Soils and Site Quality

ReTree Nebraska
November 9-10, 2016
Omaha, NE

Dr. Les Werner
UW Stevens Point
Les. Werner@uwsp.edu

What is Soil/Site Quality?

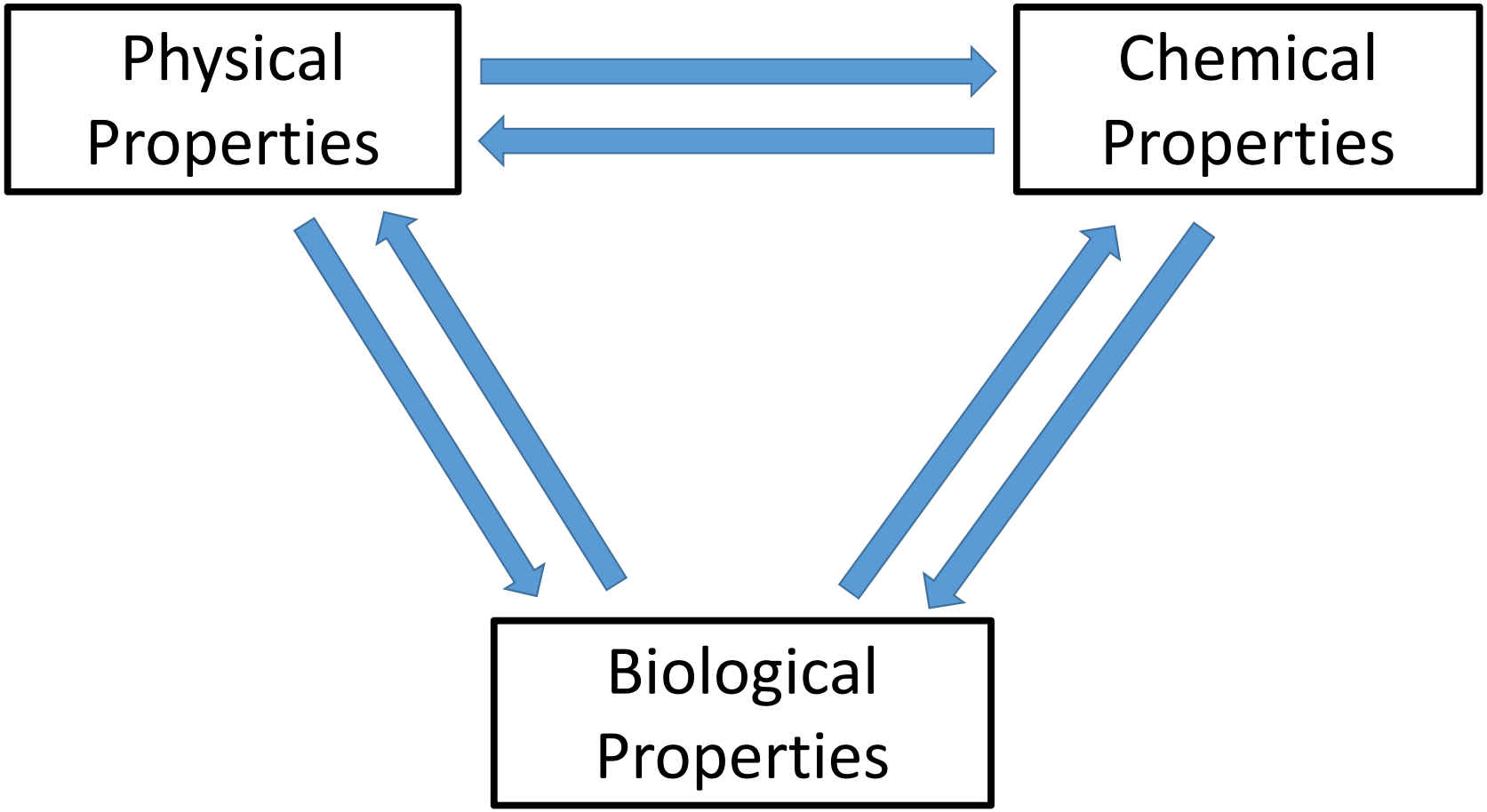
The ability to support growth within a given climatic region

Evaluations are typically based on soil attributes

- Physical properties (P)
- Chemical properties (C)
- Biological properties (B)

Complex Interactions between Properties

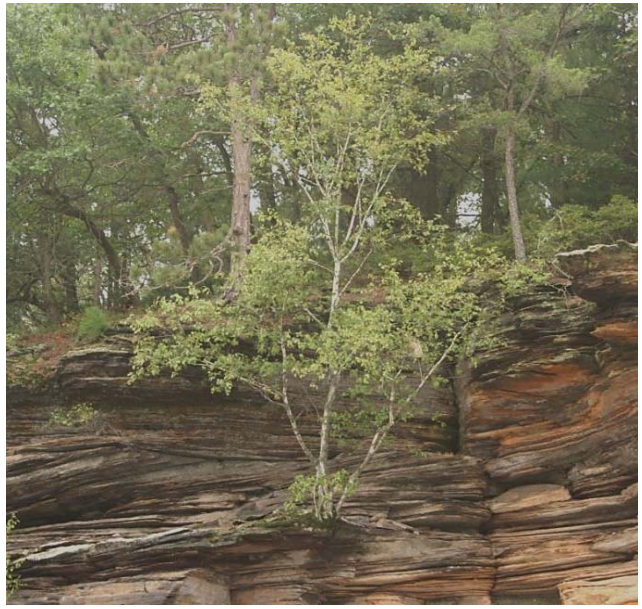
Acutely so for long-lived, woody plants



Fundamentally, this a talk about relationships!

Siberian Larch
Lava field, Mongolia

Eastern White Pine
Lake Superior

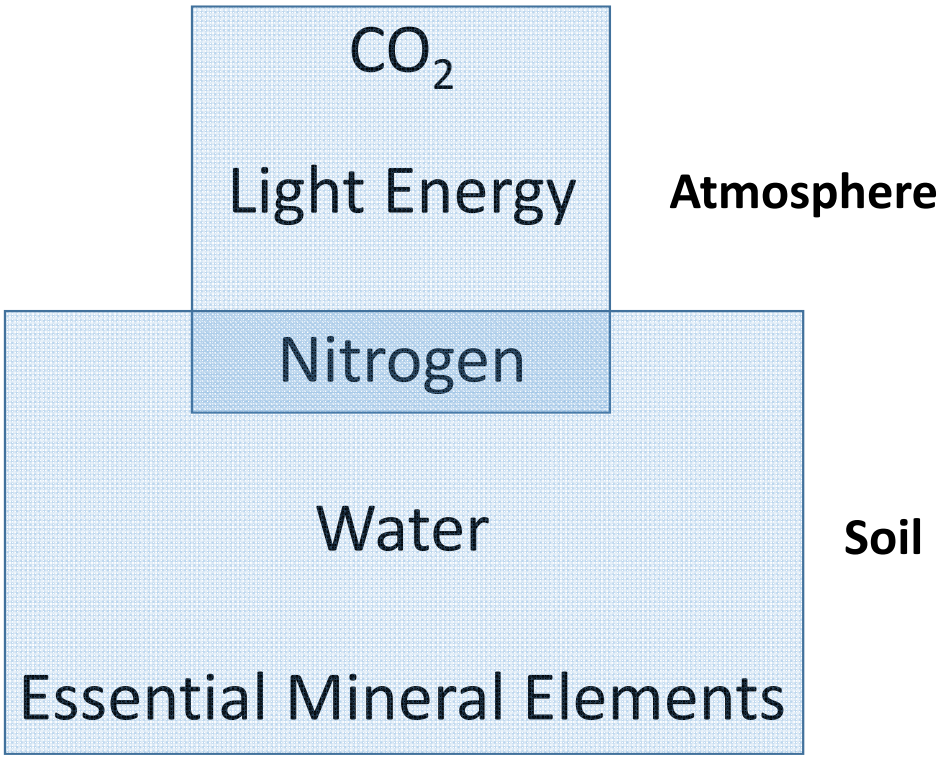


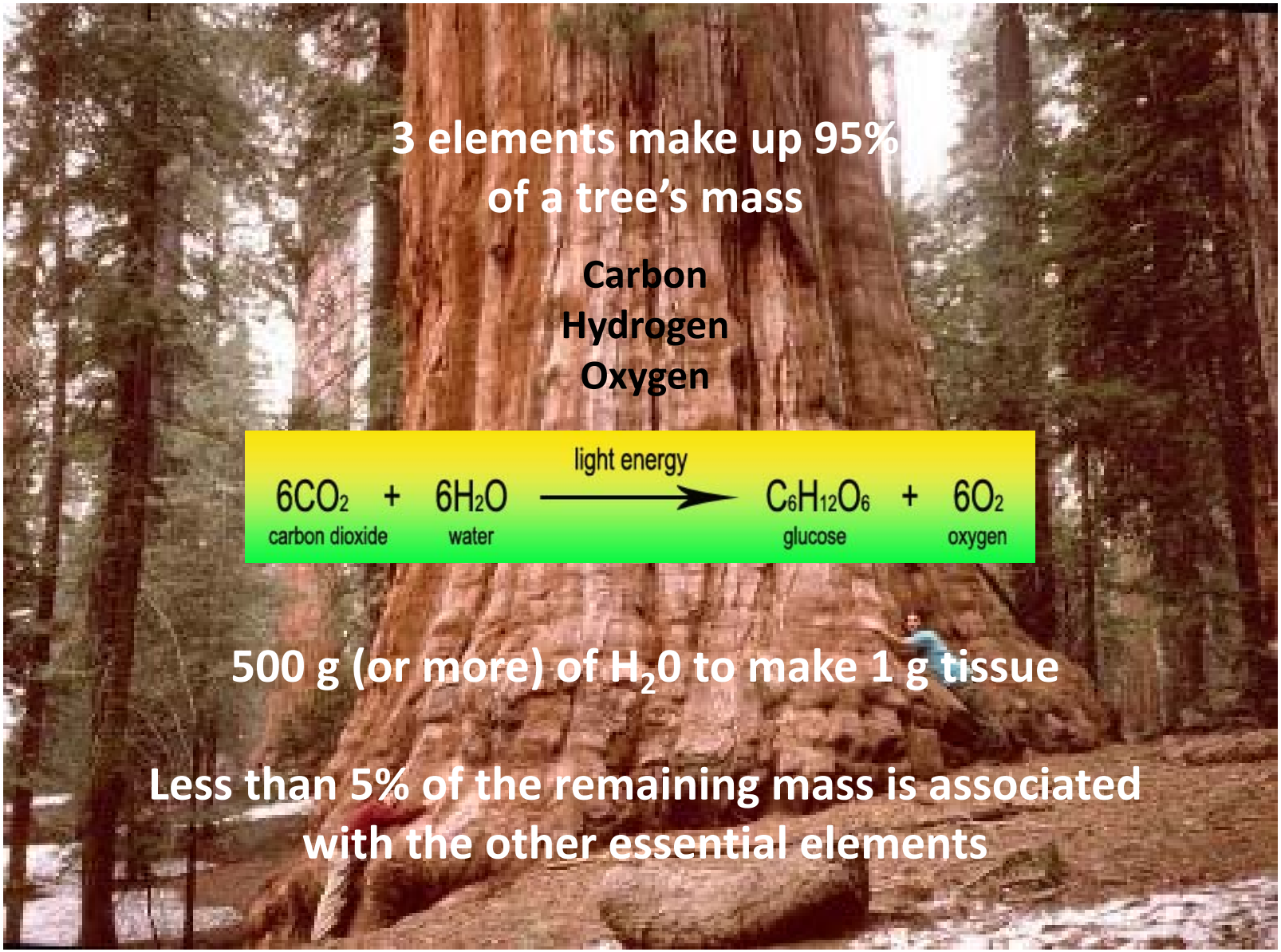
River Birch
Wisconsin River

Photos by L. Werner

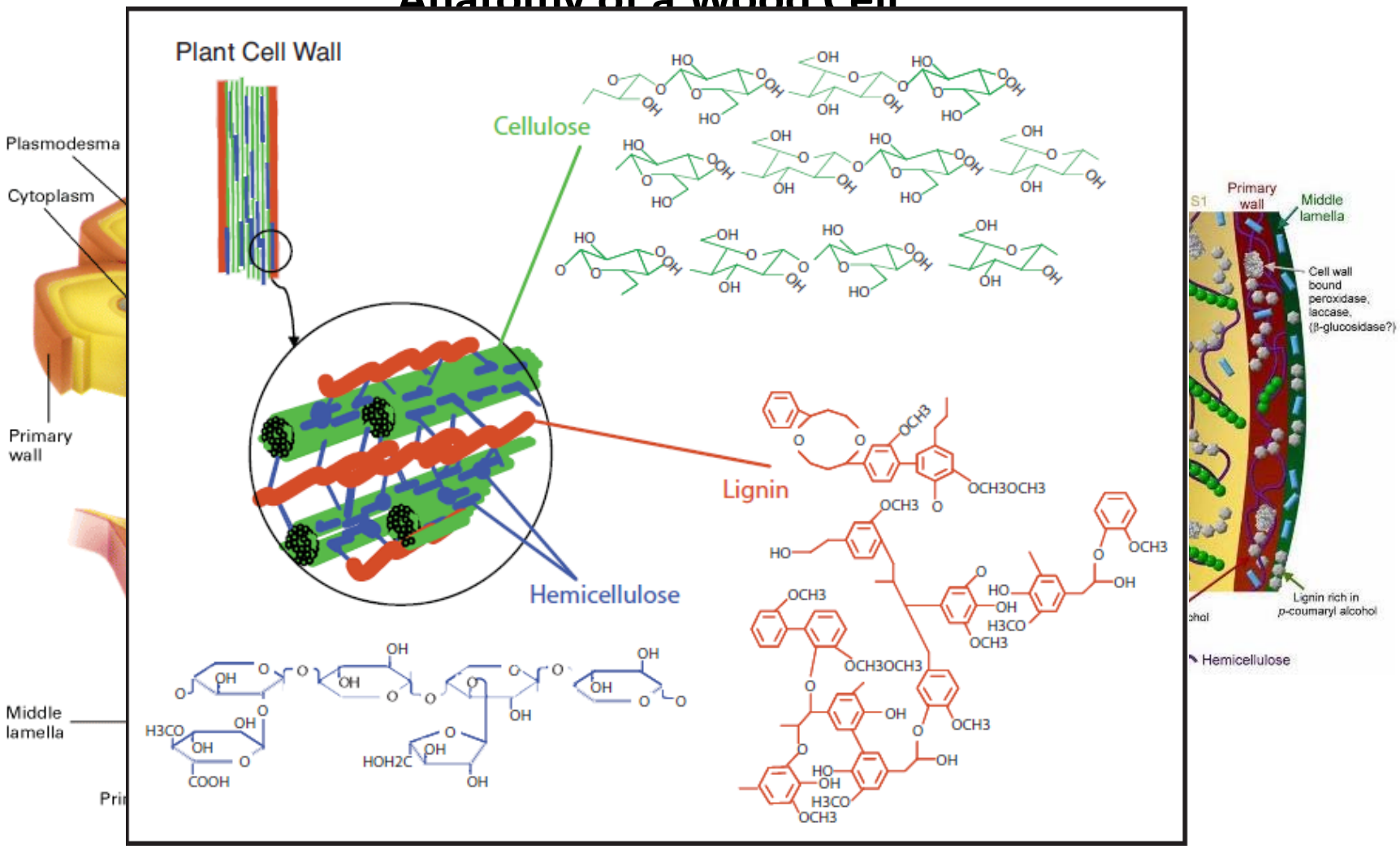
Let's start at the beginning,

What do trees need?




3 elements make up 95%
of a tree's mass
Carbon
Hydrogen
Oxygen
light energy
6CO2 + 6H2O → C6H12O6 + 6O2
carbon dioxide
water
glucose
oxygen
500 g (or more) of H20 to make 1 g tissue
Less than 5% of the remaining mass is associated
with the other essential elements

Anatomy of a Wood Cell



Relative Abundance of the Remaining 5%

Element	Percent	Relative # of Atoms	
Molybdenum	-	1	Micro
Copper	-	100	
Zinc	-	300	
Manganese	-	1,000	
Iron	-	2,000	
Boron	-	2,000	
Chlorine	-	3,000	
Sulfur	0.1	30,000	Macro
Phosphorus	0.2	60,000	
Magnesium	0.2	80,000	
Calcium	0.5	125,000	
Potassium	1.0	250,000	
Nitrogen	1.5	1,000,000	

Essential Mineral Elements

Derived from “Plant Analysis Handbook II” – Mills and Jones, 1996

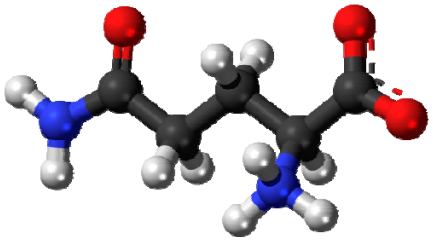
Element	Sufficiency Range*	Mobility
Nitrogen	1 - 6%	M
Phophorus	0.2 - 0.5 %	M
Potassium	1.5 - 4%	M
Calcium	0.5 - 1.5 %	I
Magnesium	0.15 - 0.40 %	M
Sulfur	0.15 - 0.5 %	I
Iron	50 - 75 ppm	I
Manganese	10 - 200 ppm	M
Zinc	5 - 10 ppm	-
Molybdenum	0.15 - 0.30 ppm	-
Copper	3 - 7 ppm	I
Chlorine	50 - 200 ppm	-
Boron	~ 20 ppm	-

* Sufficiency concentrations are based on newly developed tissues (leaves)

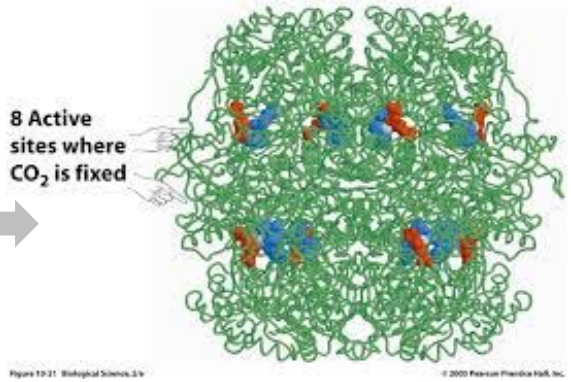
Focus on Nitrogen

Inorganic N is used to make amino acids

(the primary N bearing compounds in trees)



Amino acids are used to make proteins



Sources of Essential Elements to Support Tree Growth

(excludes C, H, O)

Internal Cycling

Atmospheric Deposition

Biological Fixation

Soil

- Weathering of mineral soil

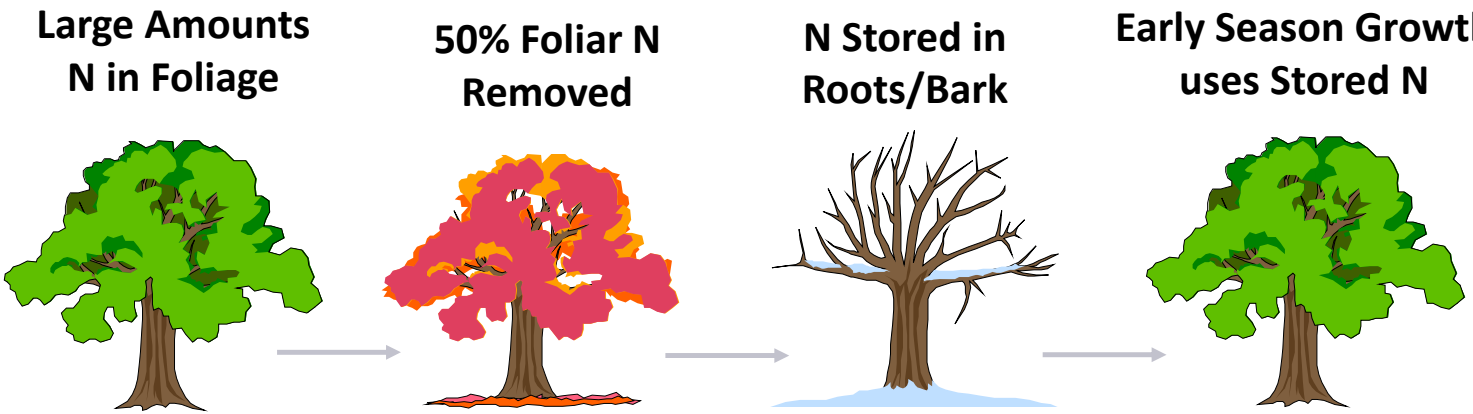
- Decomposition/Mineralization of organic matter

Internal Cycling

Acquisition of resources is expensive

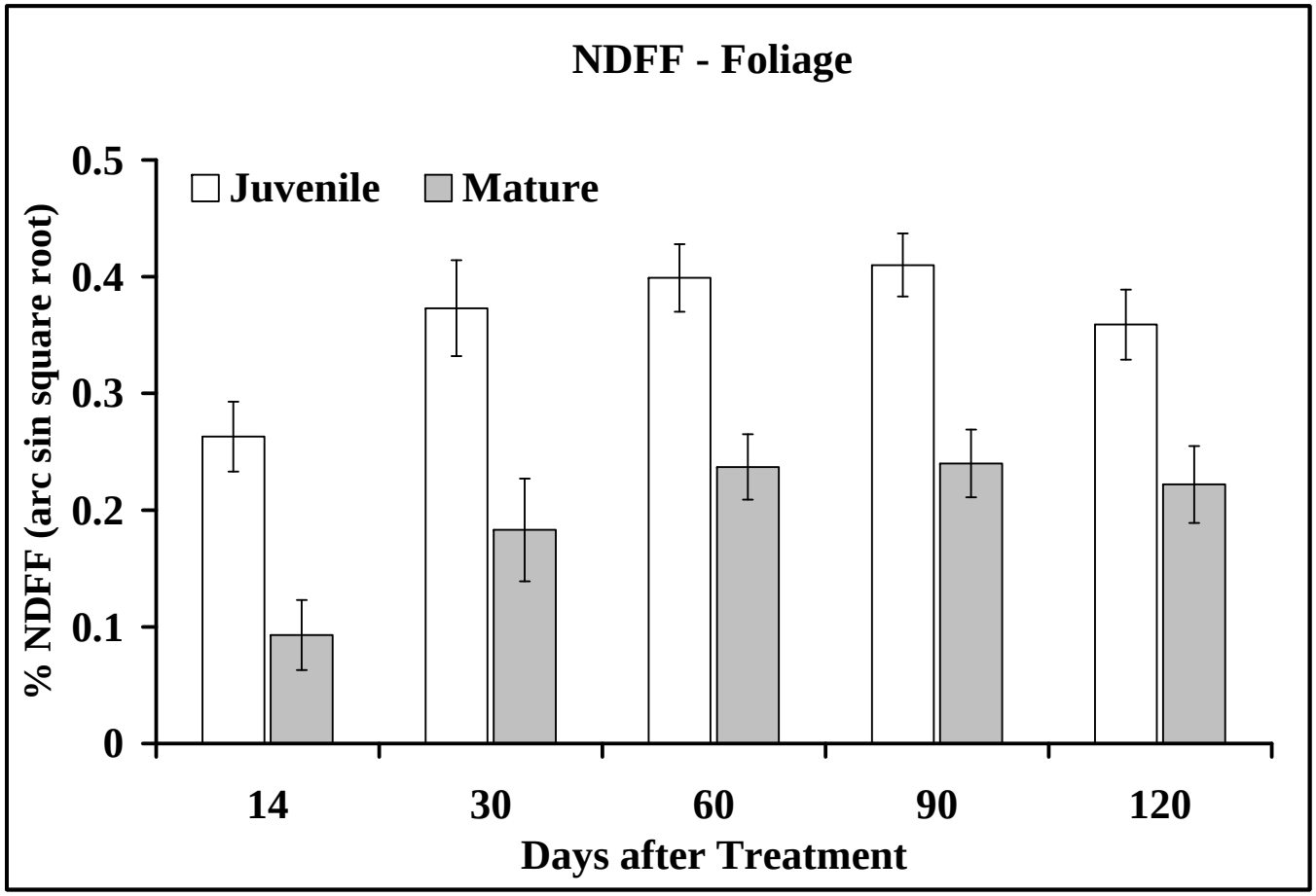
Mobile Elements

N, P, K, Mg, Mn



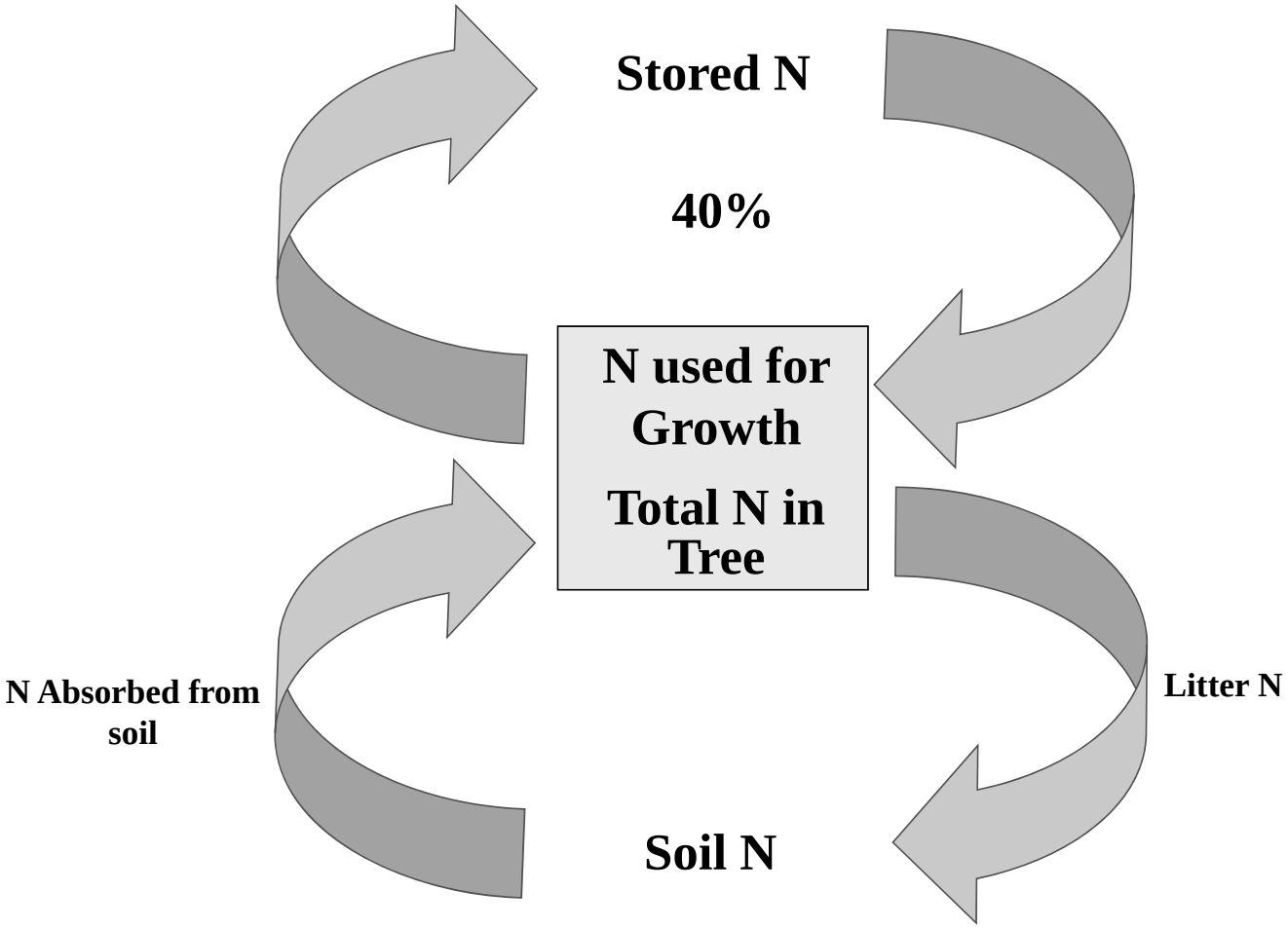
Aerts, 1996 Nutrient resorption from senescing leaves of perennials: Are there general patterns? Ecology 84:597–608.

Internal Cycling



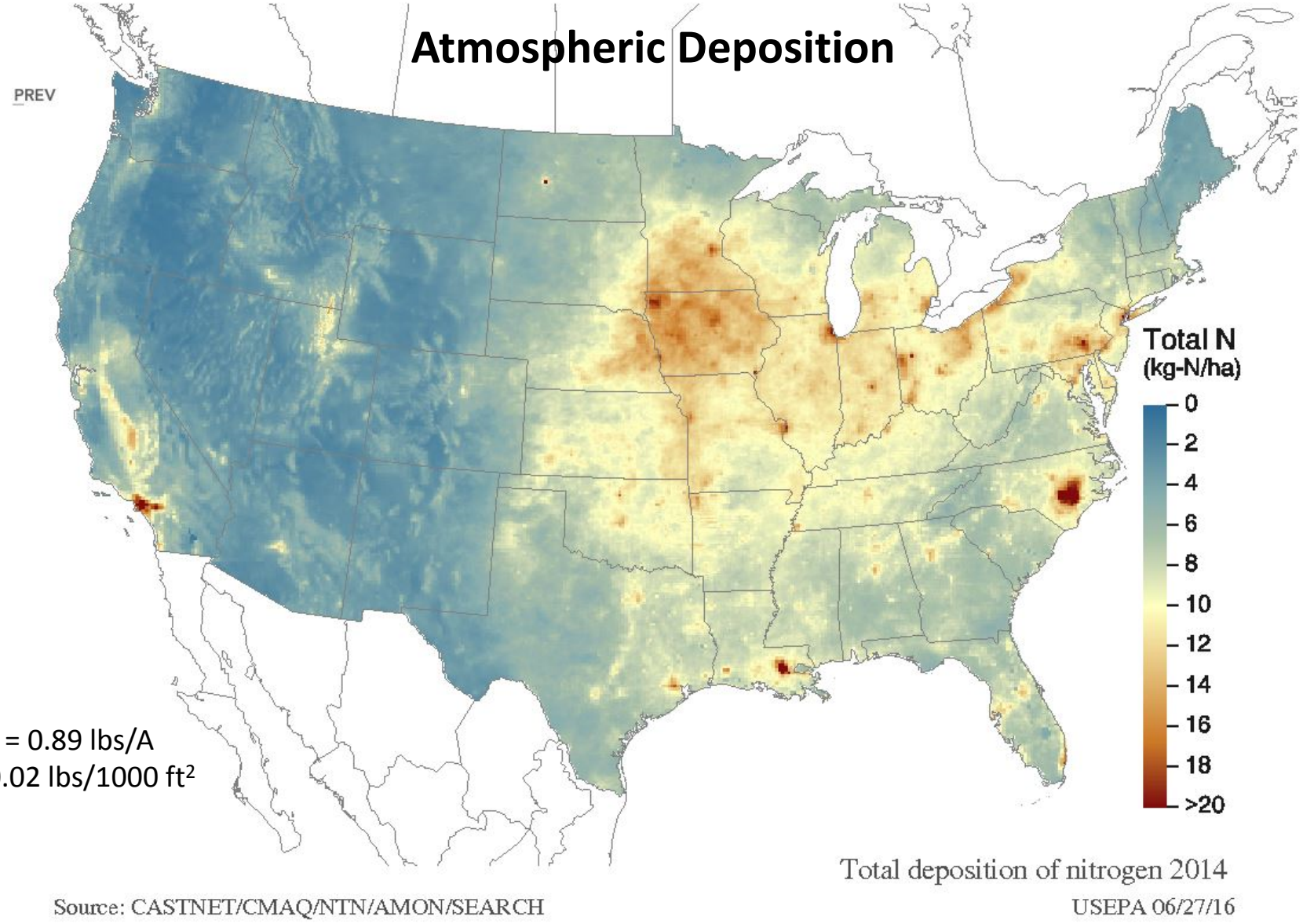
Werner and Jull, 2012

Internal Cycling



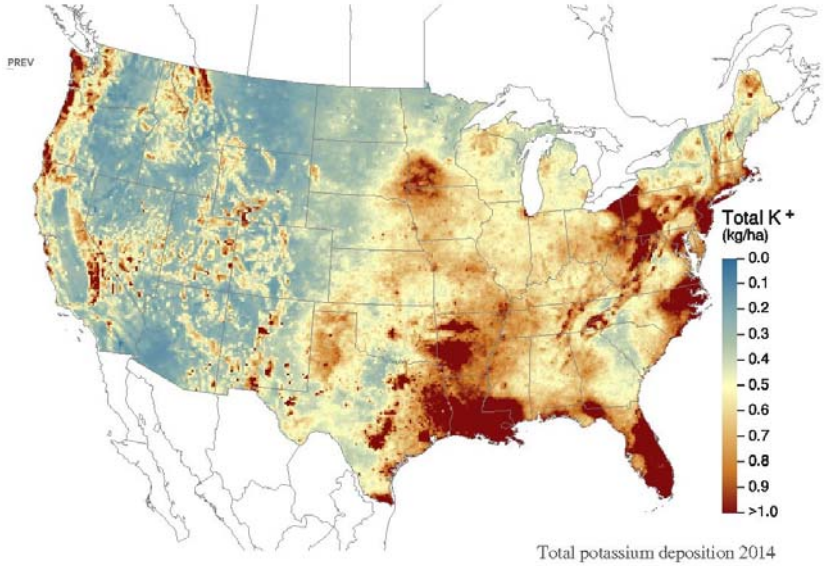
Adapted from: Koslowski, T.T., Pallardy, Physiology of Woody Plants

Atmospheric Deposition

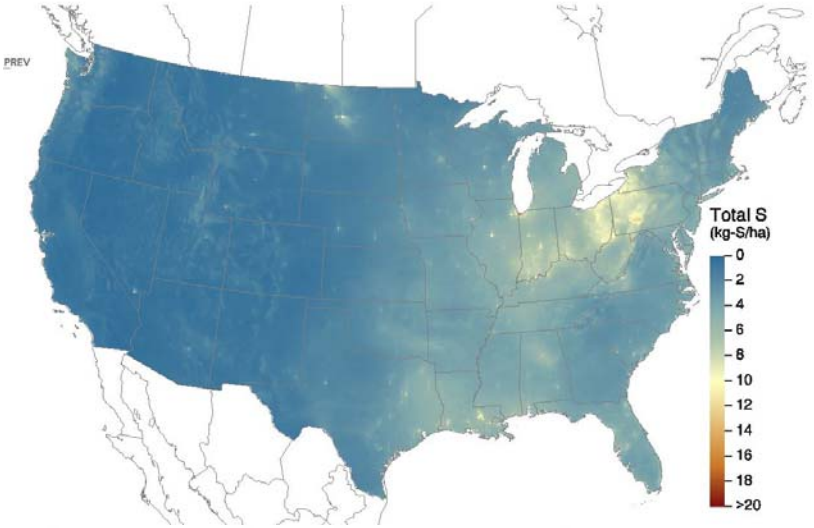


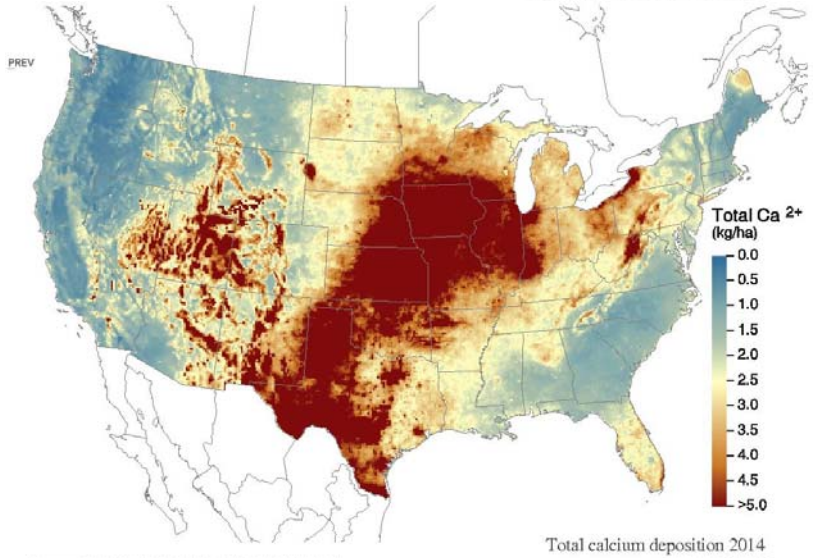
1 kg/ha = 0.89 lbs/A

1 kg/ha = 0.02 lbs/1000 ft^2



Total potassium deposition 2014

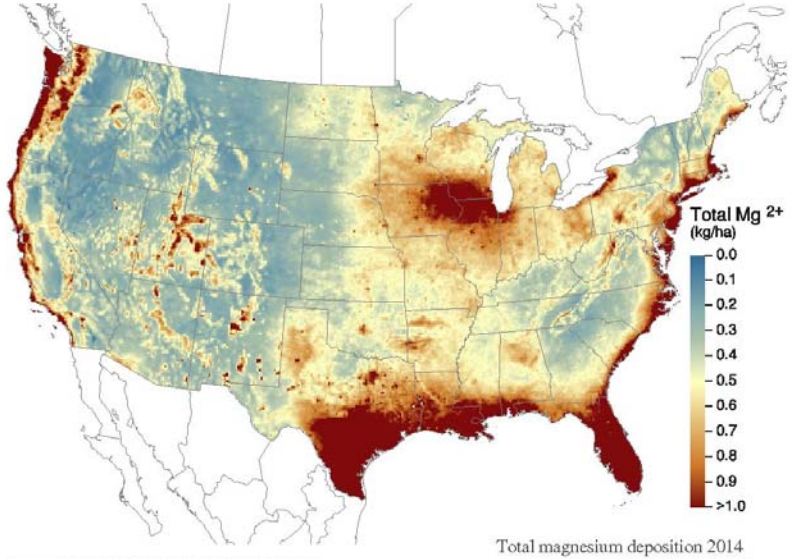




Total calcium deposition 2014

Source: CASTNET/CMAQ/NTN/AMON/SEARCH

USEPA 06/27/16



Total magnesium deposition 2014

Source: CASTNET/CMAQ/NTN/AMON/SEARCH

USEPA 06/27/16

Biological Fixation

Symbiotic relationship between bacteria
(Frankia – non-legume, Rhizobium – legumes)

Black Locust
Mimosa
Golden Chain Tree
Alder
Redbud
Autumn Olive
Kentucky Coffee Tree

Symbiotic N Fixation can be Significant

Biologically fixed N equalled 66.4% of the N in leaf litter in alder (*Alnus hirsuta*)*

Peak assimilation occurred after leaves matured

N fixation stopped when leaves were shed

* Tobita, H. et al. 2013. Growth and N2 fixation in Alnus hirsuta…

Biological Fixation

Free-living, non-symbiotic bacteria & archaea

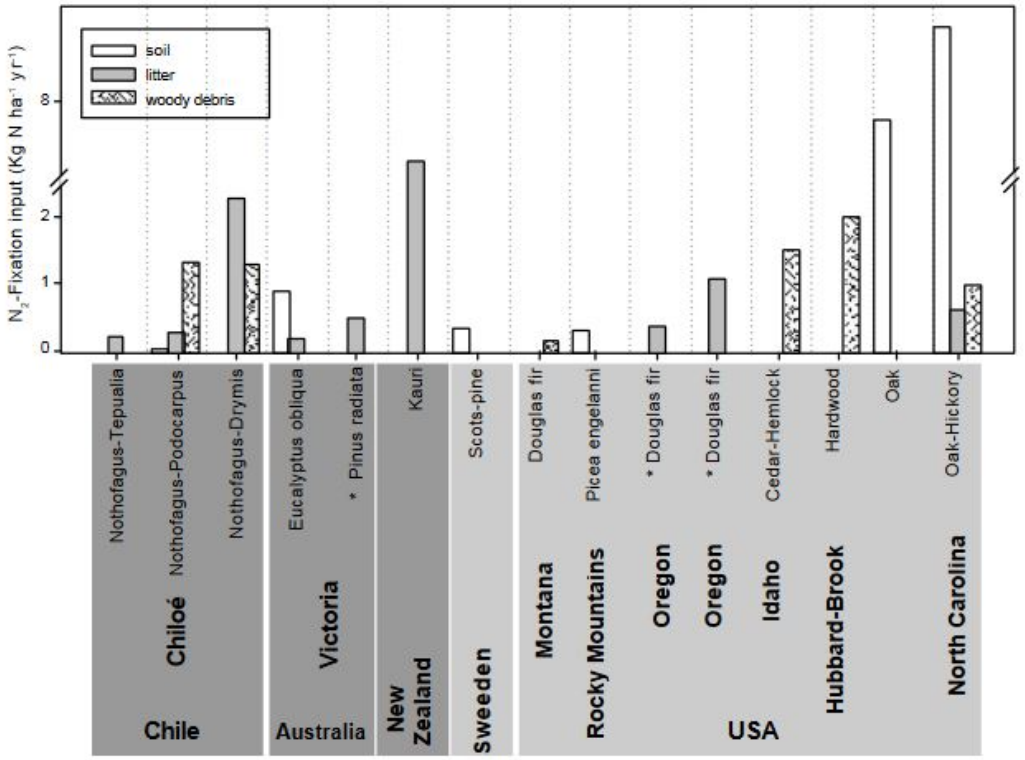


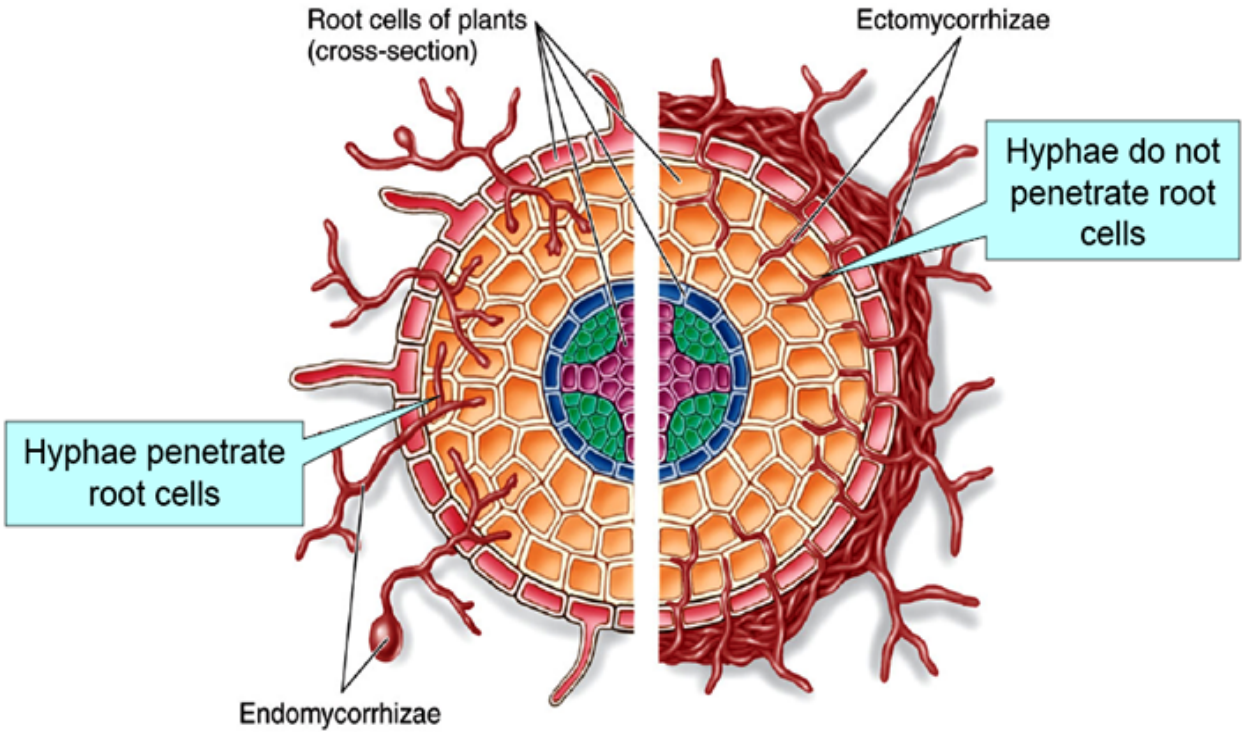
FIGURE 2. Annual non-symbiotic N fixation rates in southern (darker panel) and northern hemisphere temperate forests (lighter panel), estimated for three soil compartments: surface mineral soil, litter and coarse woody debris. In some cases data were not available for a given soil compartment. Asterisks indicate successional or plantations forests, all others are old-growth stands. References are: Roskoski 1980, Dawson 1983, Baker & Attiwill 1984, Jones & Bangs 1985, Heath *et al.* 1988 , Jurgensen *et al.* 1987.

Convert free nitrogen (including organic forms) into soluble forms

Soluble forms are available for uptake by trees

Litter and coarse woody debris in the O horizon provide the substrate

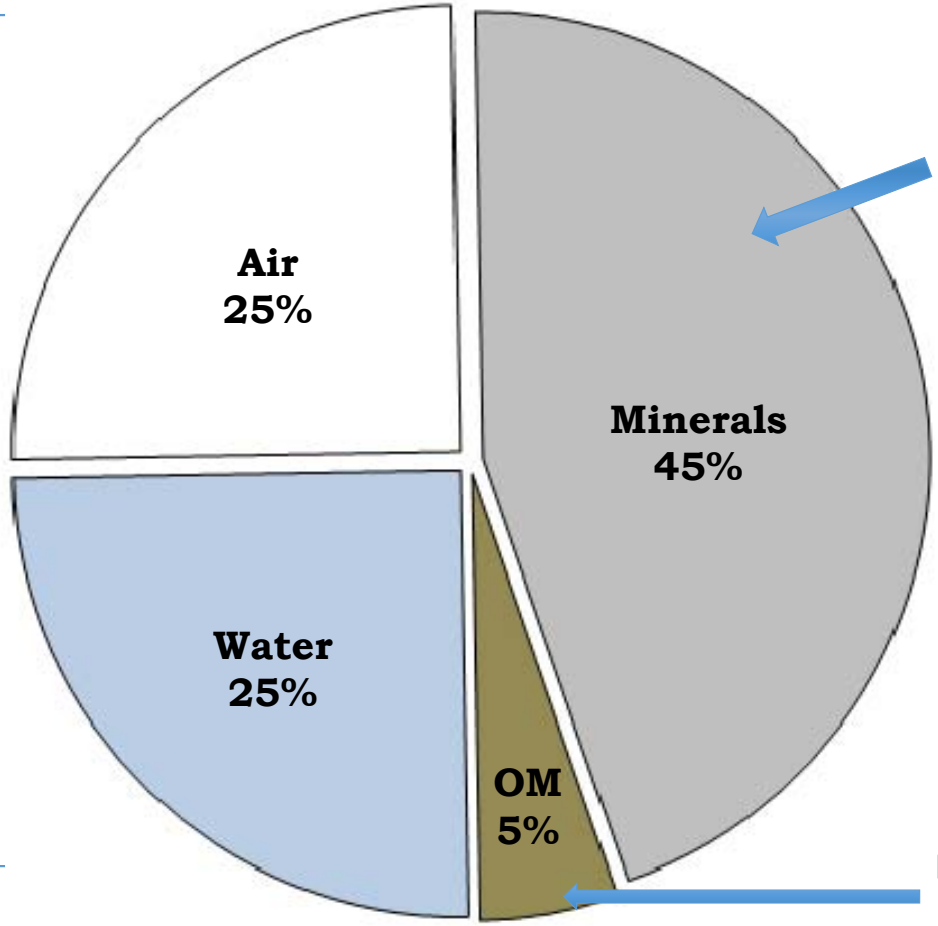
Mycorrhizae



Ectomycorrhizae

http://www.cultivosforestales.com/es/preguntas-frecuentes/informacion-de-producto/tag/trufa%20en%20la%20raiz%20del%20arbol

Soil



Collectively called pore space

Weathered products from parent material

End products of organic litter decomposition

Soils develop over time

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

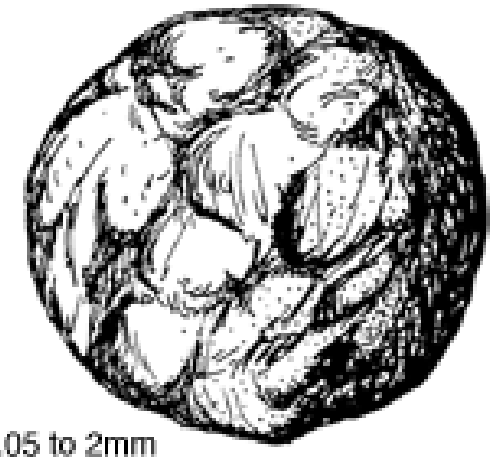
Minerals

Fragmented/Fine Parent Material

Bulk Parent Material

Physical Weathering

Photo: L. Werner, King George Island, Antarctica



Sand .05 to 2mm
feels gritty

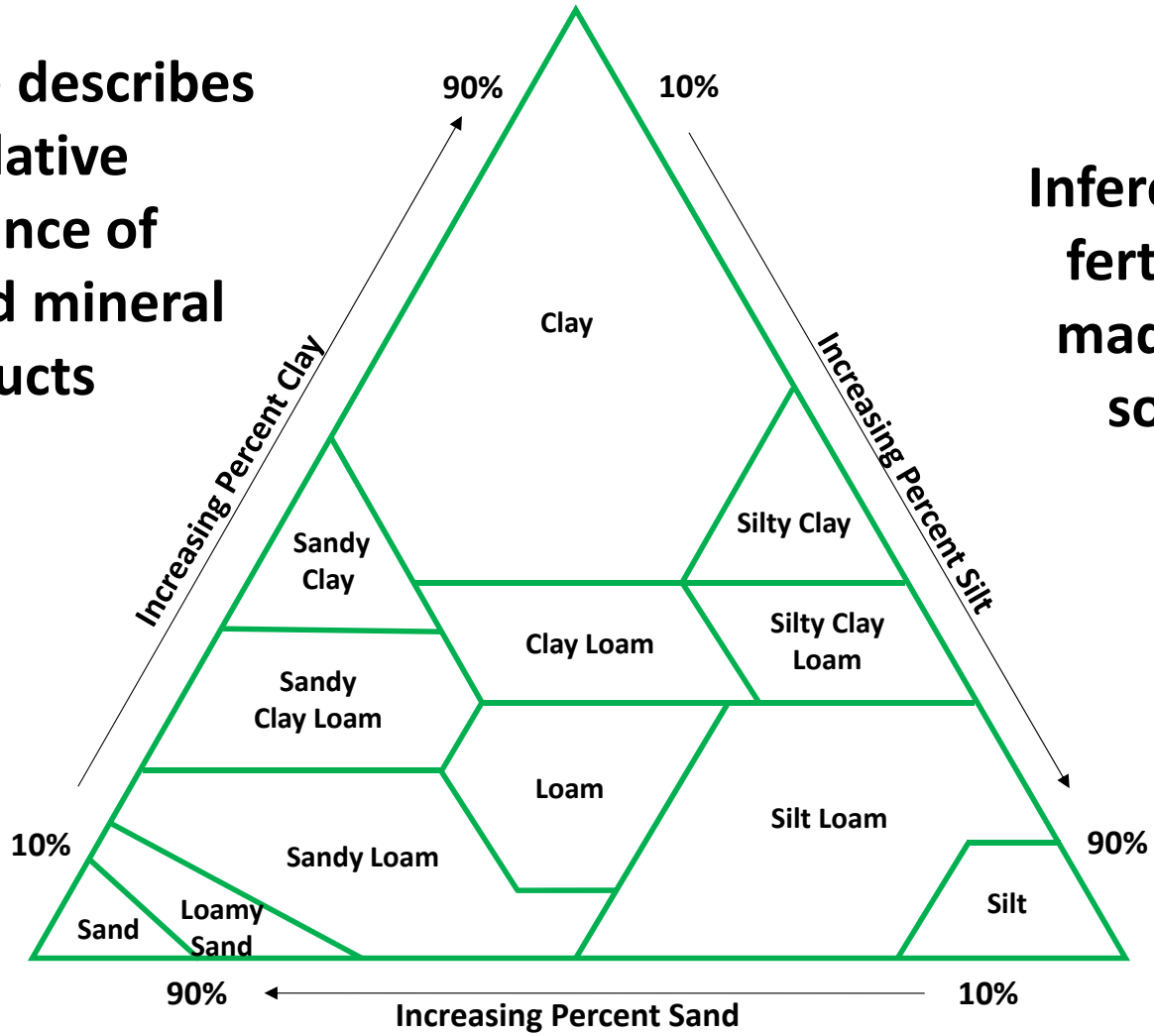
Silt .002 to .05 mm
feels smooth

Clay <.002 mm
feels smooth

The weathered products of parent materials have different sizes and shapes

The sizes and shapes influence soil texture and resource availability

Soil texture describes the relative abundance of weathered mineral products



Inferences on soil fertility can be made based on soil texture

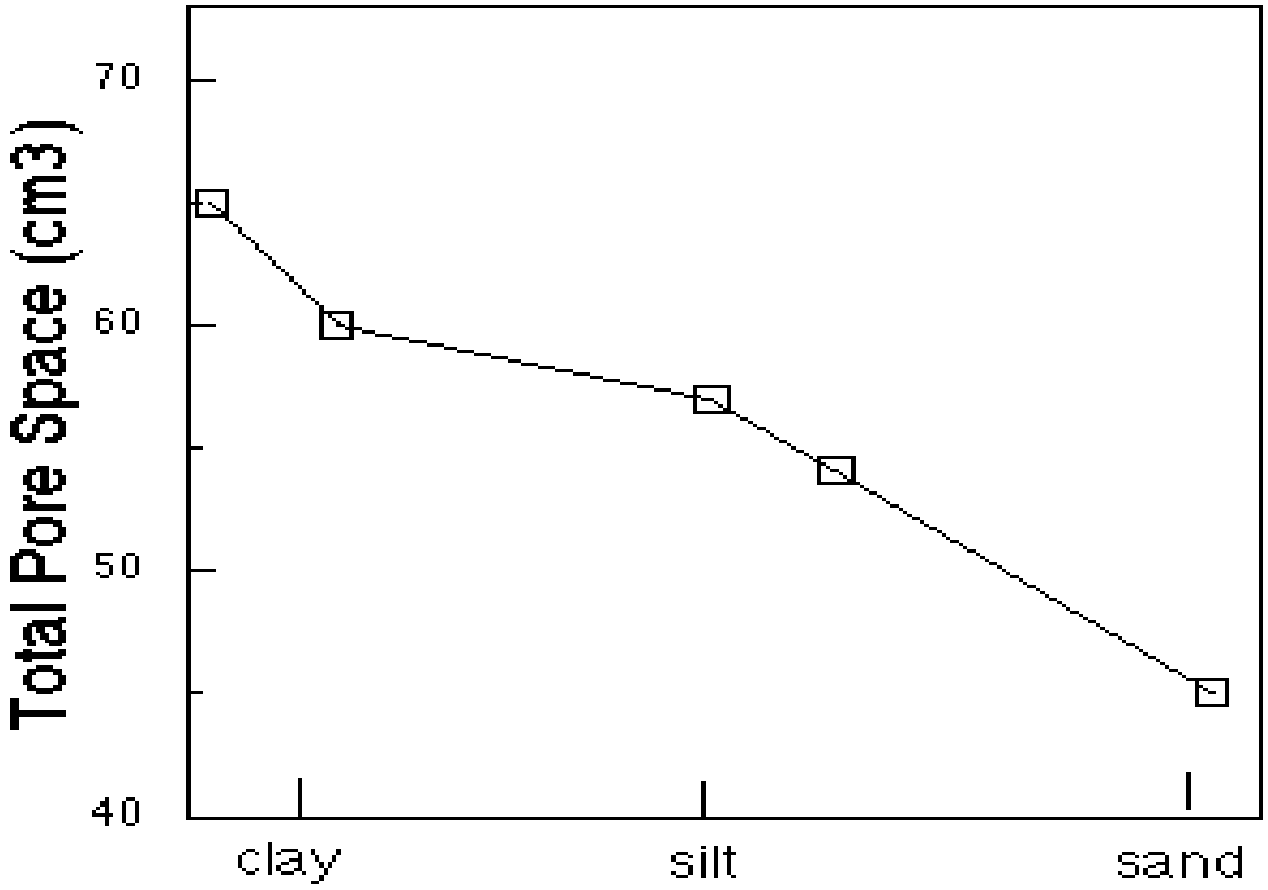
Pore spaces develop between particles

Pores filled with water or air

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

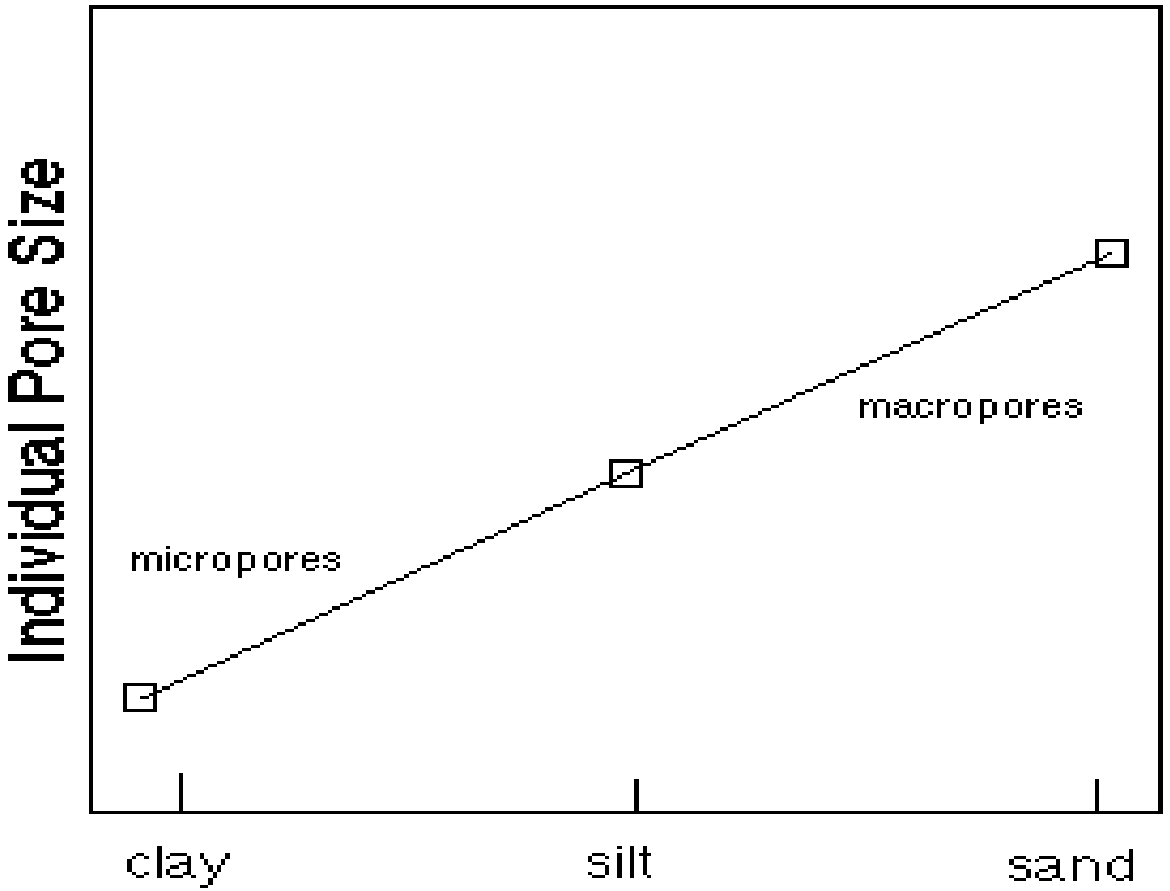
Source: Russell and Appleyard, 1915

Pore space increases as the particles get smaller

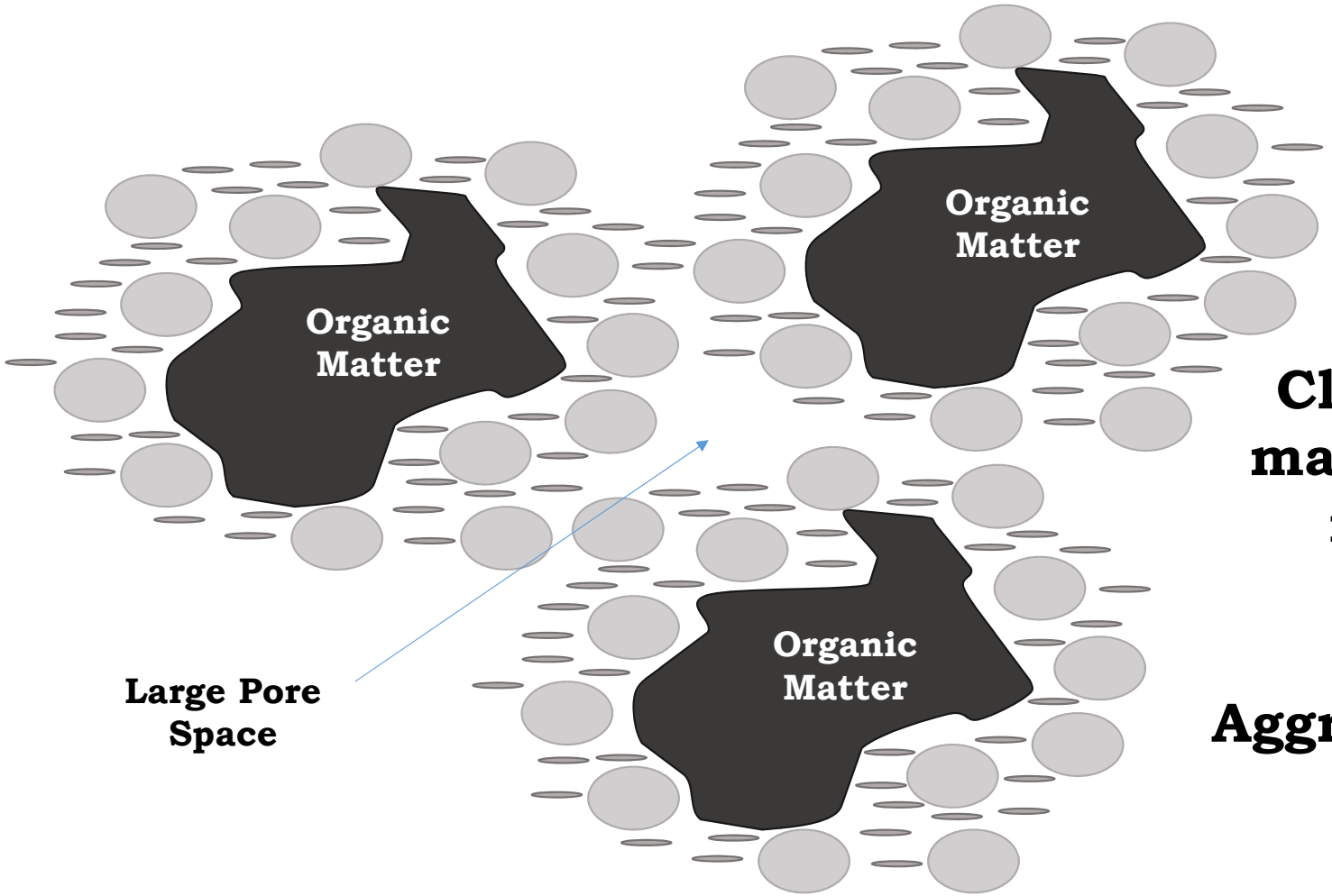


http://soils.cals.uidaho.edu/Soils206/Manual/two.htm

Size of the pore space increases as particles get larger



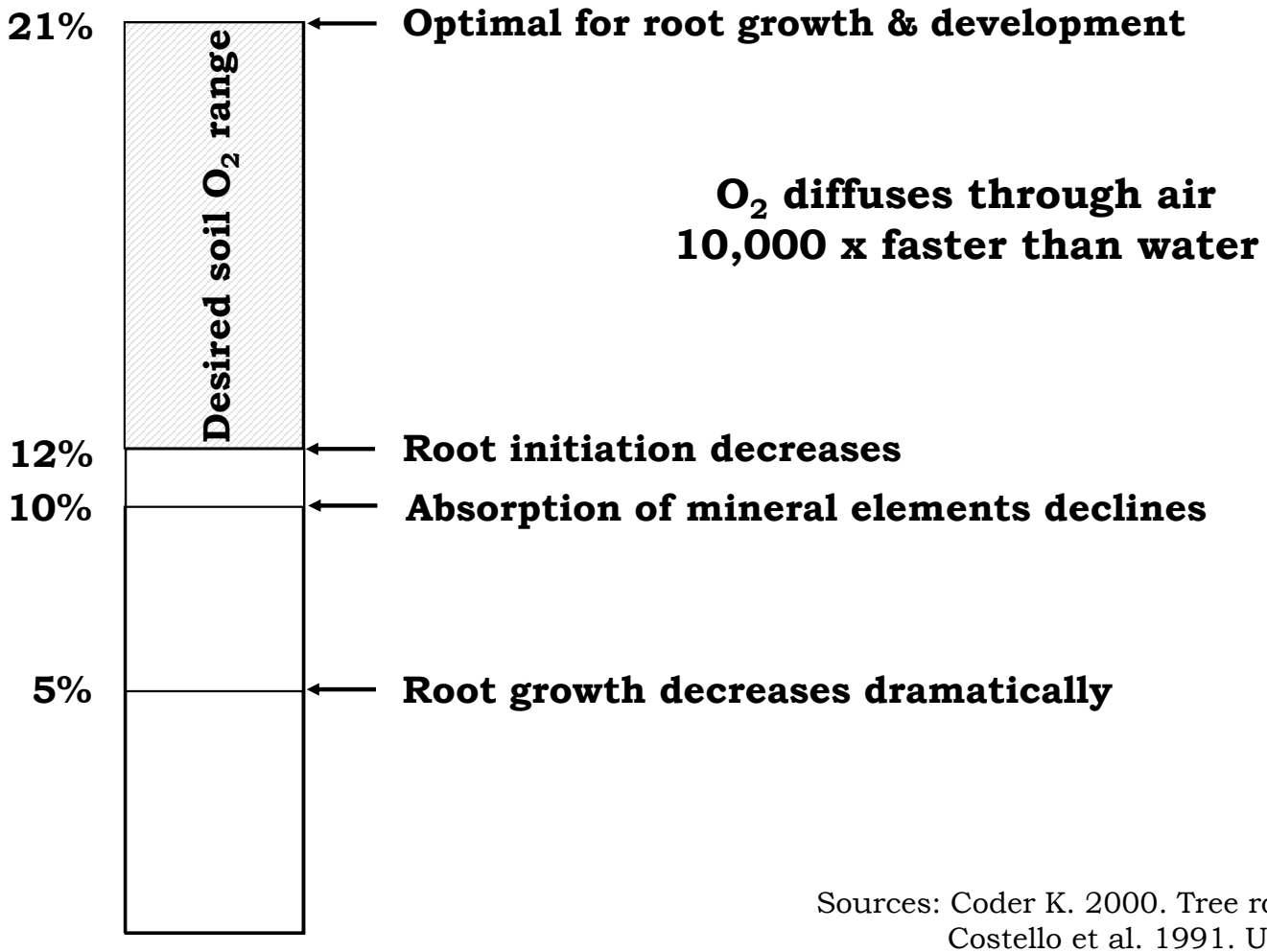
http://soils.cals.uidaho.edu/Soils206/Manual/two.htm



Clay, soil organic matter and organic residues form aggregates

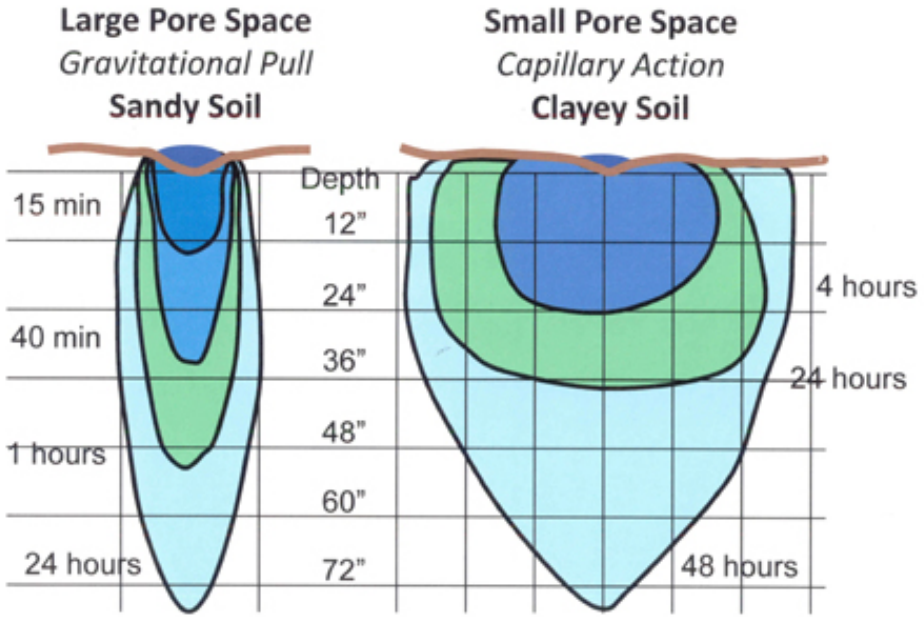
Aggregation improves porosity

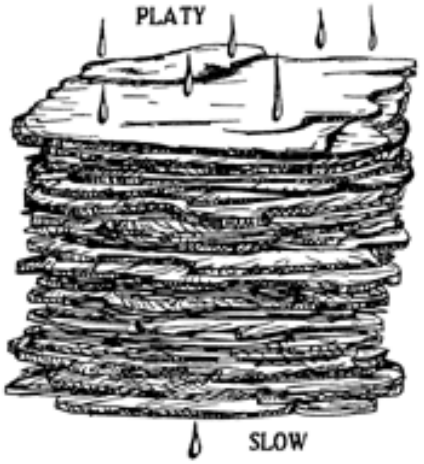
Pores provide roots with Oxygen



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

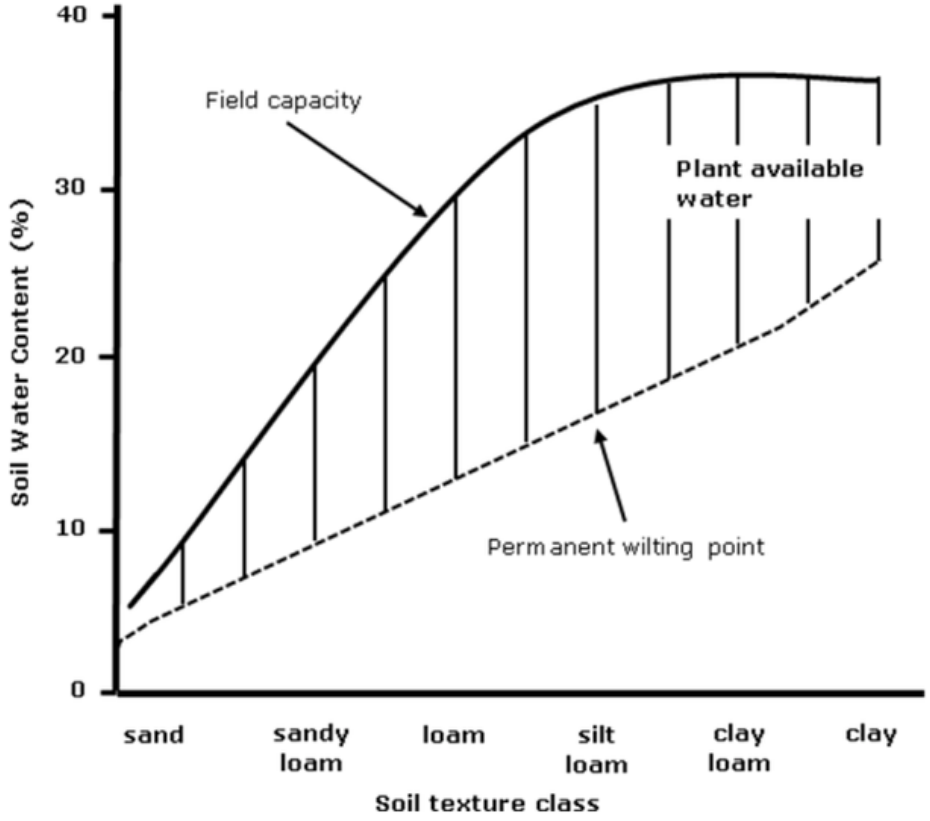
Soil texture influences how quickly water enters and drains from soil





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

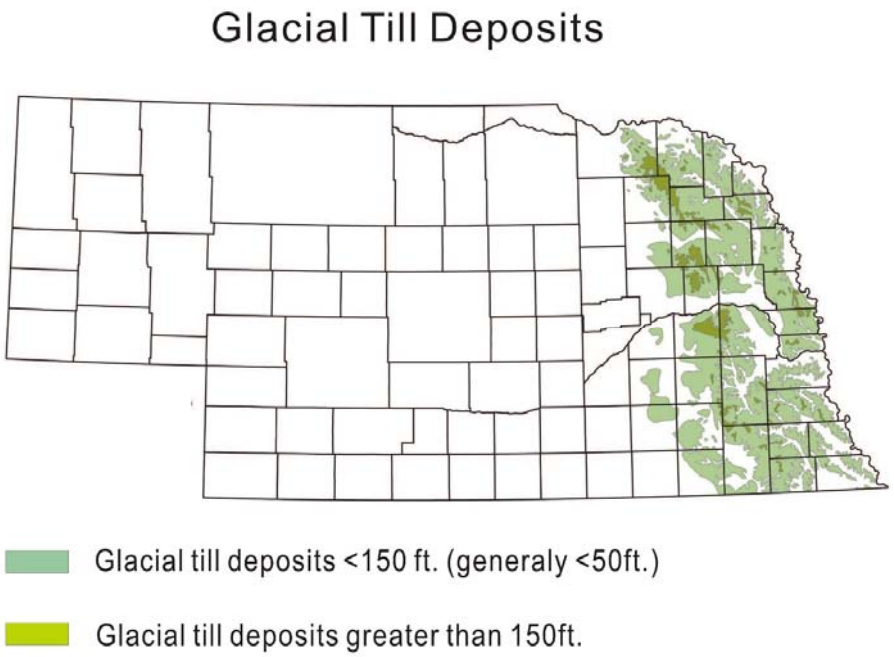
Soil texture influences water holding capacity and plant available water



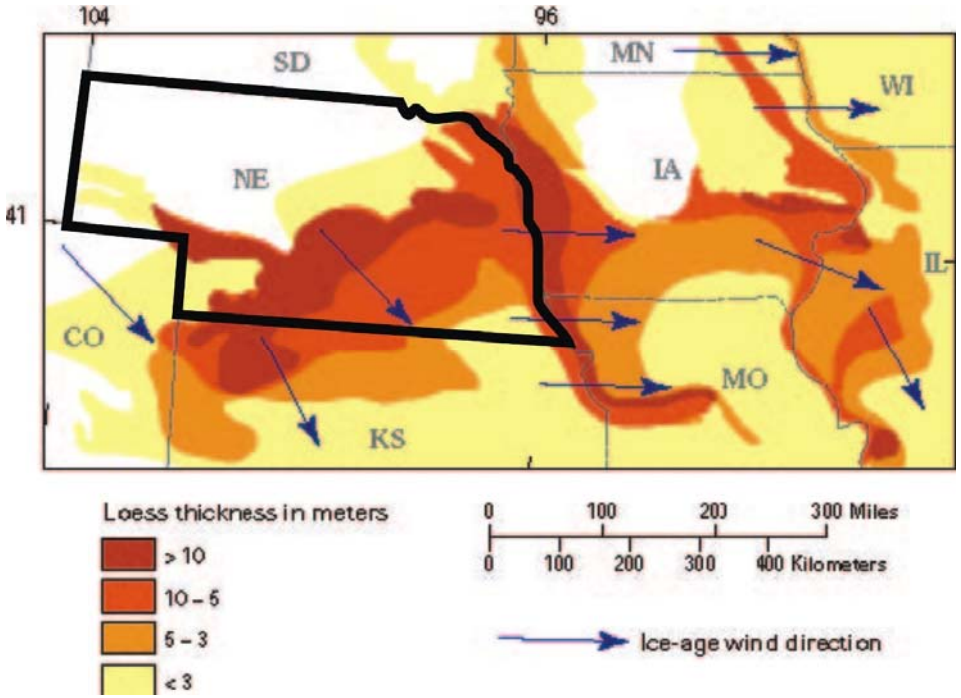
O'Geen, A. T. (2012) Soil Water Dynamics. Nature Education Knowledge 3(6):12

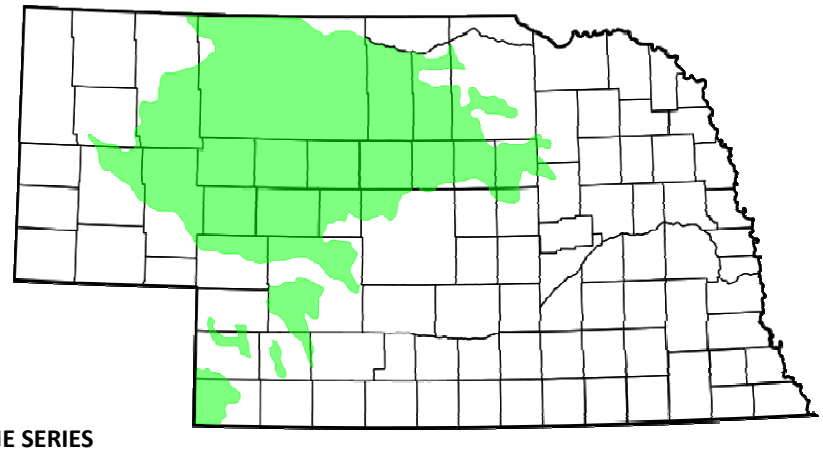
In the Mid-West, much of the parent material from which soils develop is the product of glacial activity

Parent material is a mix of minerals


Glacial Till Deposits
Glacial till deposits <150 ft. (generaly <50ft.)
Glacial till deposits greater than 150ft.

Loess deposited over glacial till





VALENTINE SERIES

The Valentine series consists of very deep excessively drained soils formed in eolian sands.

TYPICAL PEDON:
A1--0 to 1 inch; light brownish gray fine sand, dark brown moist; single grain; loose; moderately acid

A2--1 to 5 inches; brown fine sand, dark brown moist; weak medium granular structure; very friable, soft; moderately acid

AC--5 to 10 inches; brown fine sand, brown moist; weak coarse granular structure; very friable, soft; slightly acid

C1--10 to 18 inches; pale brown fine sand, yellowish brown moist; single grain; loose; slightly acid

C2--18 to 33 inches; very pale brown fine sand, brown moist; single grain; loose; slightly acid

C3--33 to 50 inches; very pale brown fine sand, light yellowish brown moist; single grain; loose; neutral

C4--50 to 80 inches; very pale brown fine sand, pale brown moist, single grain, loose;

Nebraska Sand Hills

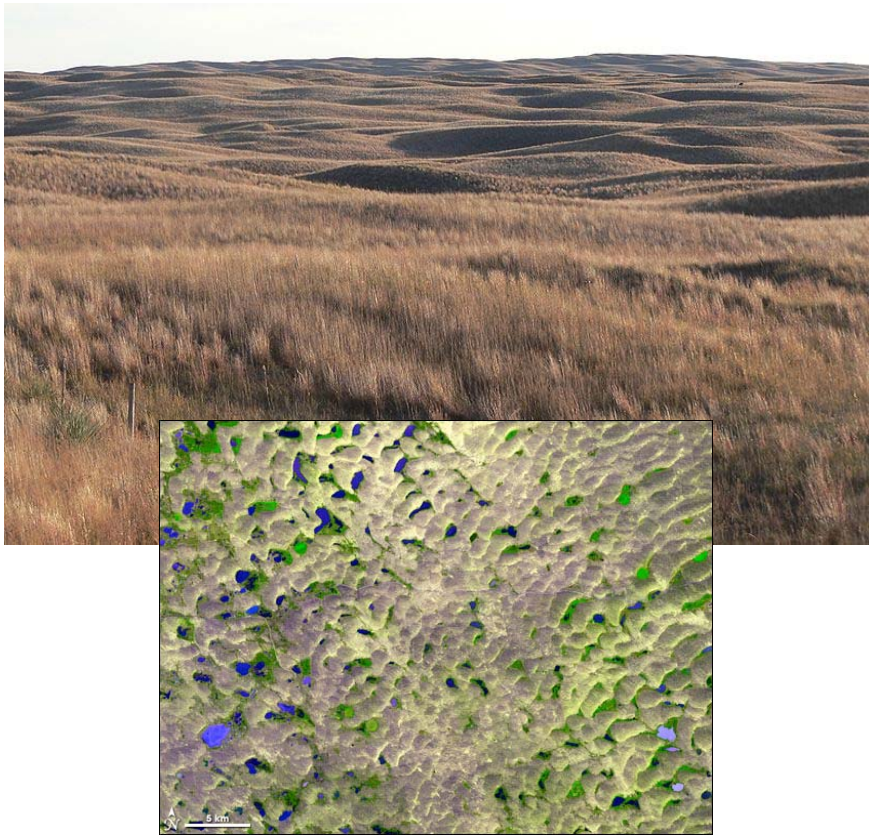


Photo courtesy of NASA

TABLE 14–1. • The average chemical composition of some common parent materials

	Granodiorite (Granitic)	Basalt	Shale	Sandstone	Limestone
SiO_2	65.1	49.3	58.10	78.30	5.20
Al_2O_3	15.8	14.1	15.40	4.80	0.80
Fe_2O_3	1.6	3.4	4.00	1.10	0.50
FeO	2.7	9.9	2.40	0.30	—
MgO	2.2	6.4	2.40	1.20	7.90
CaO	4.7	9.7	3.10	5.50	42.60
Na_2O	3.8	2.9	1.30	0.40	0.05
K_2O	3.5	3.2	1.30	0.33	—
P_2O_5	0.1	0.5	0.17	0.08	0.04
SO_3	—	—	0.60	0.07	0.05
CO_2	—	—	2.60	5.00	41.50

Source: Adapted from Bohn et al., 1979.

The type of parent materials from which soil is formed influences

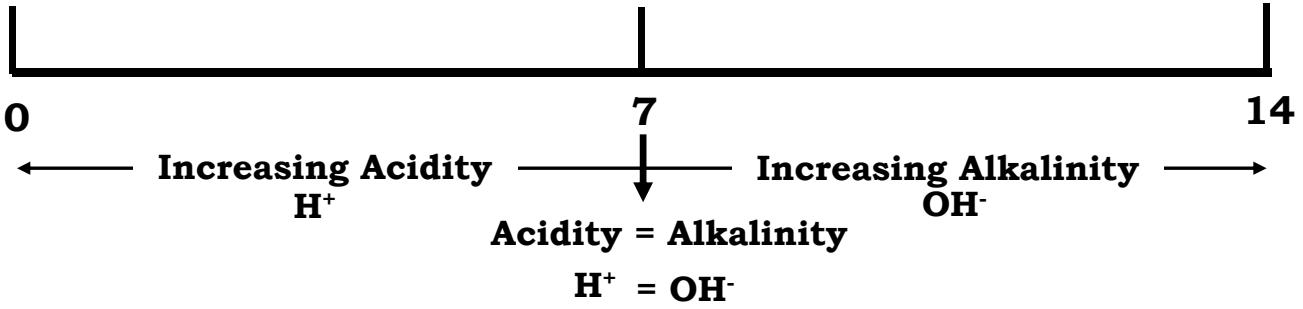
Native Fertility

-EE

-Water holding

pH

Understanding pH



pH = negative log of the H concentration

-log of 0.0000001M = 7

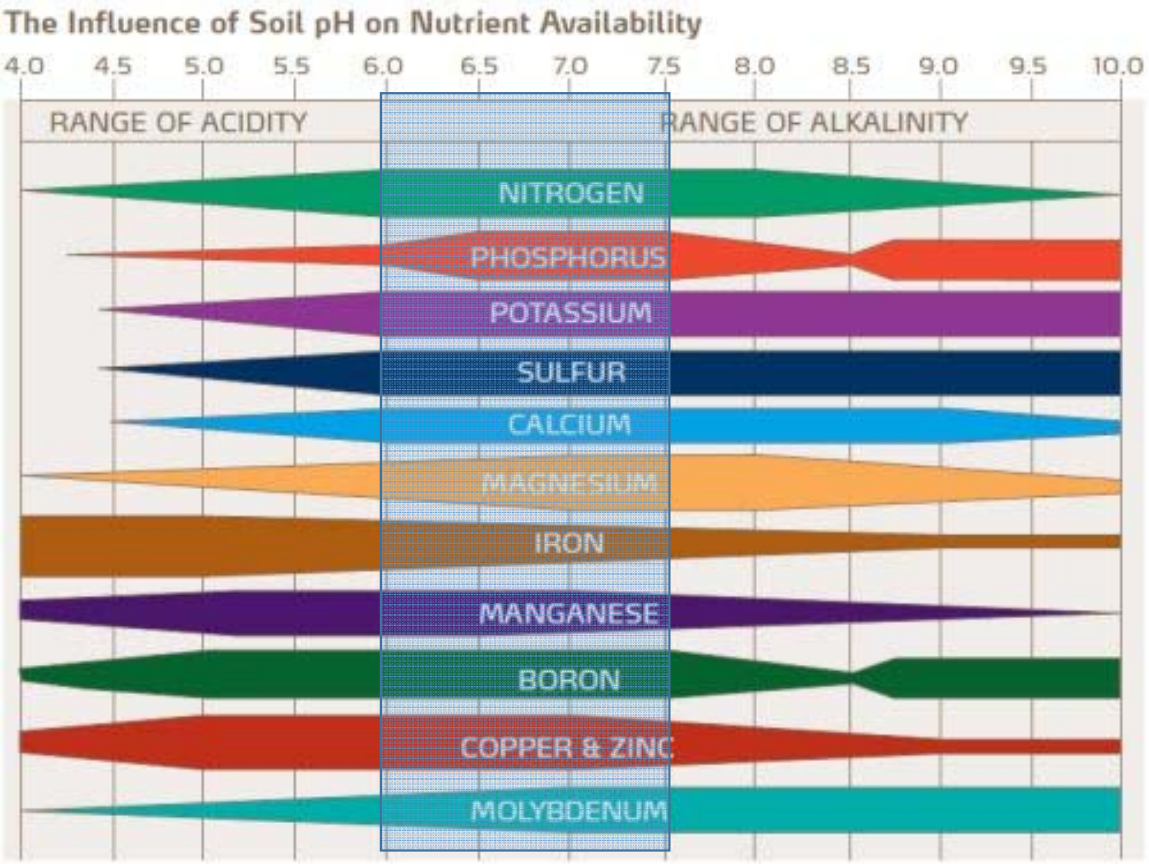
(10^x = 0.0000001, x = -7)

-log of 0.000001M = 6

-log of 0.00001M = 5

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

pH



pH controls the availability/solubility of essential elements

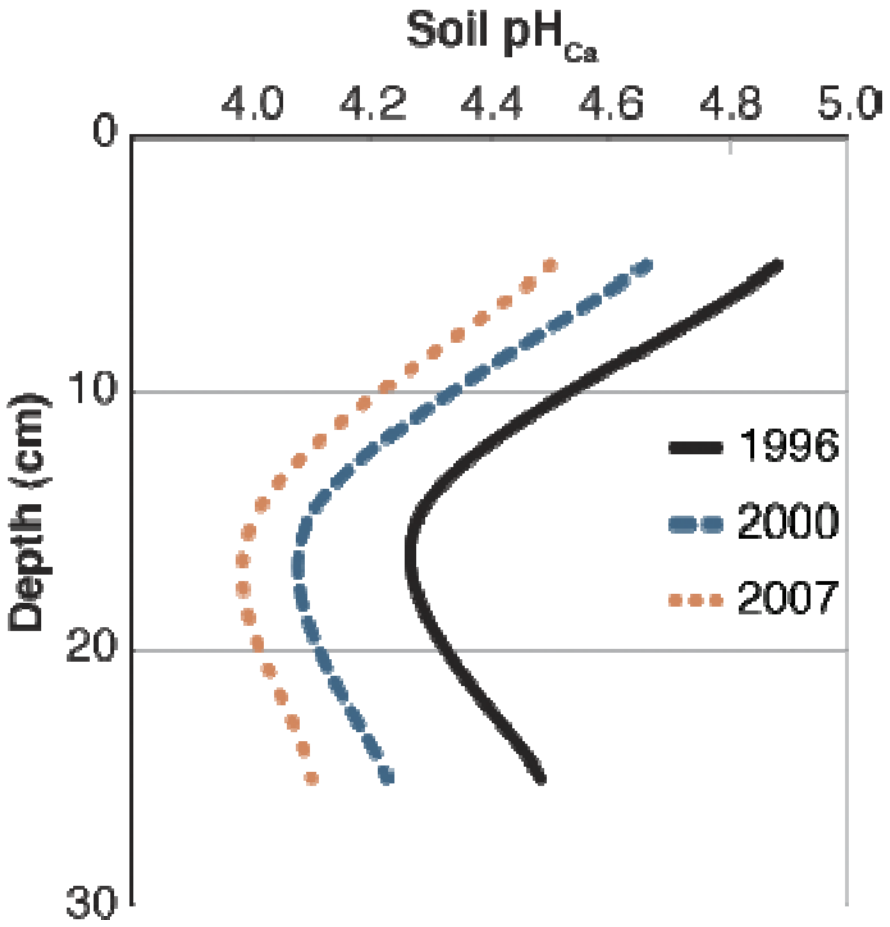
Charged elements complex with:

OH-

(alkaline conditions)

H+

(acidic conditions)



Soil becomes more acidic over time

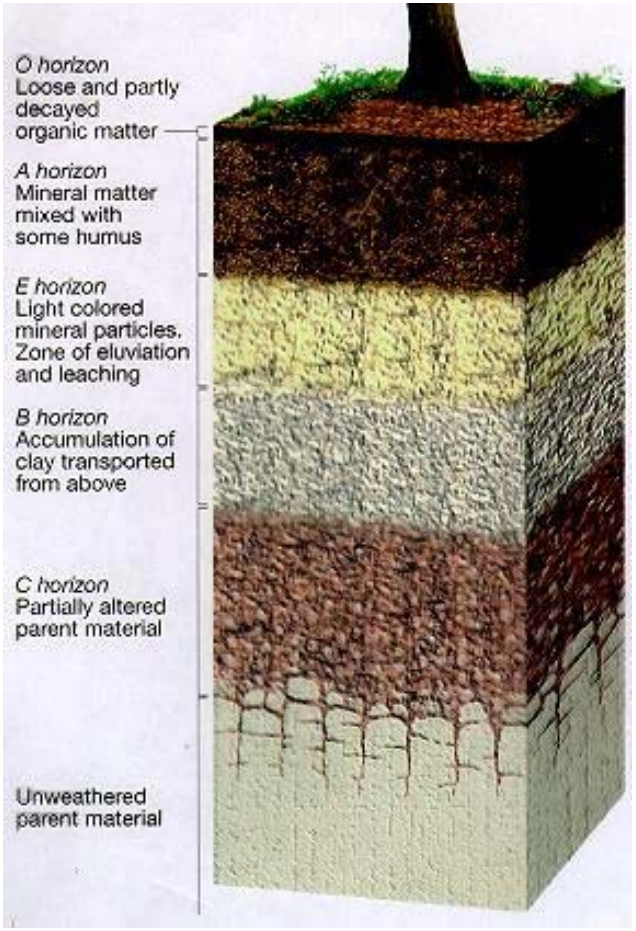
Leaching

Bio-accumulation

Acidic deposition

- Rainfall
- Root exudates
- Fertilizers

In forested environments, an organic layer (O Horizon) develops over the mineral horizons



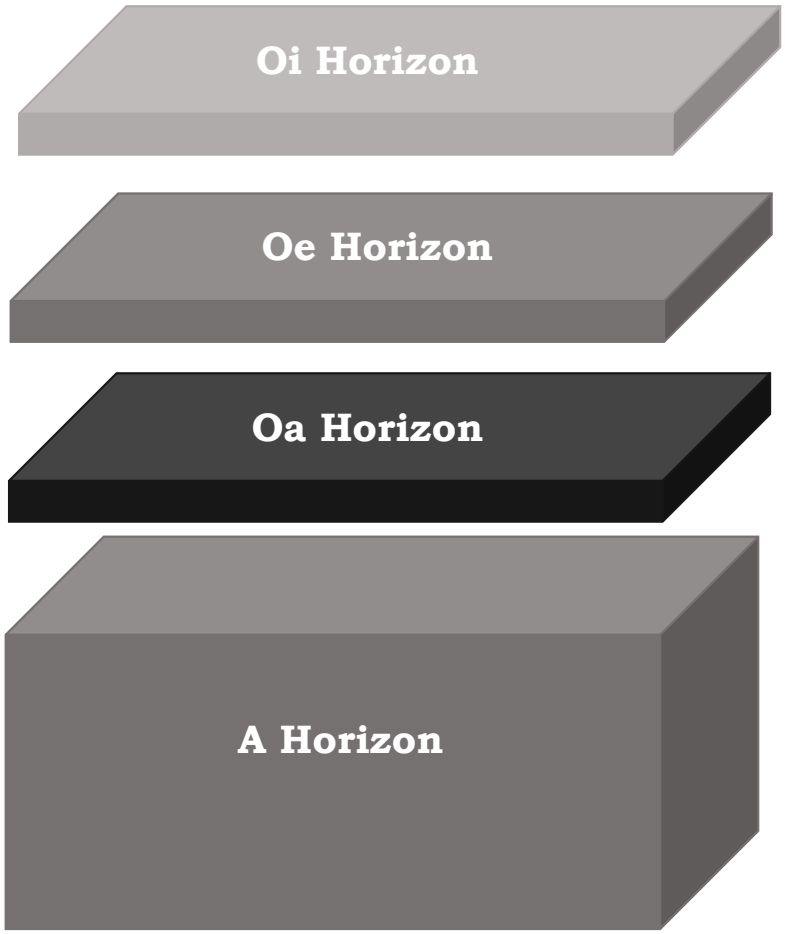
The Organic Horizon has litter in various stages of decomposition

Intact organics

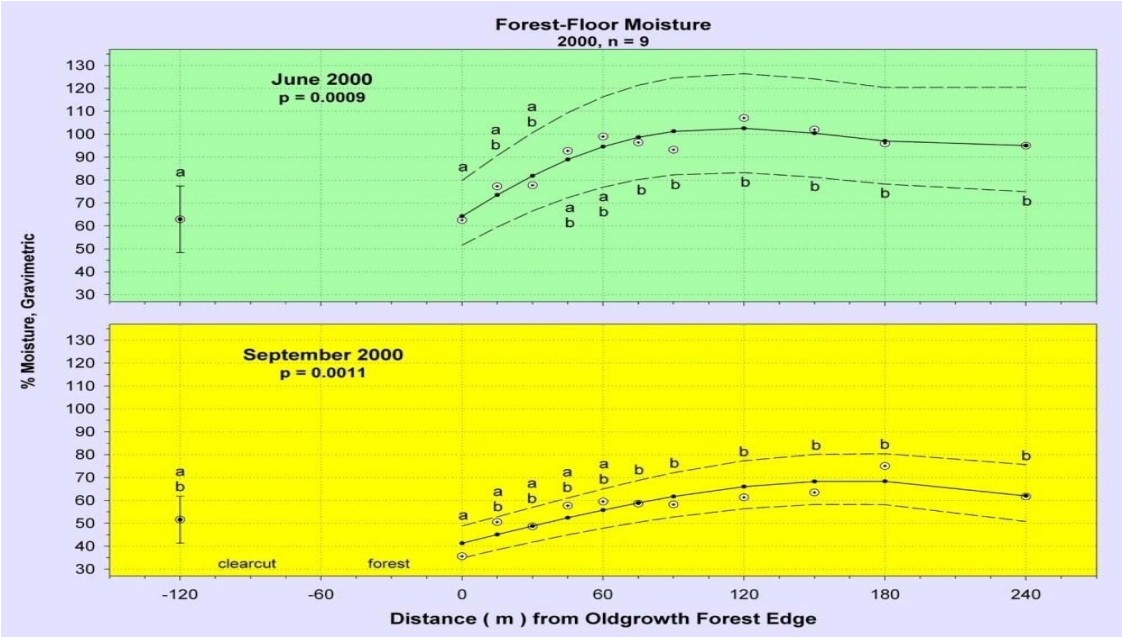
Partially decomposed organics

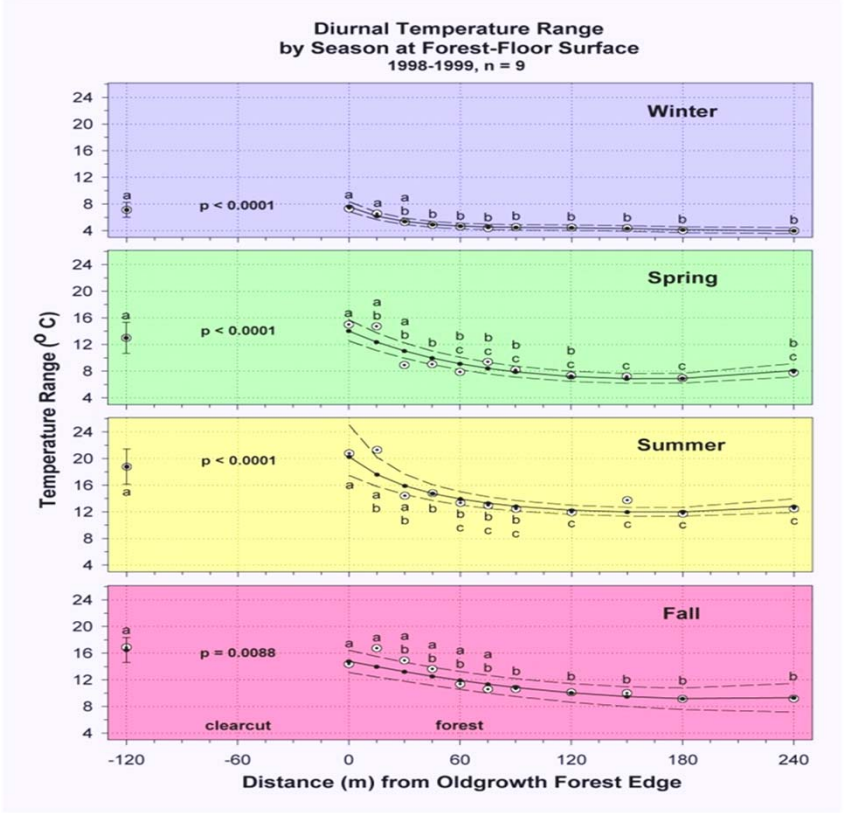
Highly decomposed, humified organics

Mixing of humified organics with mineral soil



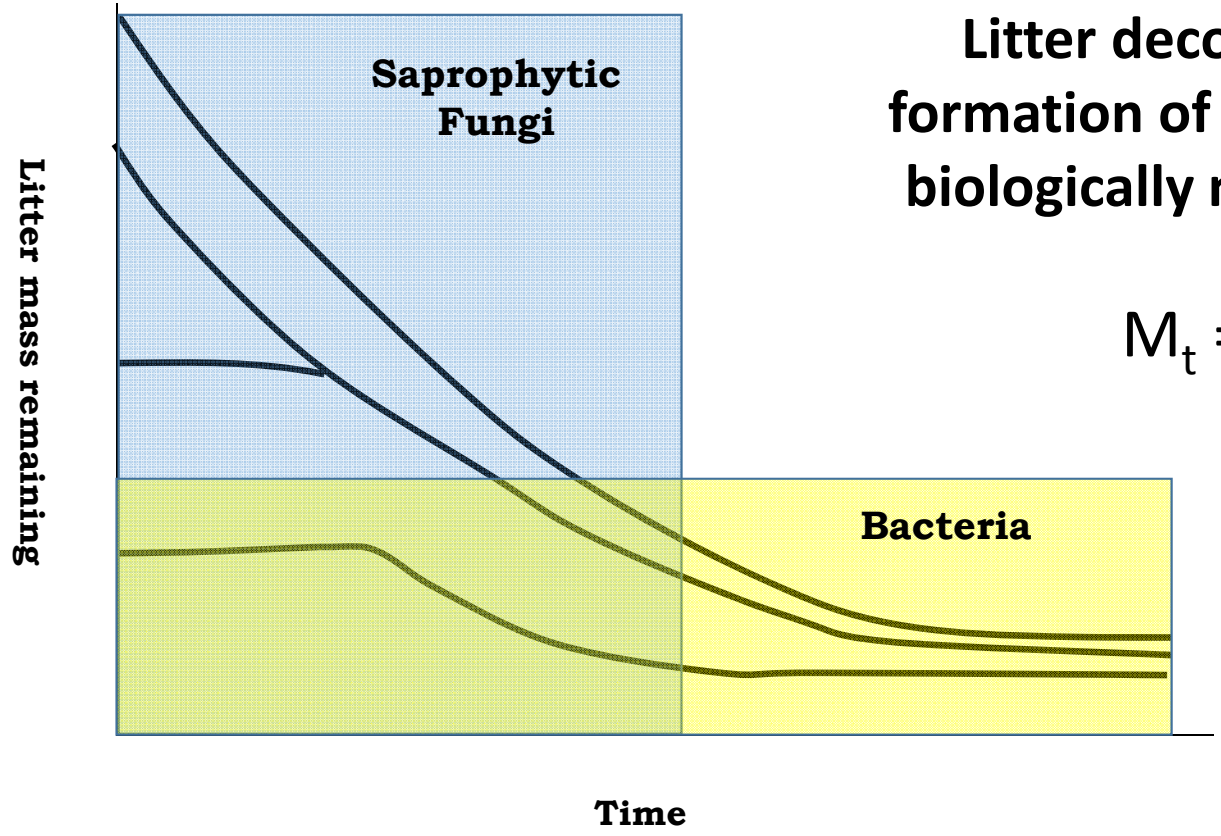
The organic layer modifies moisture and temperature swings





Hayes, T., R. Griffiths, and C. D'Antonio, 1997, "Biogeochemical Attributes of Old-growth Forest-Clearcut Edges," Bulletin of the Ecological Society of America 78 (4):105.

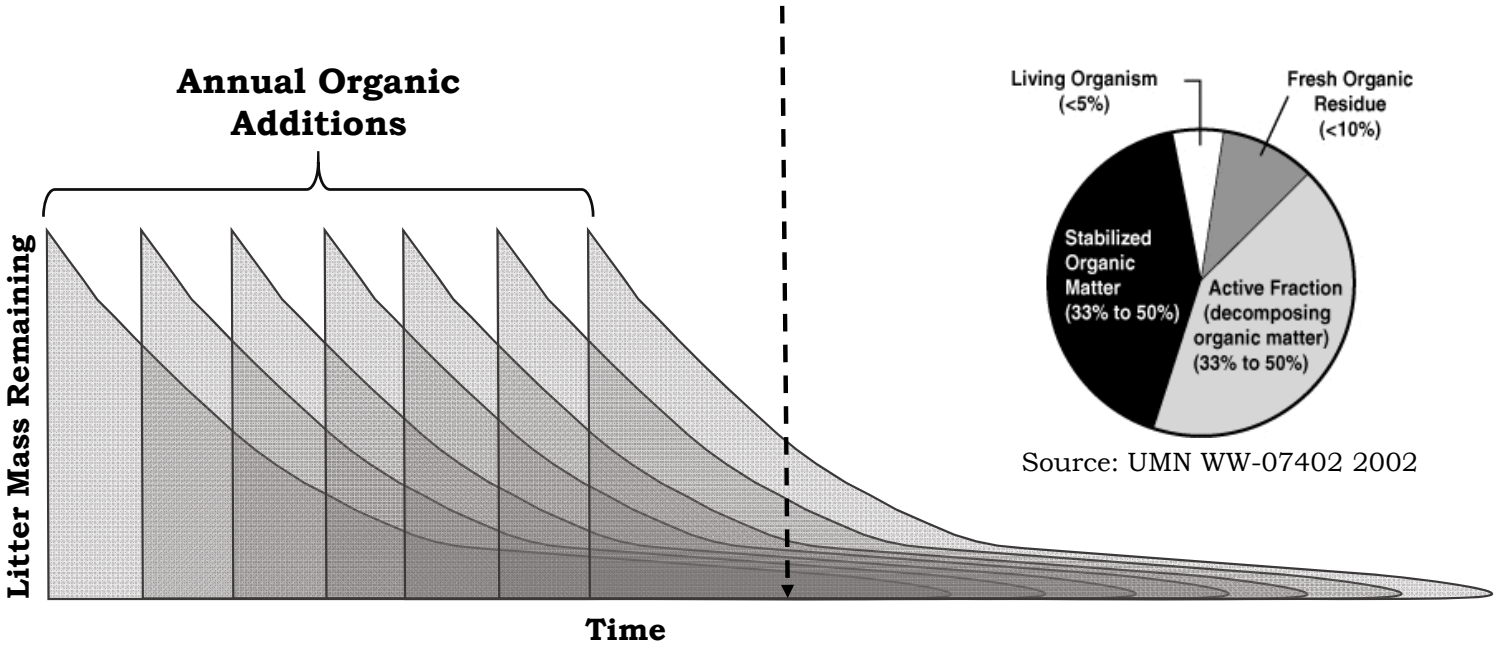
O Horizon Formation



Litter decomposition and formation of the O Horizon is a biologically mediated process

$$M_t = M_o e^{-kt}$$

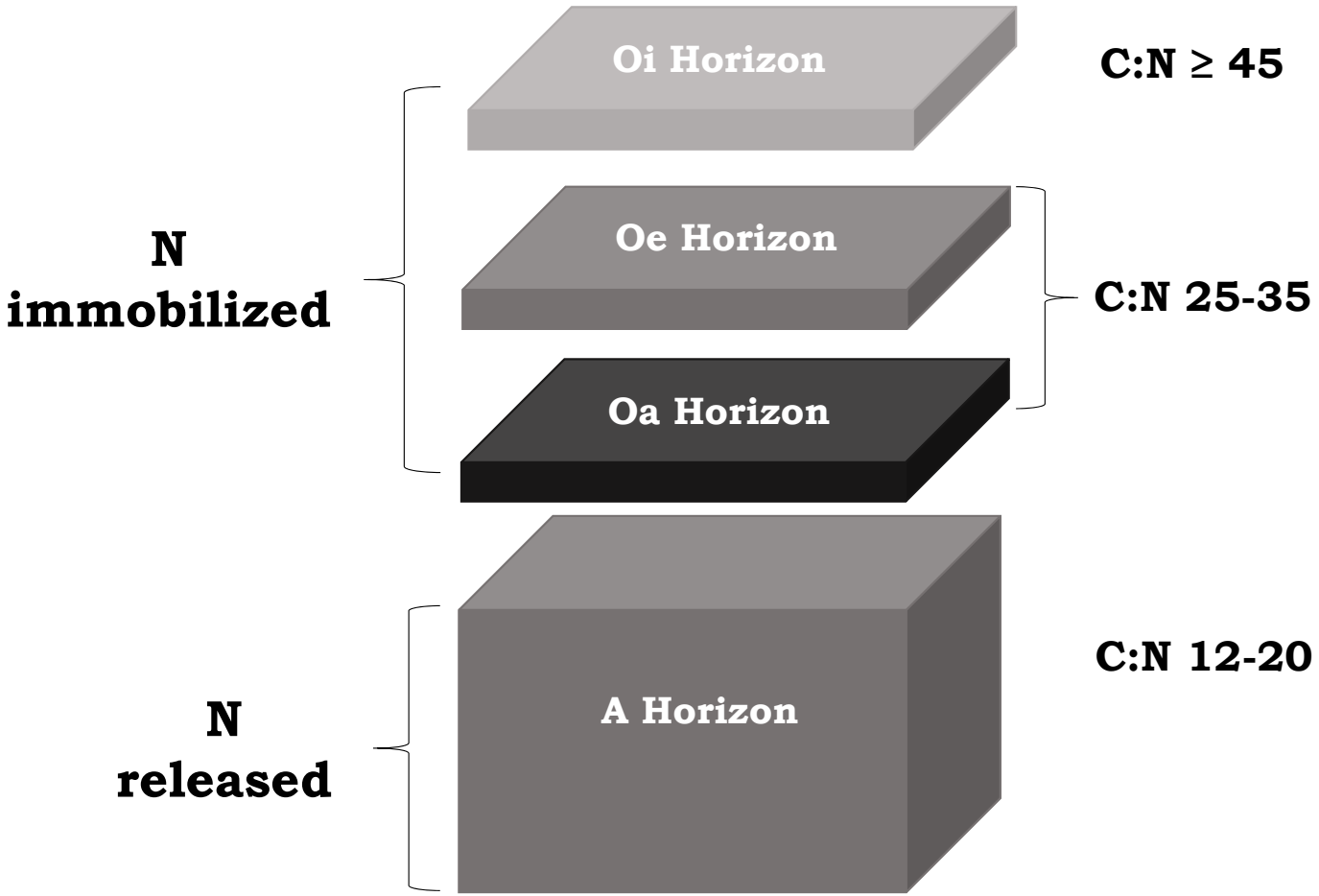
At any point in time, the organic fraction of the soil is a mix of compounds in various stages of decomposition…



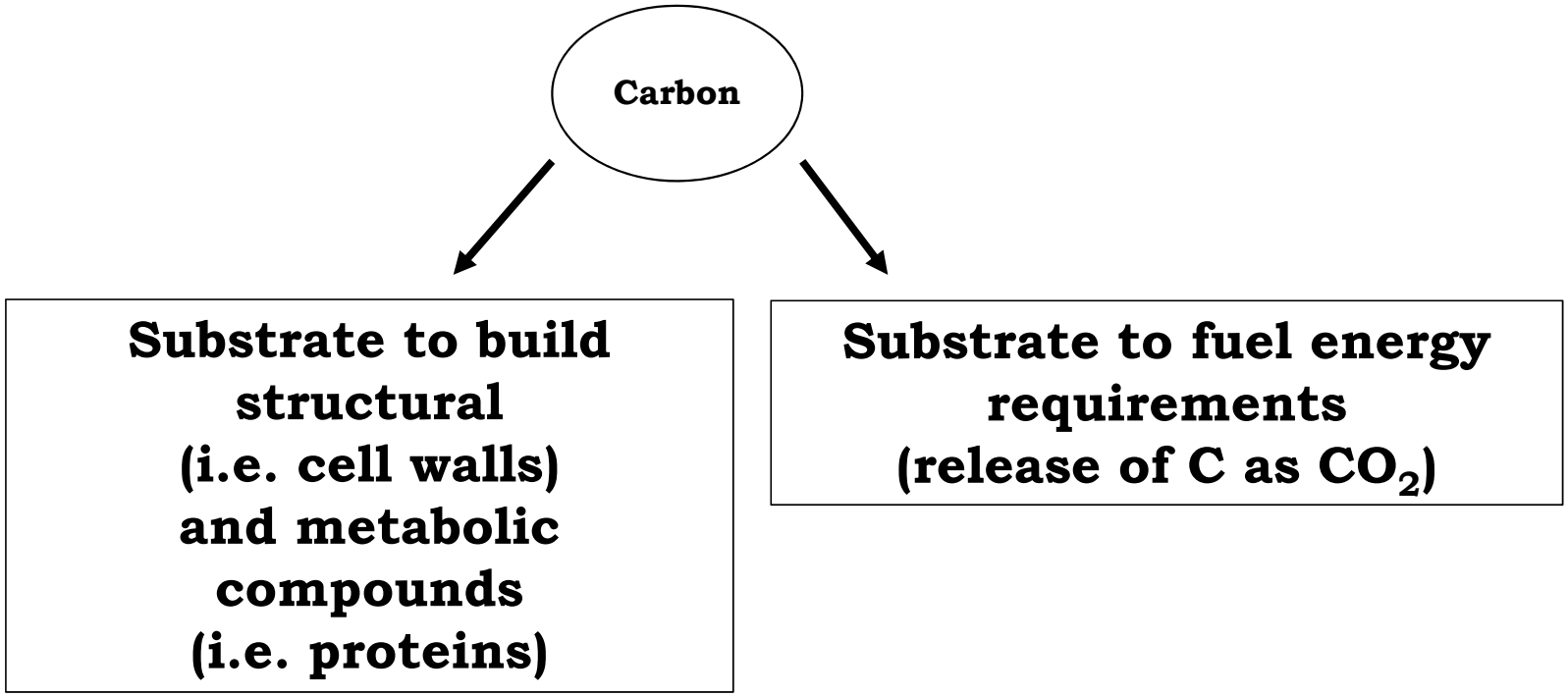
Source: UMN WW-07402 2002

…and, a diverse array of micro-organisms

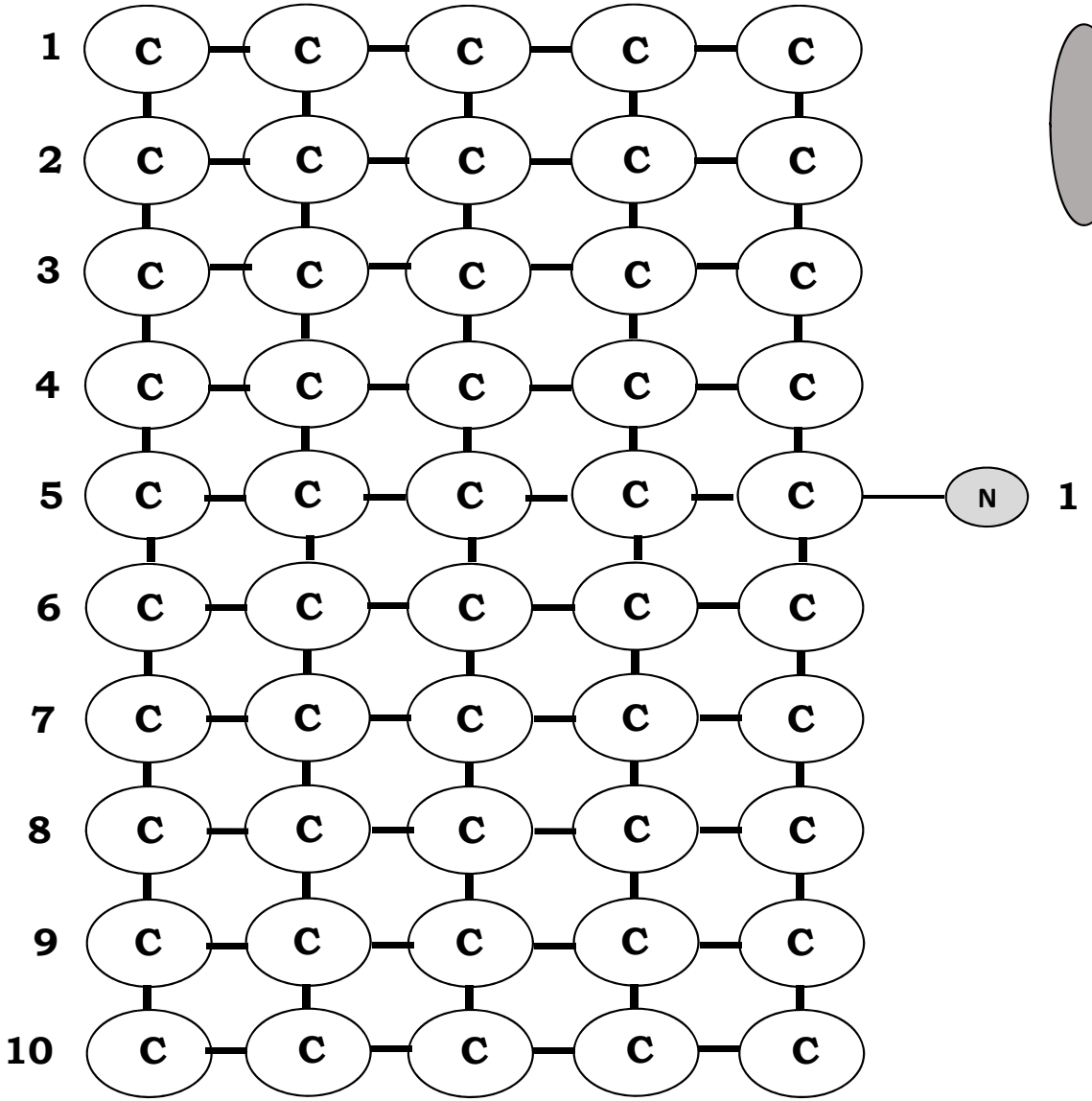
So, what happens during decomposition of the formation of the organic layer?

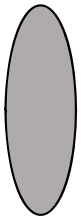


Soil microbes (bacteria, fungi) digest litter to obtain C and essential elements to support growth and metabolic functioning



Only a fraction of the Carbon is used for growth

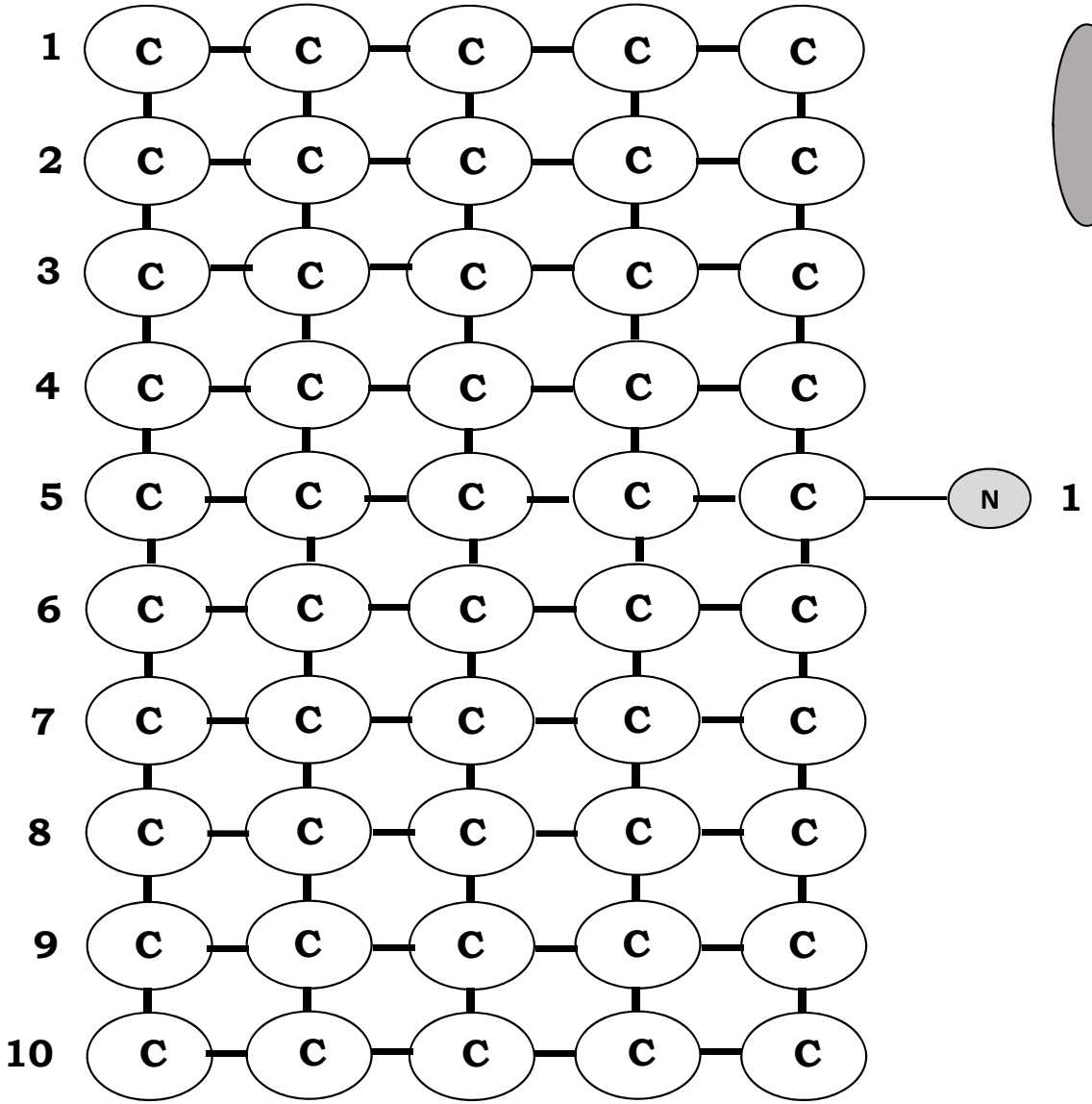


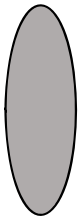


Soil Bacteria

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:

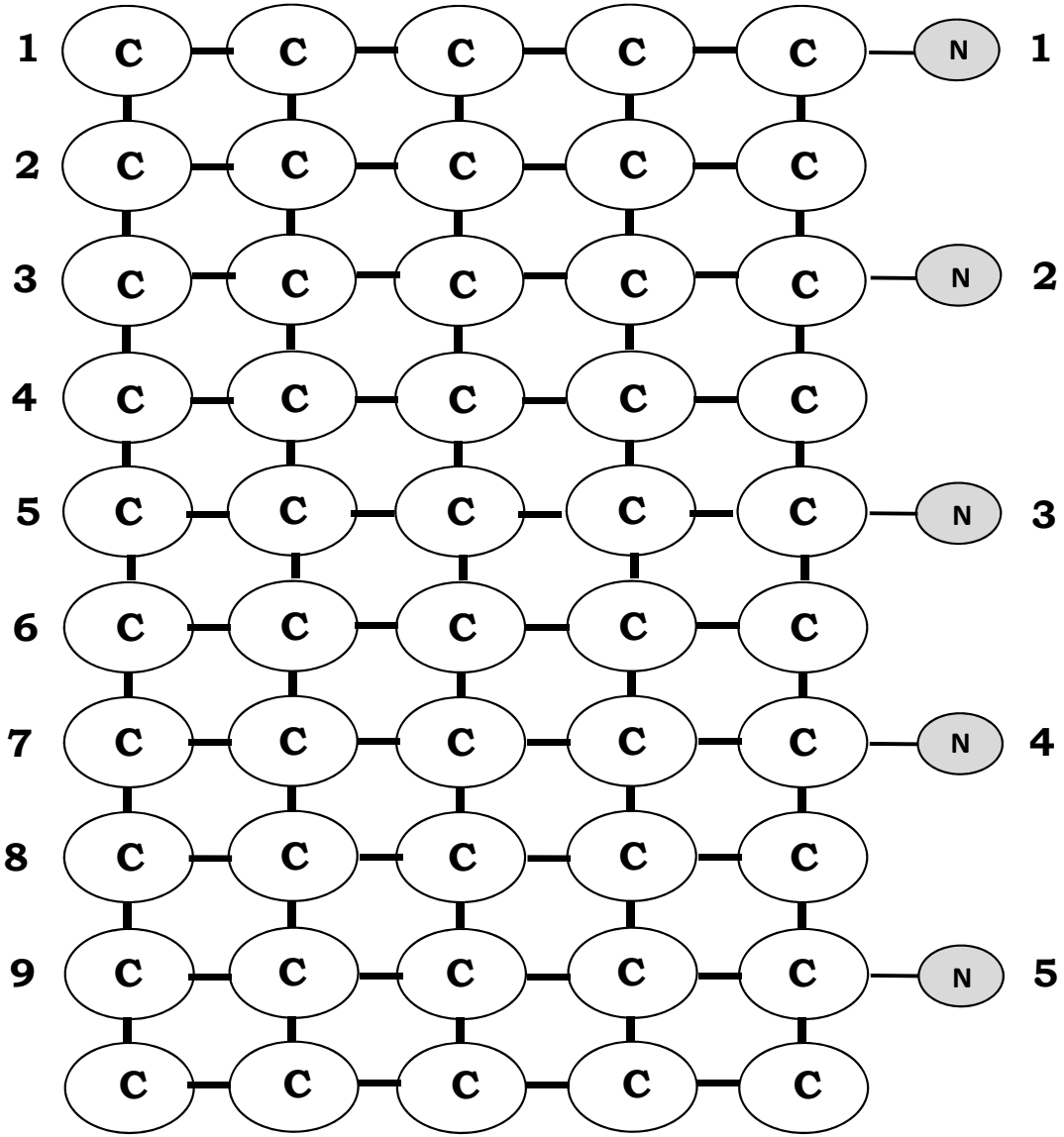
20 carbons for growth

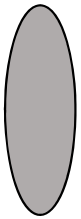
30 carbons respired as CO_2

Bacterial C:N of 10:1

20 C requires 2 N

1 additional N is needed





Soil Bacteria C:N = 10

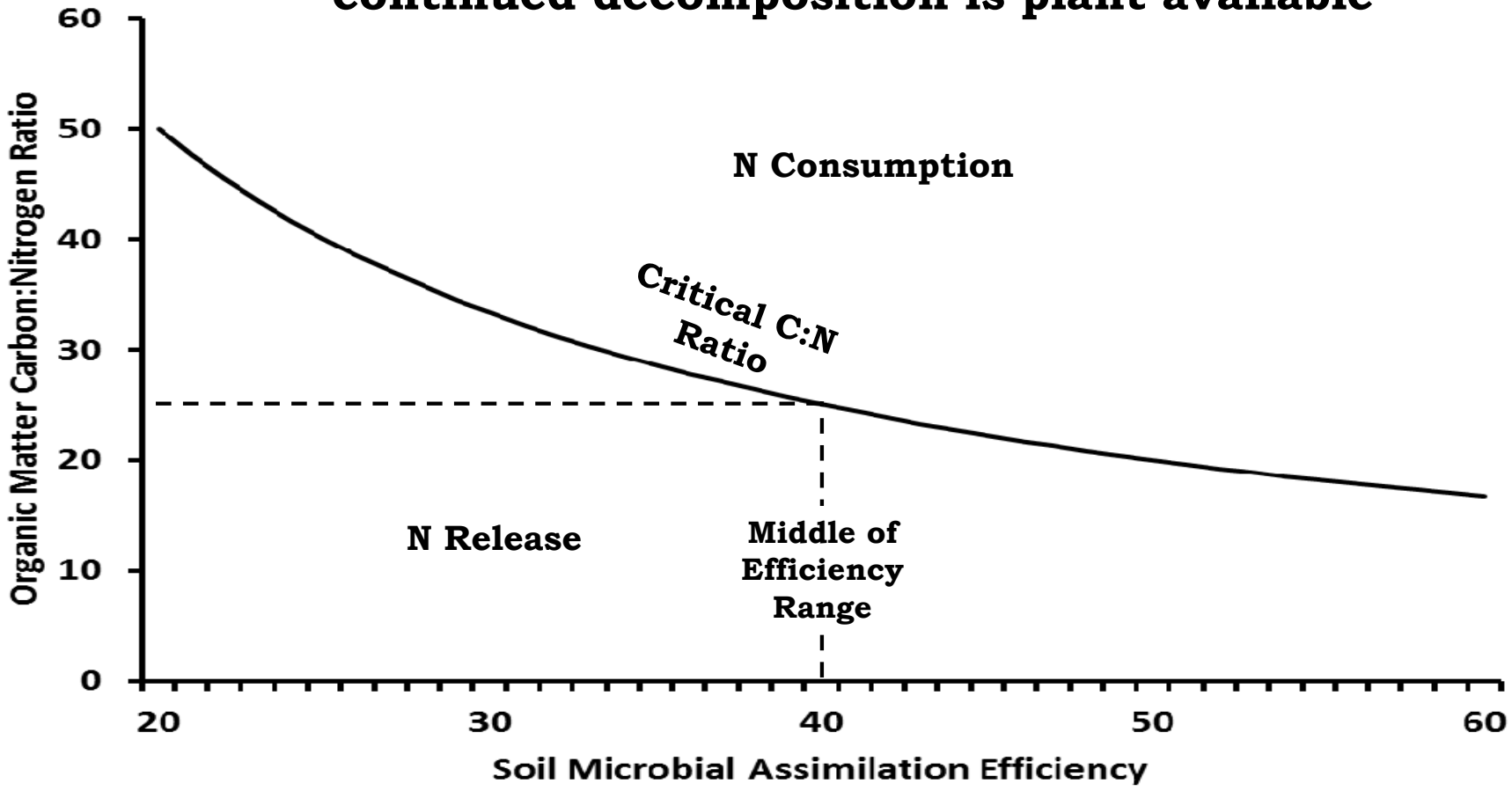
The organic matter has a 50 carbons and 5 N
C:N = 10

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

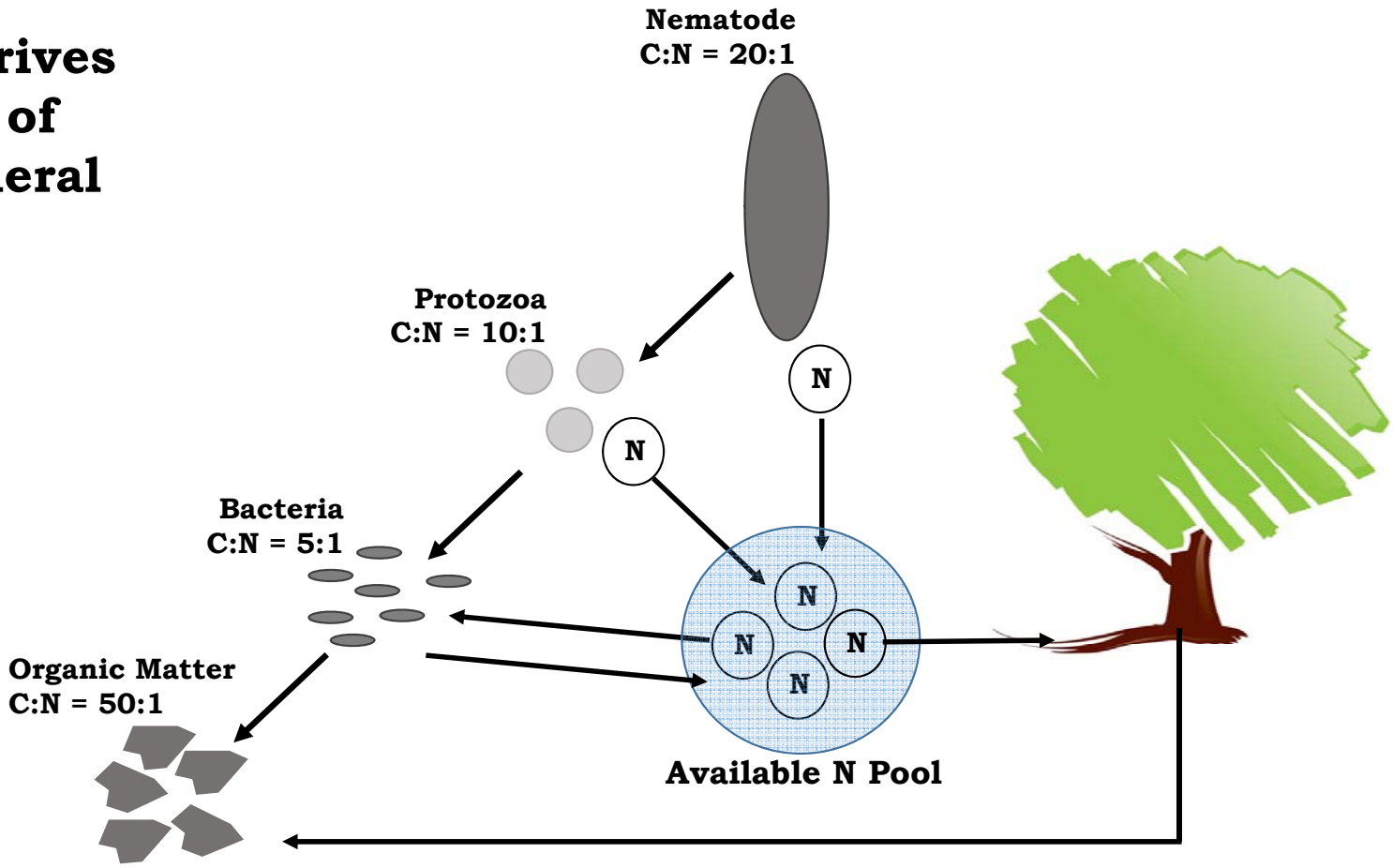


Soil's N supplying power can estimated based on soil OM content (%)

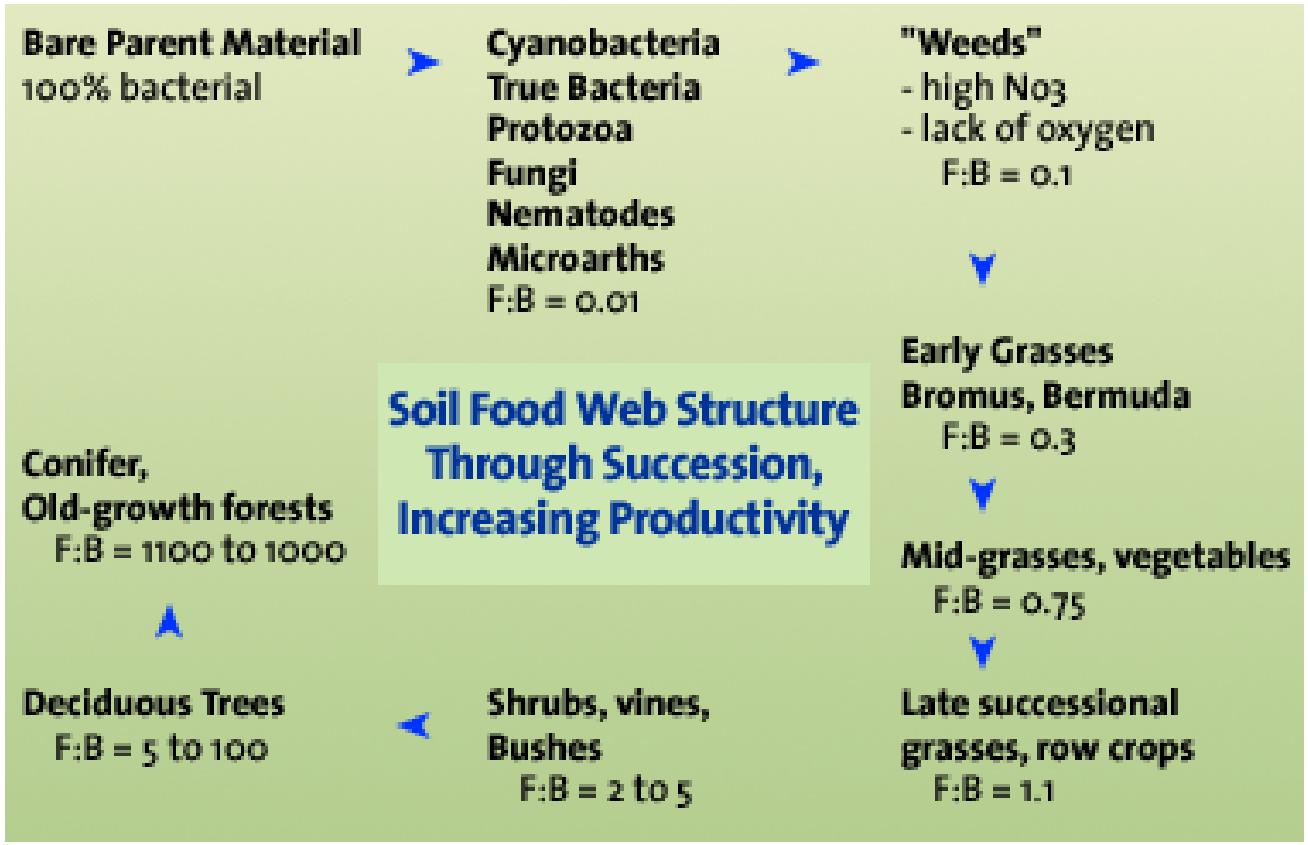
2,000,000	lbs soil/A
x 5%	Soil organic matter content
100,000	lbs soil OM/A
x 5%	N content in soil organic matter
5,000	lbs N /A
x 1%	Mineralization rate per year
50	lbs N /A per year

Soil Food Web

Soil biology drives the cycling of essential mineral elements



Soil microbes control decomposition and nutrient cycling



Chemical (pH) and physical (OM, clay) environments influence composition of the microbial community

http://www.soilfoodweb.com/03_about_us/approach_pgs/a_06_succession.html

An examination of soil microbial communities and litter decomposition in five urban land-uses in metropolitan Milwaukee, WI.

K. Turnquist, L. Werner, B. Sloss

No difference in soil organic matter content (%, LOI) and pH

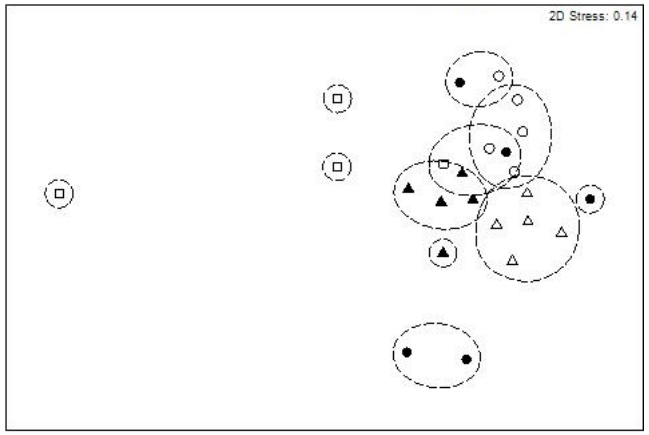


Figure 2. 2-D MDS plots from the TRFLP bacterial communities B1, B2, and B3 and fungal communities F1, F2, and F3 as measured from soils collected on May17th and 18th, 2009 . The outlined circles indicate groupings with 65% similar bacterial or fungal populations created from a Bray-Curtis similarity cluster diagram in PRIMER v6.

Lessons Learned:

1. **Biological communities are resilient**

2. **Composition tends to be similar when soil and climate are held constant**

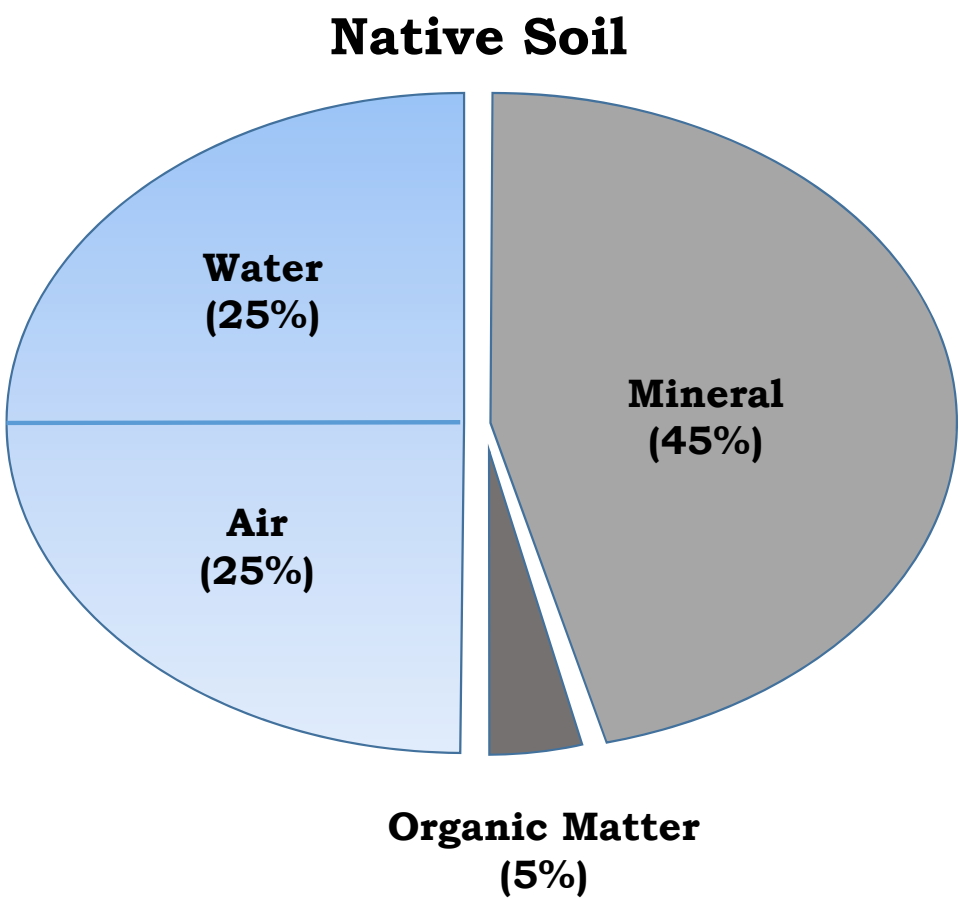
3. **If you build it, they will come**

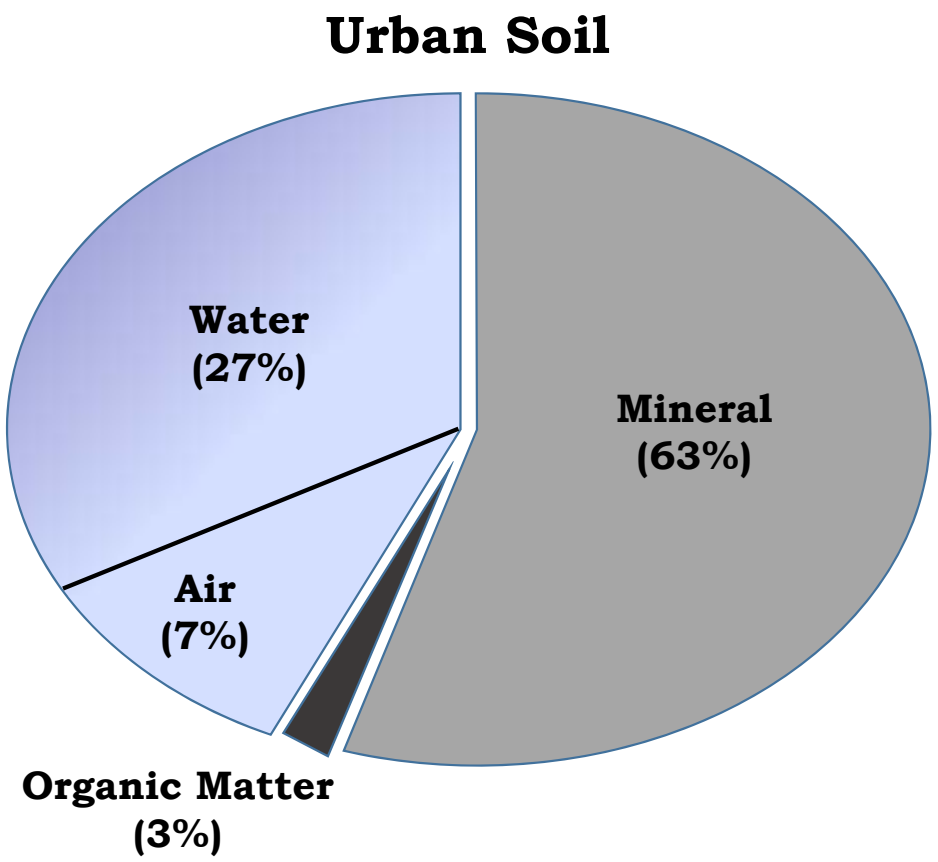
Mental Pause

Urban Soils Differ from Natural Soils

Natural Soil

Urban Soil


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


Urban Soil
Water
(27%)
Air
(7%)
Mineral
(63%)
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

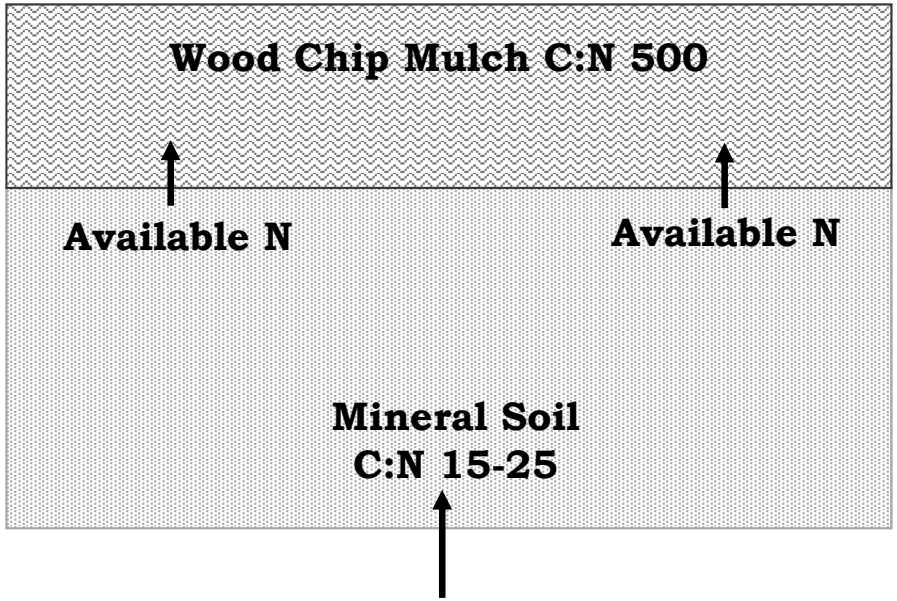
Organics removed from the site are a net loss to the nutrient cycle

1-1.5 lbs N/1000 ft²

Source: Werner and Miller, 2000, Photos from Web

Causes for Reduced Soil Fertility

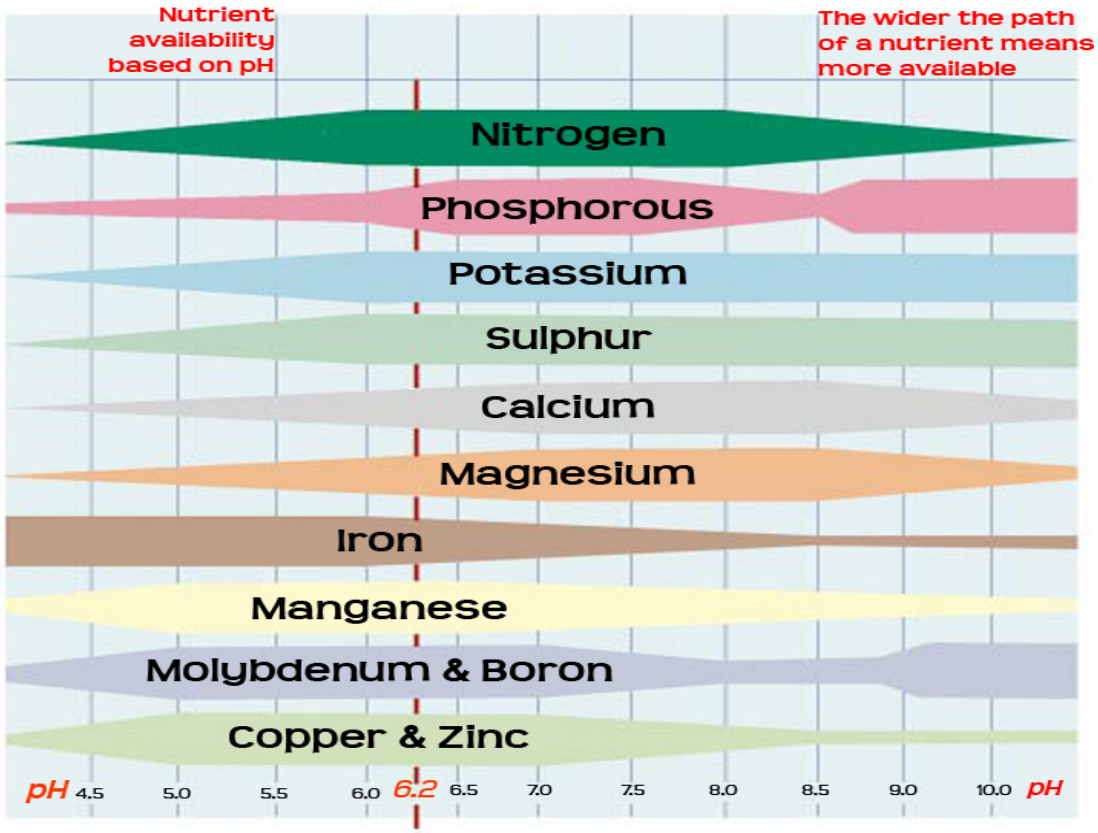
Uniform mulches can alter nutrient dynamics



Below the critical C:N ratio

Photo: L. Werner

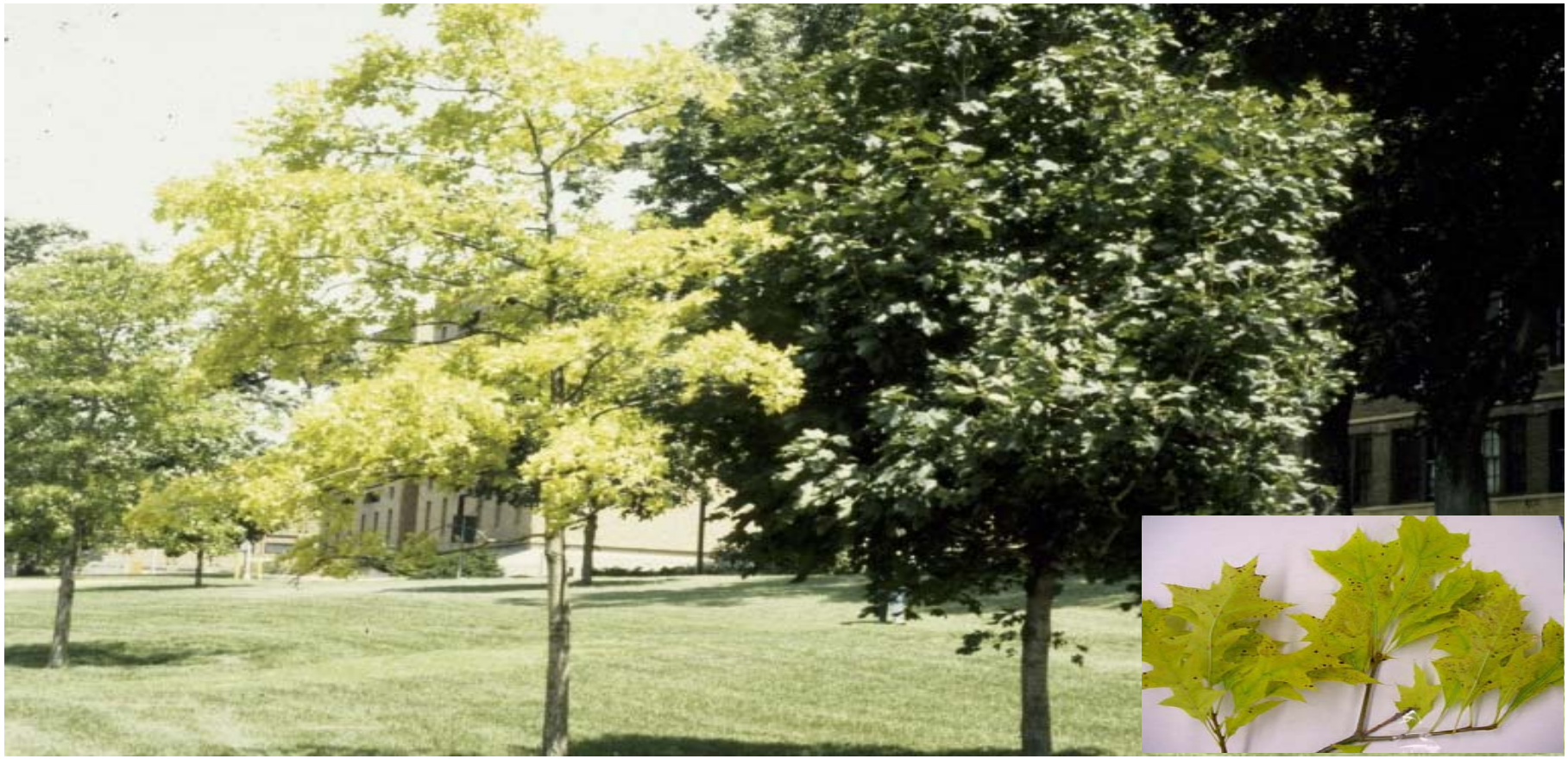
Causes for Reduced Soil Fertility



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

Causes for Compromised Soil Structure

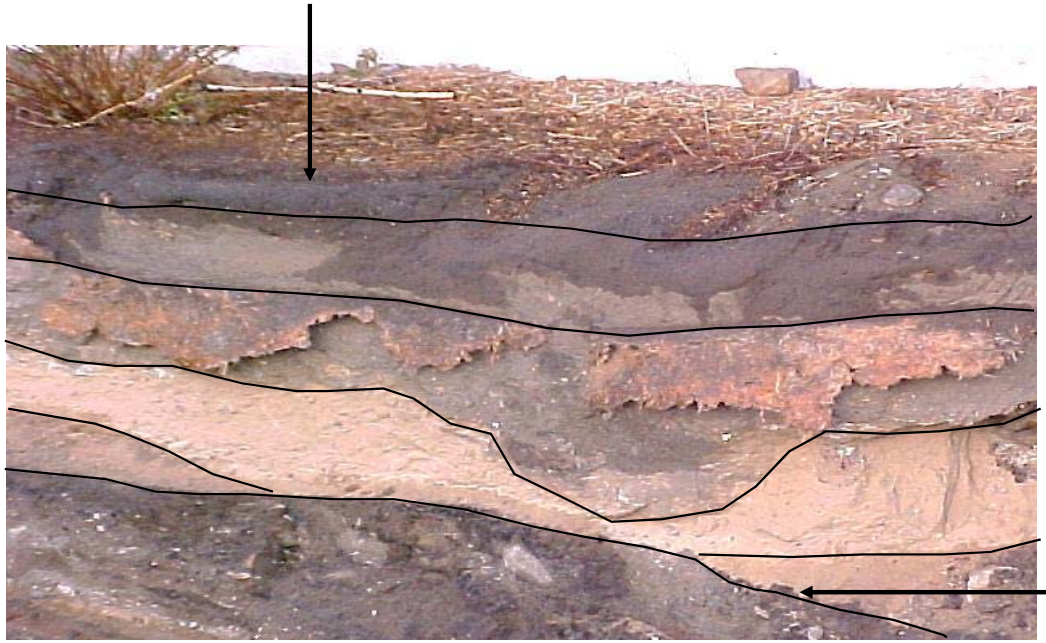
Urban Soils are Highly Disturbed

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

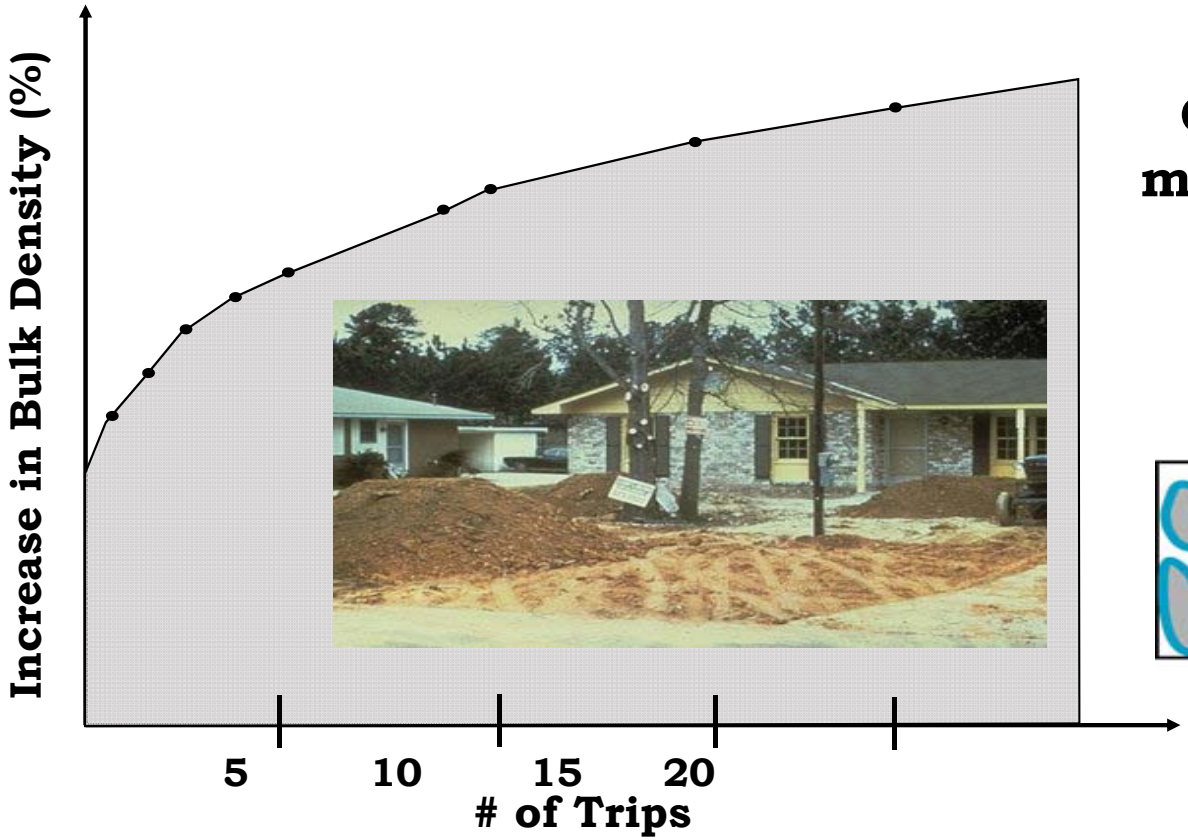
Original Soil Grade

VID00018.AVI

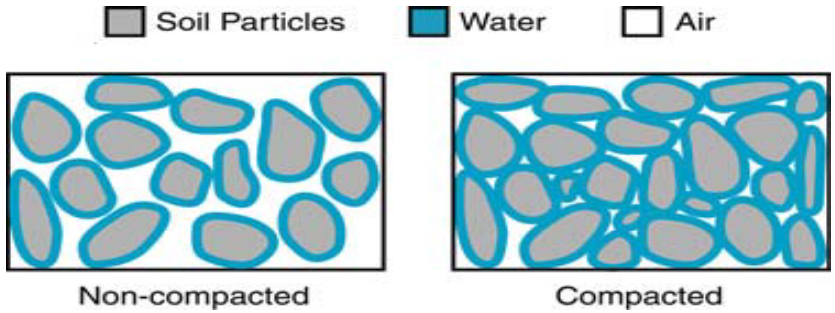
Photo: L. Werner

Causes for Compromised Soil Structure

Urban soils tend to be highly compacted



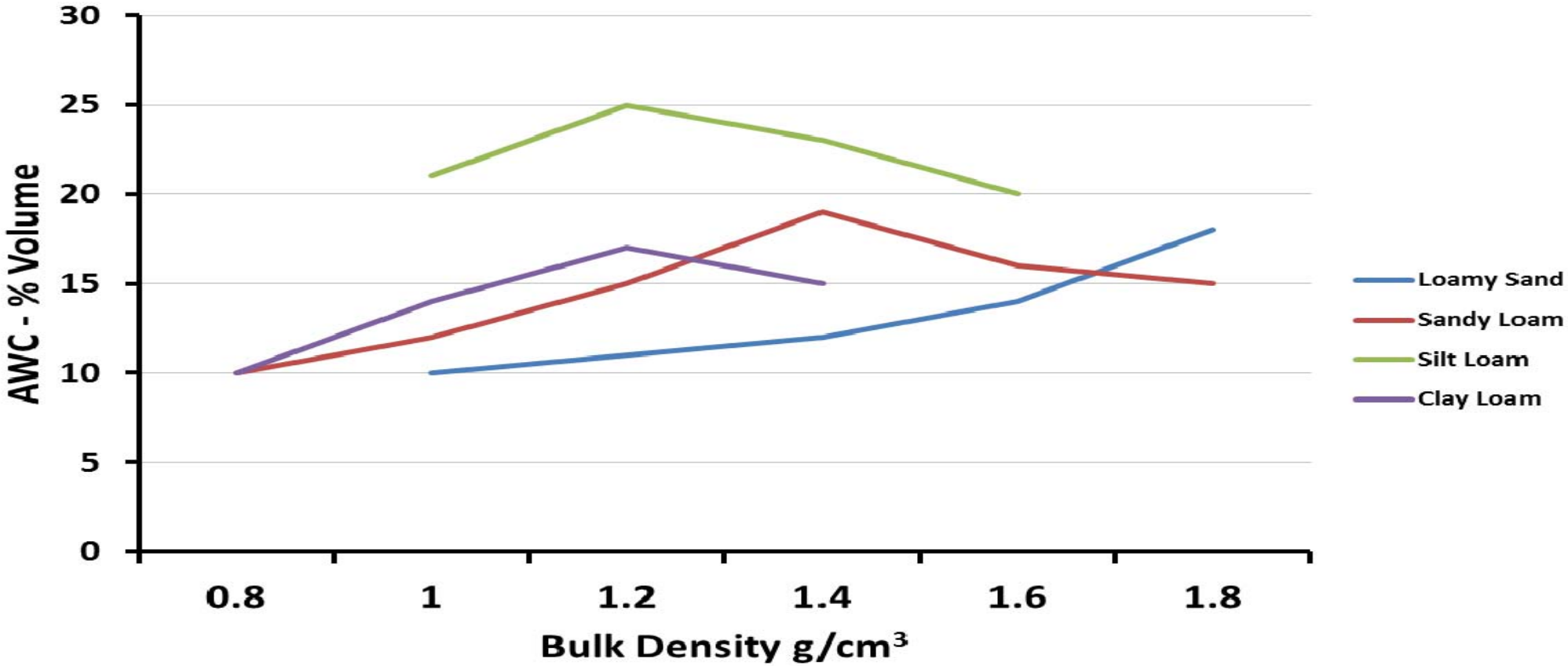
Compaction increases the mineral fraction and reduces pore space



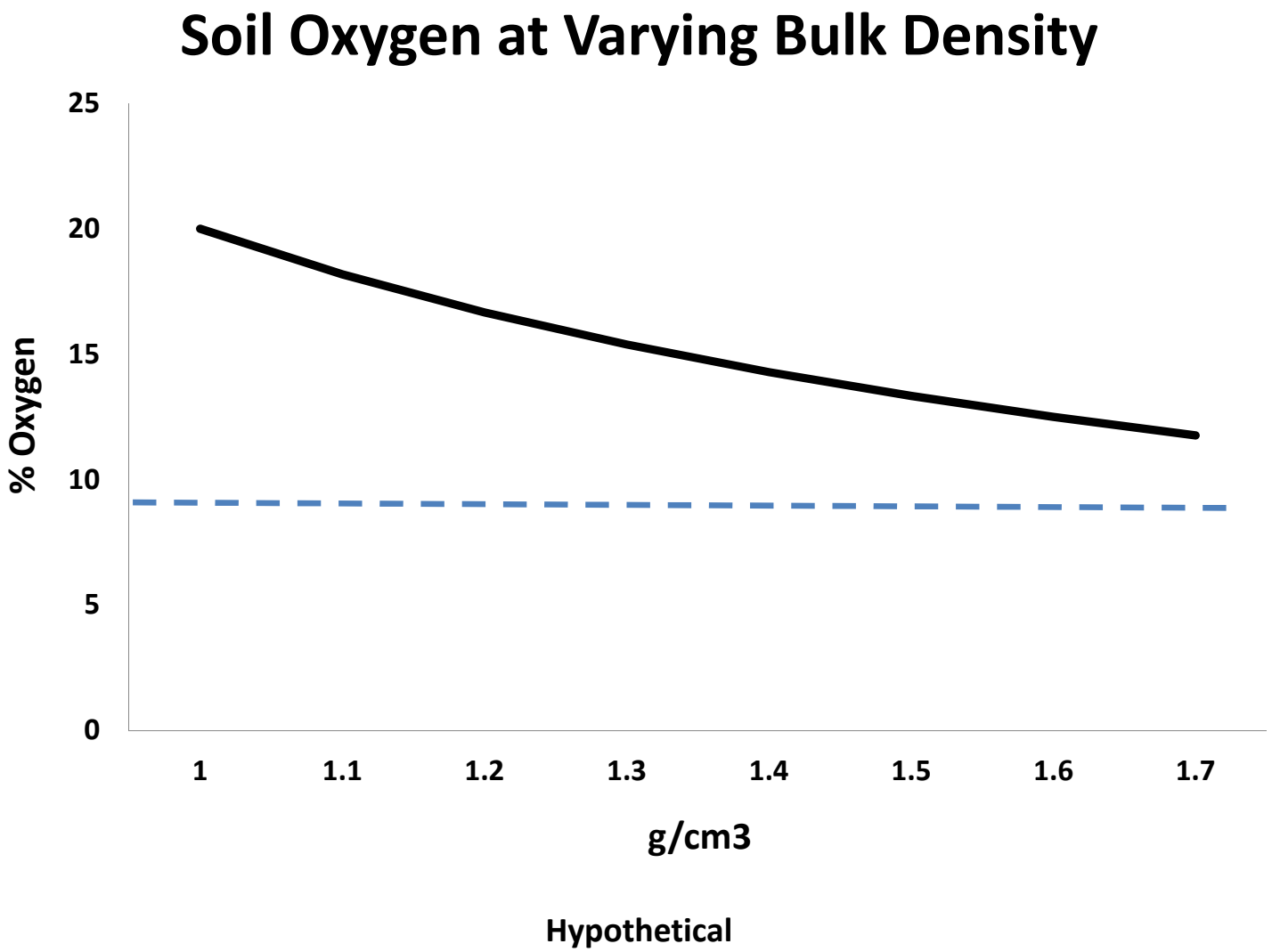
Source: NRCS Urban Soil Primer

Source: WI DNR, Forest Management Guidelines

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

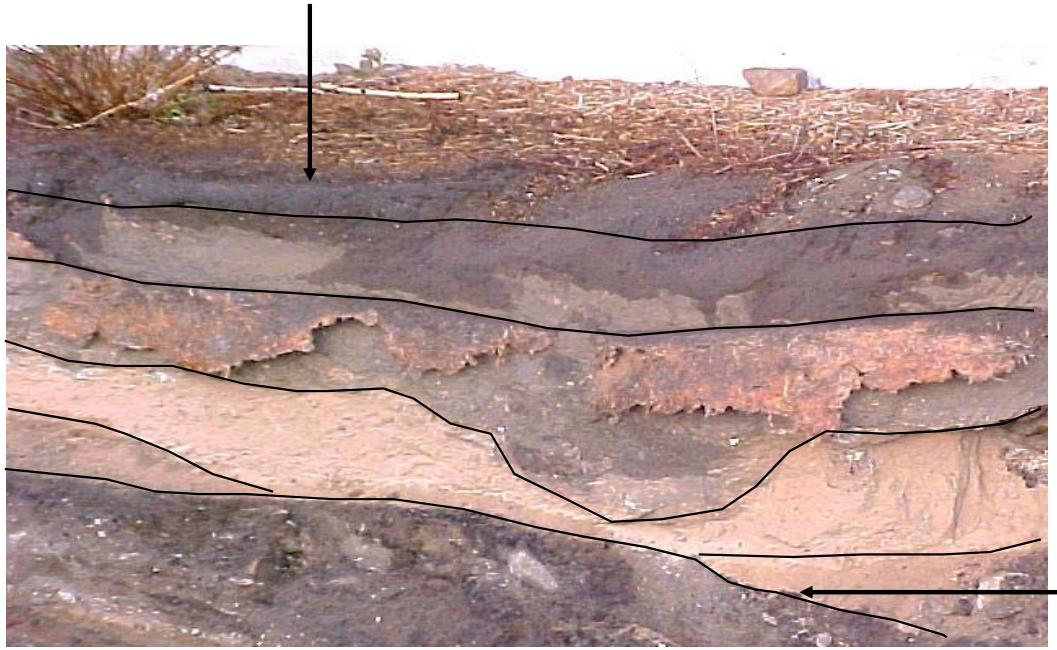


Drawn from data in Archer and Smith, 1972


Soil Oxygen at Varying Bulk Density
25
20
15
10
5
0
% Oxygen
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
g/cm3
Hypothetical

Causes for Compromised Soil Structure

Note: Saturated Surface Soil



Vertical discontinuities can impede water drainage

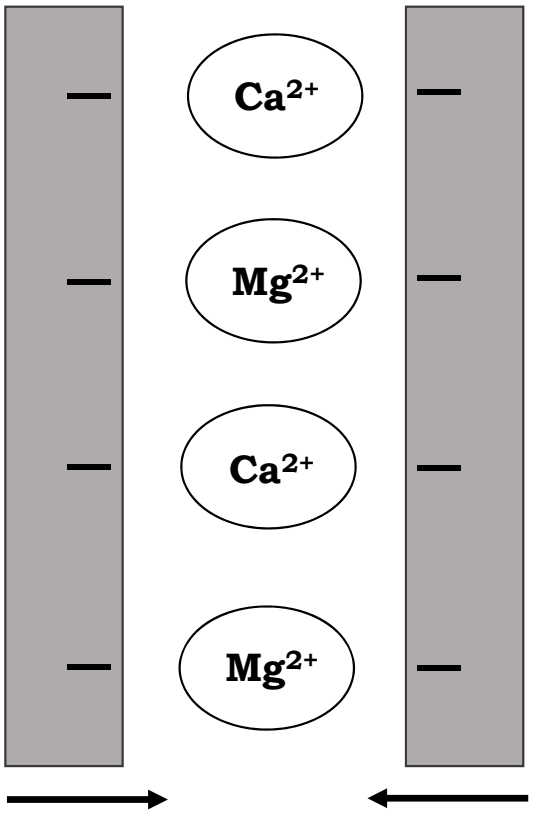
Original Soil Grade

Photo: L. Werner

Causes for Compromised Soil Structure

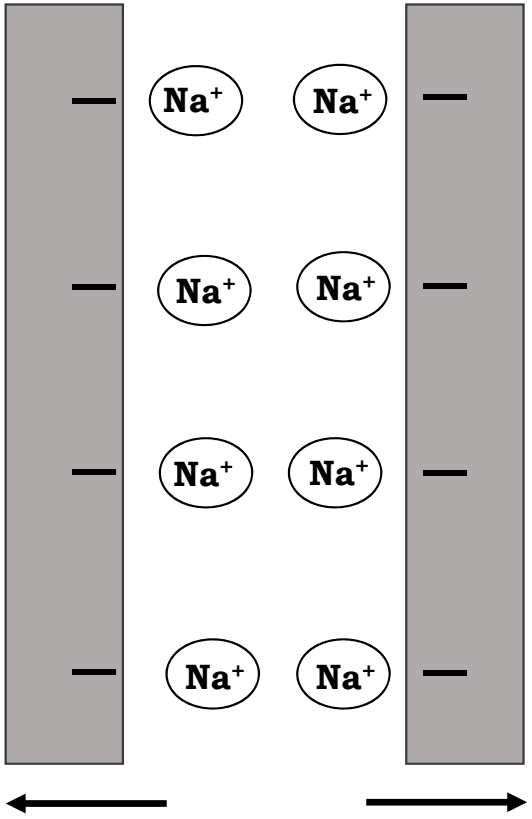
High sodium levels can destroy soil aggregates and increase compaction

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

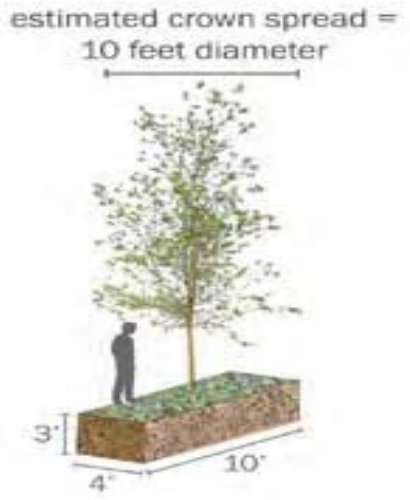


Digging out a soil profile in problem areas can be of great assistance in diagnosing soil structure

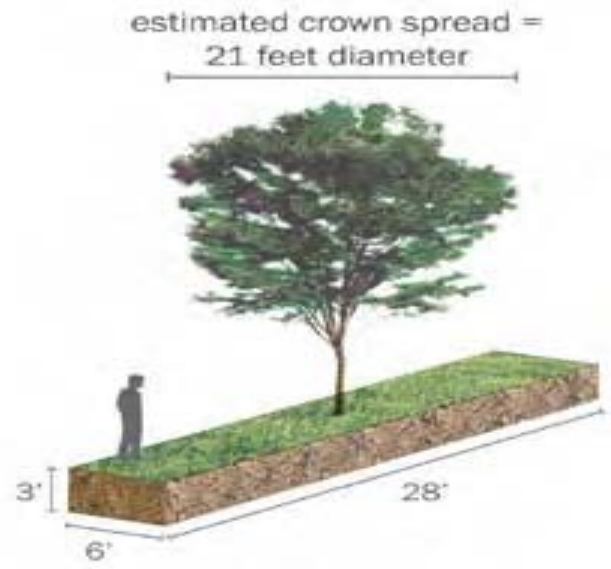
*** Thickness of Organic Layer**
*** Rooting depth**
*** Depth of soil**
*** Depth to restrictive layers**
*** Potential contaminants**

Evaluating Soil Volume

Plant available water and EE increase with increasing soil volume



120 ft^3 of Soil



500 ft^3 of Soil

1000 ft^3 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? Need?

Table 1. Soil volume and soil area recommendations for planting trees in urban areas.

Recommendation	Reference
Soil Volume	
minimum 100 ft^3 soil	Urban 1989
400 ft^3 soil	Urban 1996
1000 ft^3	Urban 2003
Soil Volume Per Crown Projection	
2.5 ft^3 soil/1 ft^2 crown projection	Bakker 1983
2.5 ft^3 soil/1 ft^2 crown projection	Lindsey and Bassuk 1991
1.4 to 1.6 ft^3 soil/1 ft^2 crown projection	Urban 1996, 2000
Soil Volume Per dbh	
27 ft^3 soil/1 in. dbh	Perry 1980
60 ft^3 soil/1 in. dbh	Perry 1985
50 to 65 ft^3 soil/1 in. dbh	Urban 1996, 2000
Soil Area	
6 x 6 ft tree well or planter strip	City of Davis (no date)
4-x-8 ft island planter	City of Davis (no date)
45–100 ft^2 for trees < 30 ft tall	Gilman 1997
100–200 ft^2 for trees 31–40 ft tall	Gilman 1997
> 200 ft^2 for trees > 50 ft tall	Gilman 1997

Soil Volume is also about structural roots

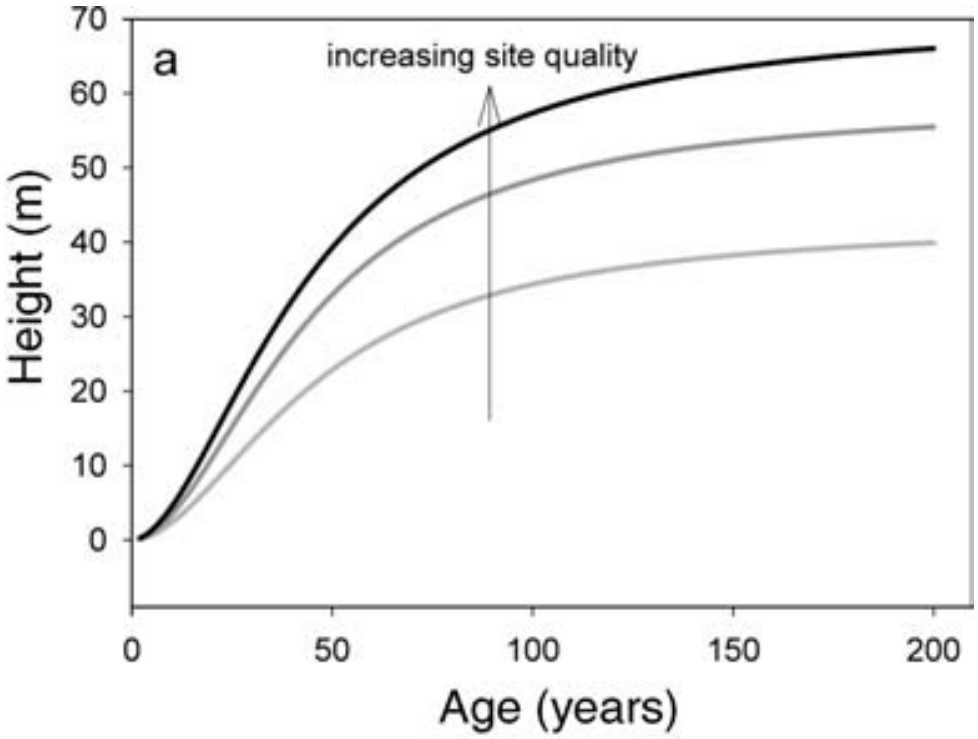
Photo: C. Wells

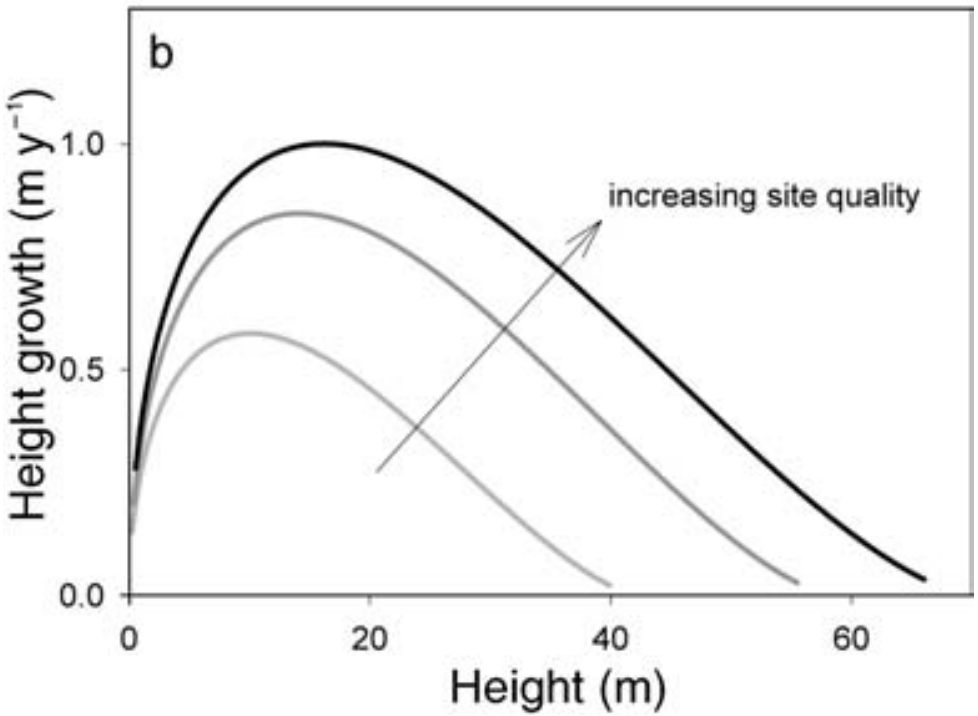
Photo: L. Werner

Photo: A. Uhen

Site Quality

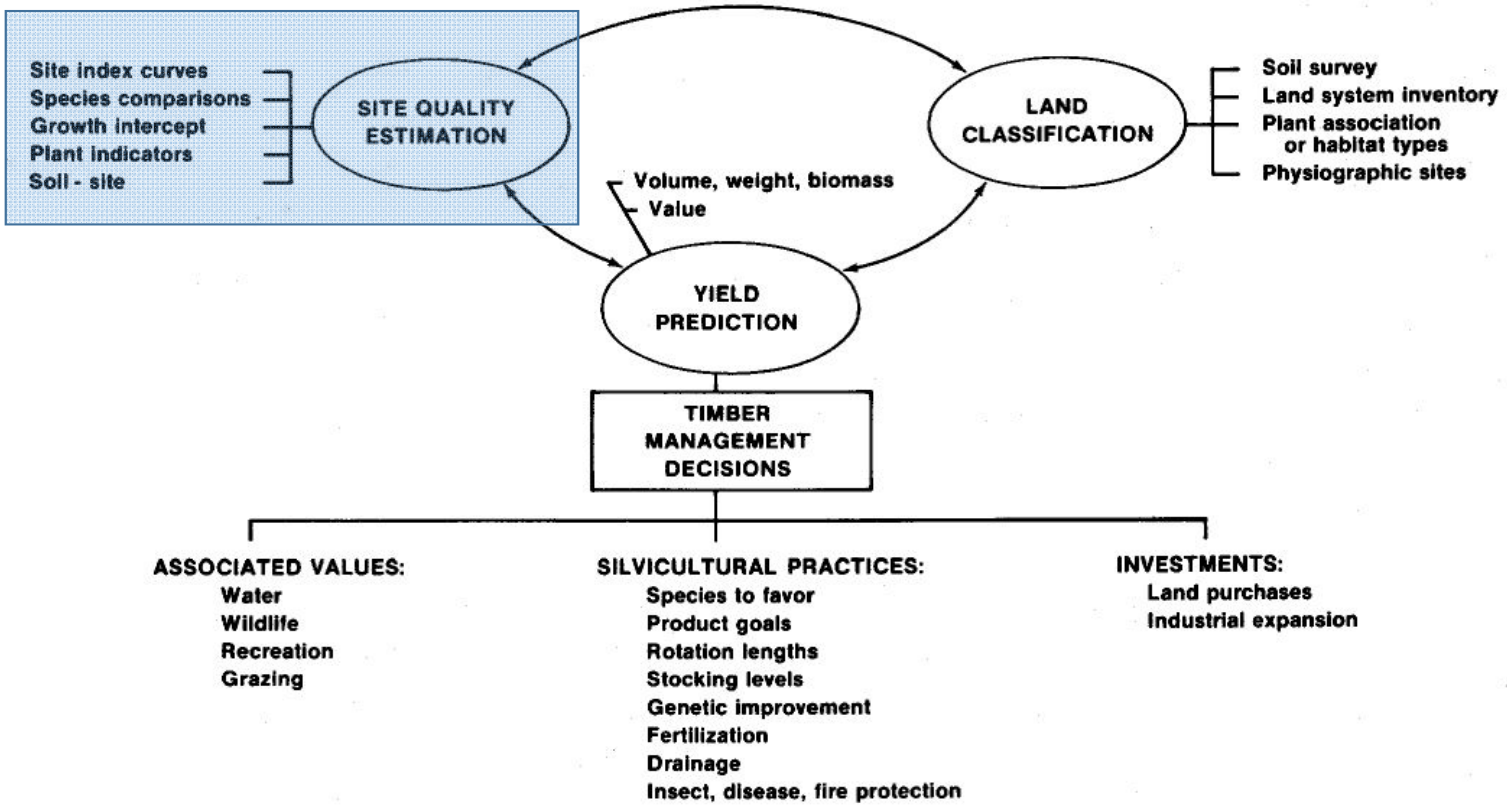
Generally, increased resource availability results in greater growth





Bond et al. Tree Physiology 27: 441-453.

The Goal of Forest Management is too Make Sound Decisions



Carmean, W.H. Site Classification for Northern Forest Species 1960's

United States
Department of
Agriculture

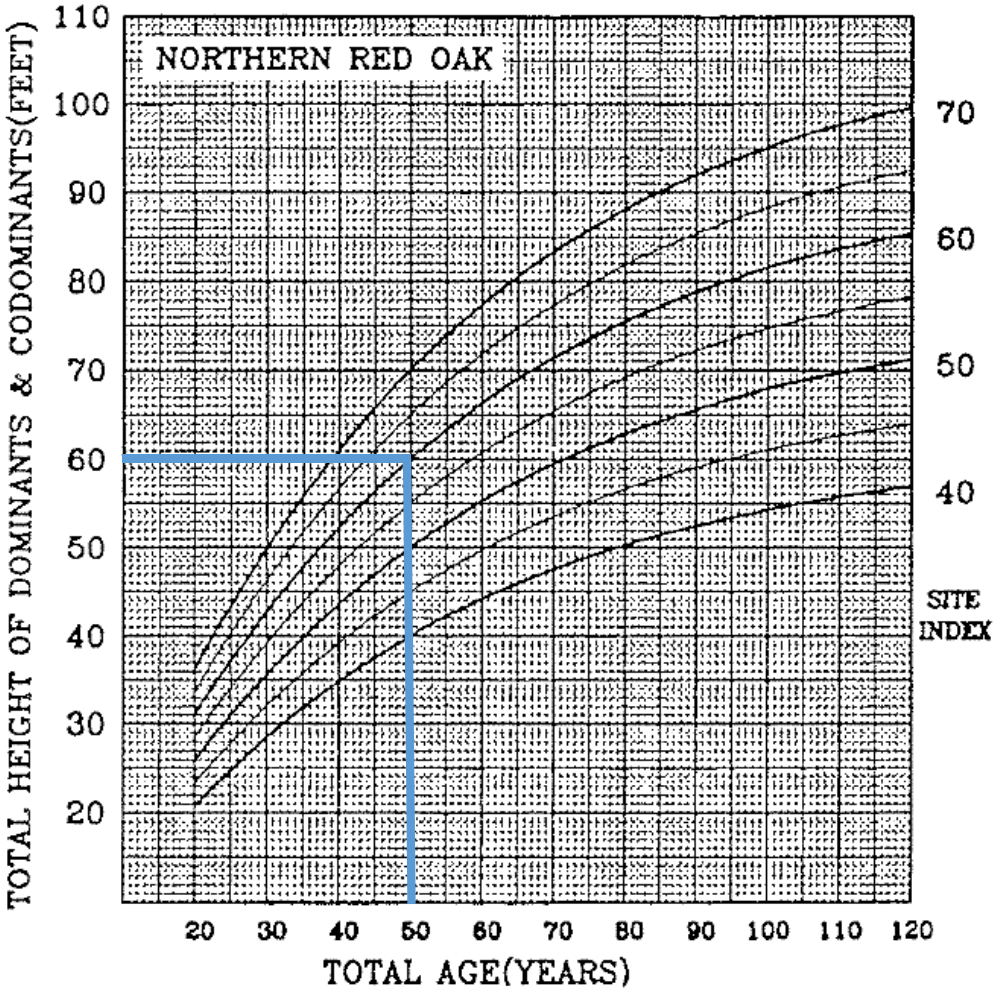
Forest
Service

North Central
Forest Experiment
Station

General Technical
Report **NC-128**

Site Index Curves for Forest Tree Species in the Eastern United States

Willard H. Carmean, Jerold T. Hahn, and Rodney D. Jacobs



Total height of dominant trees of a given species on a site at a reference/index age

Source: Carmean, W. H., J. T. Hahn, and R. D.Jacobs. 1989. *Site Index Curves for Forest Tree Species in the Eastern United States (General Technical Report NC-128)*. USDA Forest Service, North Central Forest Experimental Station, 1992 Folwell Avenue, St. Paul, MN 55108. p. 62.

Across locations within a climatic zone, site index is largely a function of soil quality

Textural Class

Depth of Soil

Soil Moisture

Soil Temperature

Nutrient Availability

Restrictive Layers

Using soil properties to predict forest productivity in southern Illinois

Woolery et al. 2002.

Table 4. Soil property model for each tree species.

White Oak Site Index = 85.810 - 1.025 (PCLAYB) + 0.339 (ROOTD) + 0.237 (CEC)

Northern Red Oak Site Index = 86.412 + 0.305 (SPM) - 2.577 (AVAILW) - 0.835 (BPERM)

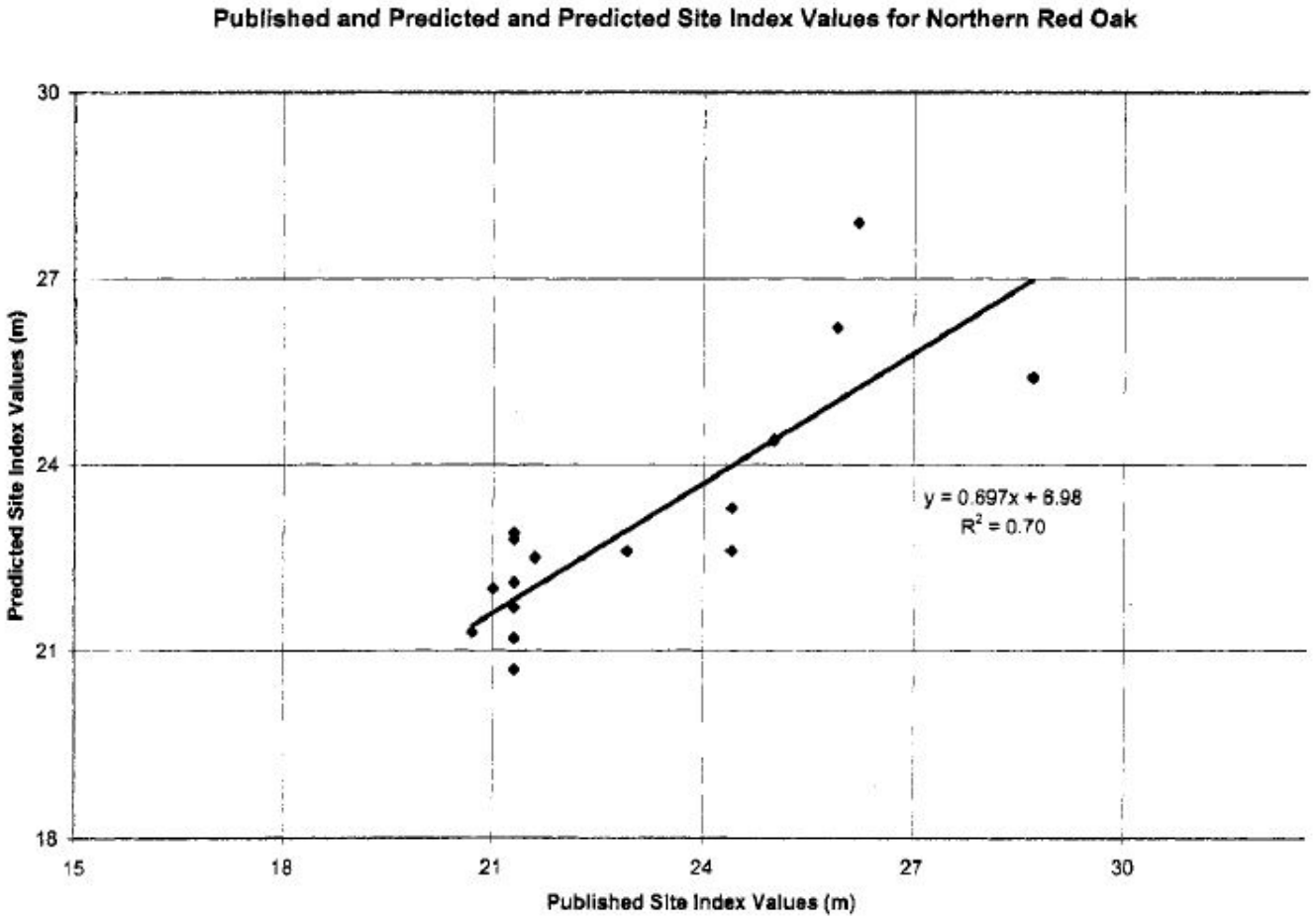
Yellow Poplar Site Index = 119.215 + 3.6086 (BPERM) - 6.183 (BPH) + 0.067 (REDOX)

Where:

PCLAYB	=	Percent clay found in the B horizon
ROOTD	=	Total rooting depth
CEC	=	Cation exchange capacity of A and E horizons
SPM	=	Depth to second parent material
AVAILW	=	Plant available water to 150 cm
BPERM	=	Permeability of the B horizon
BPH	=	B horizon pH
REDOX	=	Depth to redoximorphic features

Figure 2

Published and predicted site index values for northern red oak.



Woolery et al. 2002. Using soil properties to predict forest productivity in southern Illinois

Table 4. Soil property model for each tree species.

White Oak Site Index = 85.810 - 1.025 (PCLAYB) + 0.339 (ROOTD) + 0.237 (CEC)

Northern Red Oak Site Index = 86.412 + 0.305 (SPM) - 2.577 (AVAILW) - 0.835 (BPERM)

Yellow Poplar Site Index = 119.215 + 3.6086 (BPERM) - 6.183 (BPH) + 0.067 (REDOX)

Where:

PCLAYB	=	Percent clay found in the B horizon
ROOTD	=	Total rooting depth
CEC	=	Cation exchange capacity of A and E horizons
SPM	=	Depth to second parent material
AVAILW	=	Plant available water to 150 cm
BPERM	=	Permeability of the B horizon
BPH	=	B horizon pH
REDOX	=	Depth to redoximorphic features

Site Quality Parameters

Water Supply Capacity

Texture
Organic matter content
Clay content

Soil Depth

Depth to restrictive layer
Depth to second parent material
Depth to redoximorphic features

The Right Tree for the Right Place

from the TREE CITY USA® BULLETIN

Urban Forest management also requires an assessment site quality

Traditional Site Index Approach May Work Here!

How About Here?

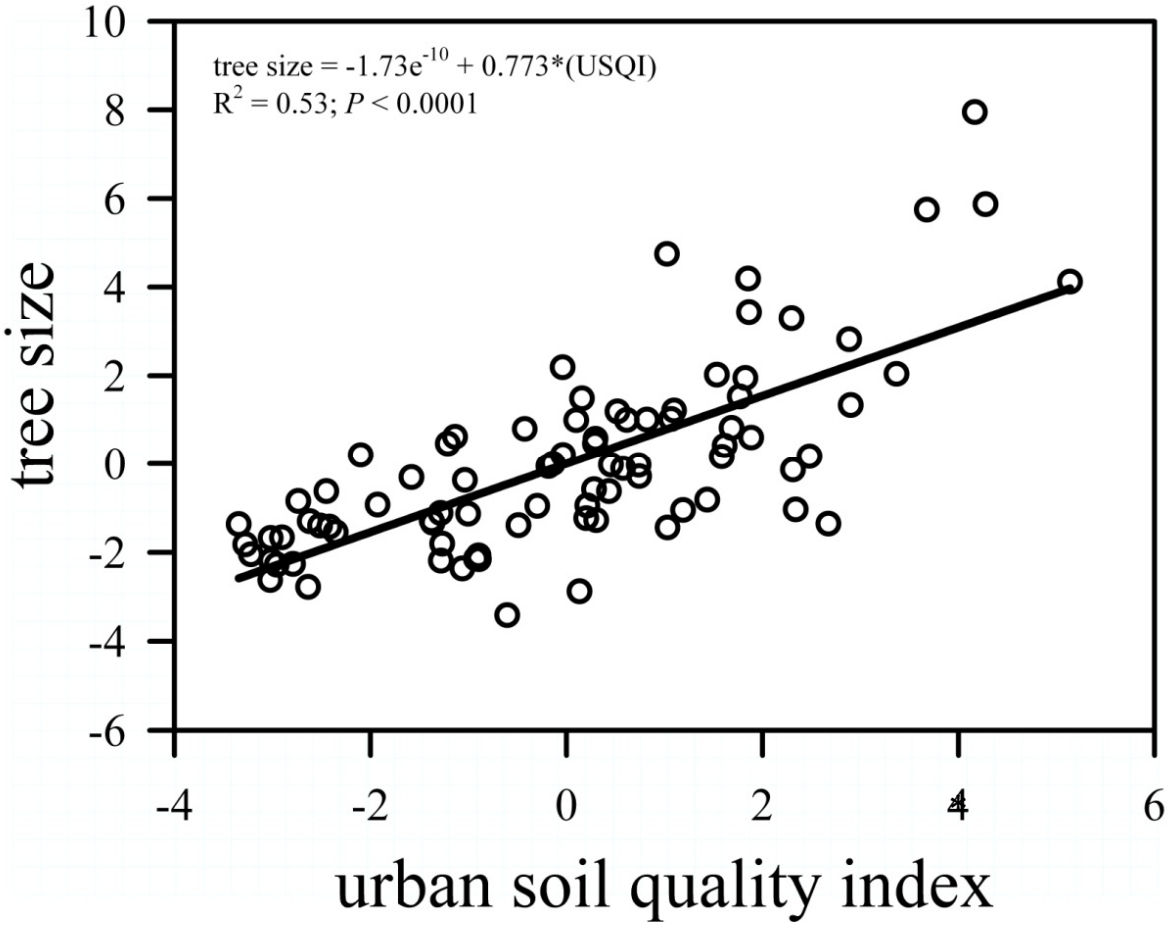
DOLLAR GENERAL
Or Here?

Or Even Here?
The Alterations to the Site and the Absence of Vegetation Requires Another Method

Urban soil quality index (USQI)

Scharenbroch, B.C. & M. Catania. 2012. Soil quality attributes as indicators of urban tree performance. Arbor. & Urb. For. 38:214-228.

1. 84 plots (5 locations & 4 genera) in western Chicago, IL USA
2. 3 site, 48 soil & 20 tree properties
3. Establish an USQI
4. Evaluate USQI for predicting urban tree attributes



*texture, bulk density, aggregate stability, pH, electrical conductivity, total and labile OM

(Scharenbroch & Catania 2012)

USQI & urban tree attributes

Tree age (R^2 = 0.78)

Tree height (R^2 = 0.77)

Crown area (R^2 = 0.75)

Trunk diameter (R^2 = 0.65)

Dia. growth rate (R^2 = 0.41)

HT growth rate (R^2 = 0.35)

Leaf chlorophyll (R^2 = 0.32)

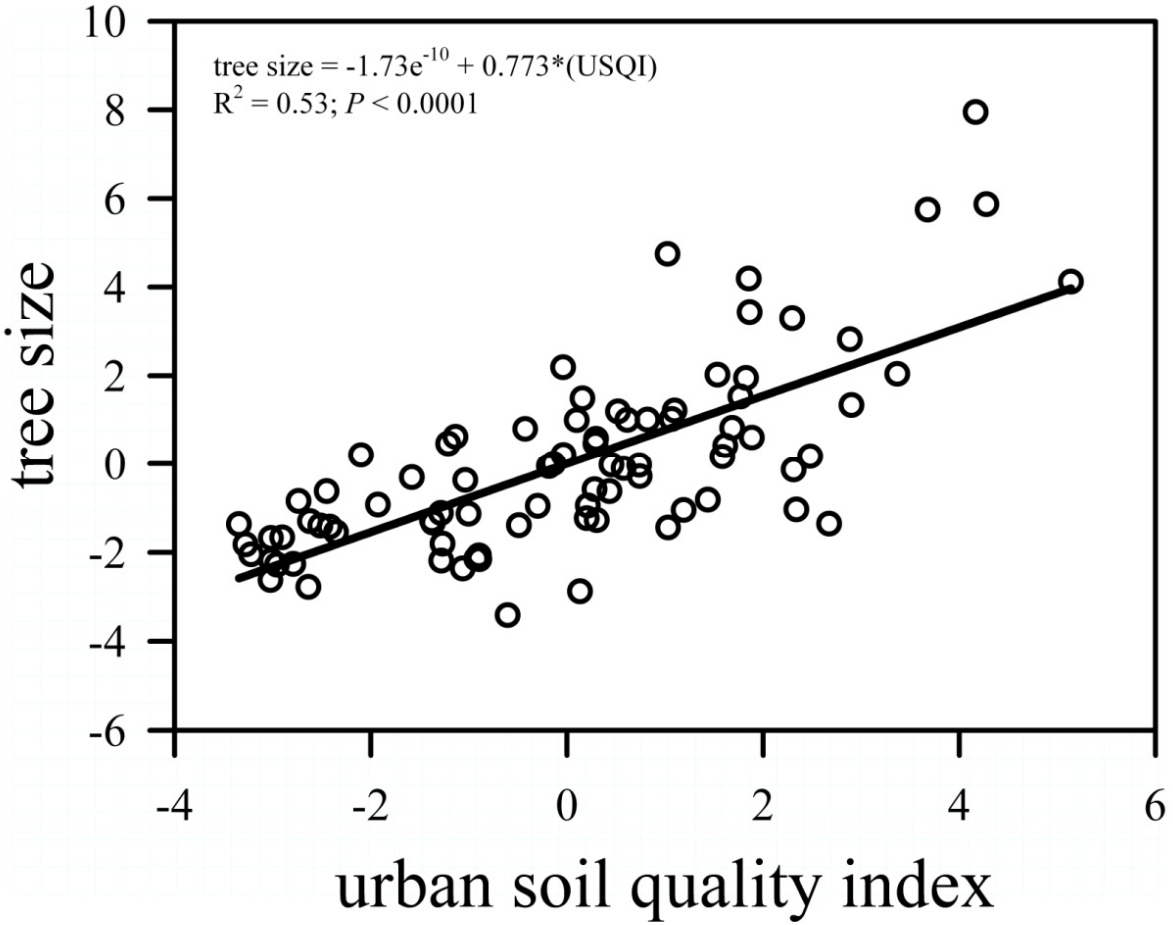
Leaf N (R^2 = 0.42)

Tree condition index (R^2 = 0.18)

RUSI	***0***	***1***	***2***	***3***
PPT	<500 mm/y	500-750	751-1000	>1000
GDD	<1000 d	1001-2500	2501-4000	>4000
EXP	0	1-2	3-4	5
TRAF	>4 lanes	2-4 w/o park	2-4 w/park	<2 lanes
SURF	non-perm or bare	patchy	thick veg	mulch
PEN	<5 cm	<20	20 (hard)	20 (easy)
INFRA	<1 m	1-5	6-10	>10
A HOR	<1 cm	1-5	6-10	>10
ERA	<5 m2	5-25	26-50	>50
TEXT	no soil	S, LS, SiC, SiCL, CL, C	SCL, SL, SC	L, SiL
STRUC	M, SG, PL	ABK	SBK	GR
WAS	no aggregates	<50% soak	<50% swirl	>50% swirl
SOM	gleyed	chip 1	chip 2-3	chip 4-5
EC	<50 or >1000 uS/cm	50-100	100-250	250-1000
pH	<4 or >9	4-4.9 or 8.1-9	5-5.9 or 7.1-8	6-7

Urban soil quality index (USQI)

Scharenbroch, B.C. & M. Catania. 2012. Soil quality attributes as indicators of urban tree performance. Arbor. & Urb. For. 38:214-228.



Soil Quality Parameters

Texture
Bulk Density
Aggregate Stability
pH
Electrical Conductivity
Total and Labile OM

THANK YOU!

Whenever possible, mimic nature

Organic Horizon Associations