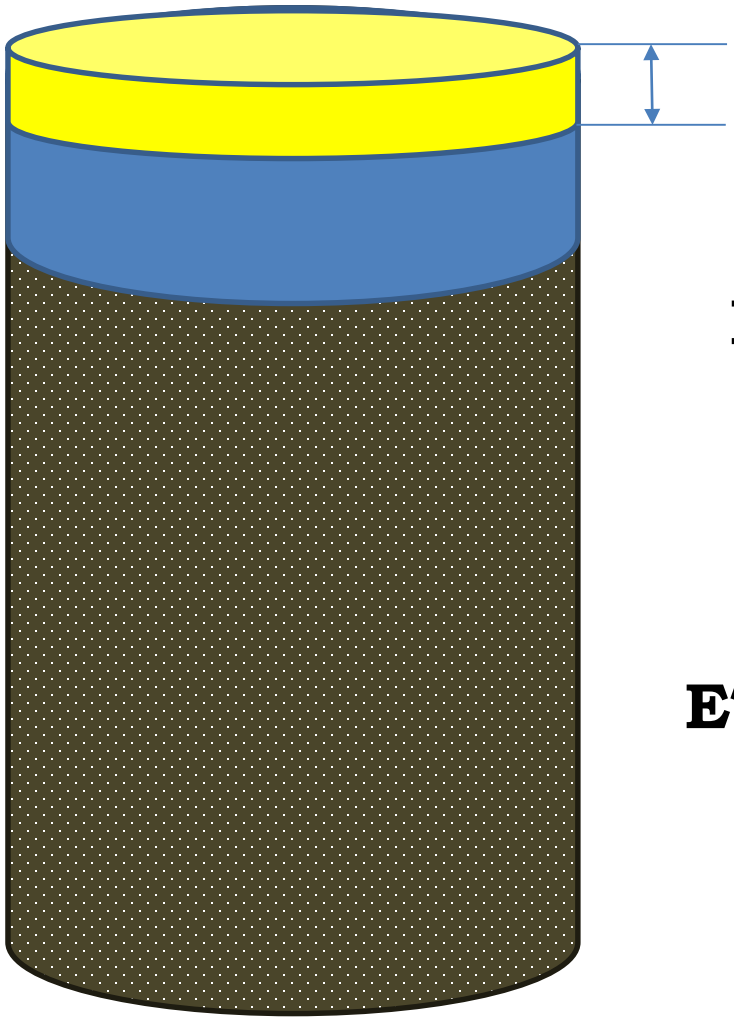
Soil Depth x θ_v = Depth of Water

Example:

θ_v = 15% = 0.15
Depth of Soil = 12”

12” x 0.15 = 1.8”

Managing Soil Water



Water Lost Through Evapotranspiration
ETc

ETc is hard to measure, so it is estimated:

ETc = ETo x Crop Coefficient

ETo = potential ET (pan/bare soil)

Crop Coefficient for deciduous trees with leaves on = 0.9

Example 1:

It has been 2 weeks since the last rain fall. How much water should be added to a tree with a 50' canopy spread?

Information Needed:

Current Volumetric Water Content (θ_v)

Estimate of θ_v at field capacity

Estimate of Rooting Depth

θ_v at Field Capacity:	**30%**
θ_v Current	**18%**
Difference	**12%**

18” Rooting Depth x 0.12 = 2.16” of Water

(1963.5 ft^2 Canopy) (2.16”) 0.623 = 2,642 gallons

$$0.623 = \frac{7.48\ gallons/ft^3}{12\ inches/ft}$$

Example 2:

The forecast is for a continued drought. I want to keep the moisture content at or near field capacity for the tree just watered (50' spread). How much water should be added on daily/weekly basis?

Information Needed:

Estimate of Average Daily ETo

Crop Coefficient Value

Average Daily ETo = 0.19” / day

Leaf On Deciduous Tree
Crop Coefficient = 0.9

(0.19”/day)0.9 = 0.17”/day

(1963.5 ft^2 Canopy) (0.17”) 0.623 = 207 gallons/day

207 gallons/day x 7 days/week = 1455 gallons/week

Soil Volume is also about structural roots

Photos: L. Werner

Photo: A. Uhen

Supplying water and EE to promote growth is not always a good idea!