Basic soil fertility

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UNIVERSITY OF MARYLAND EXTENSION

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‘What factors limit Crop Production?’ or ‘Soil Fertility writ Large’

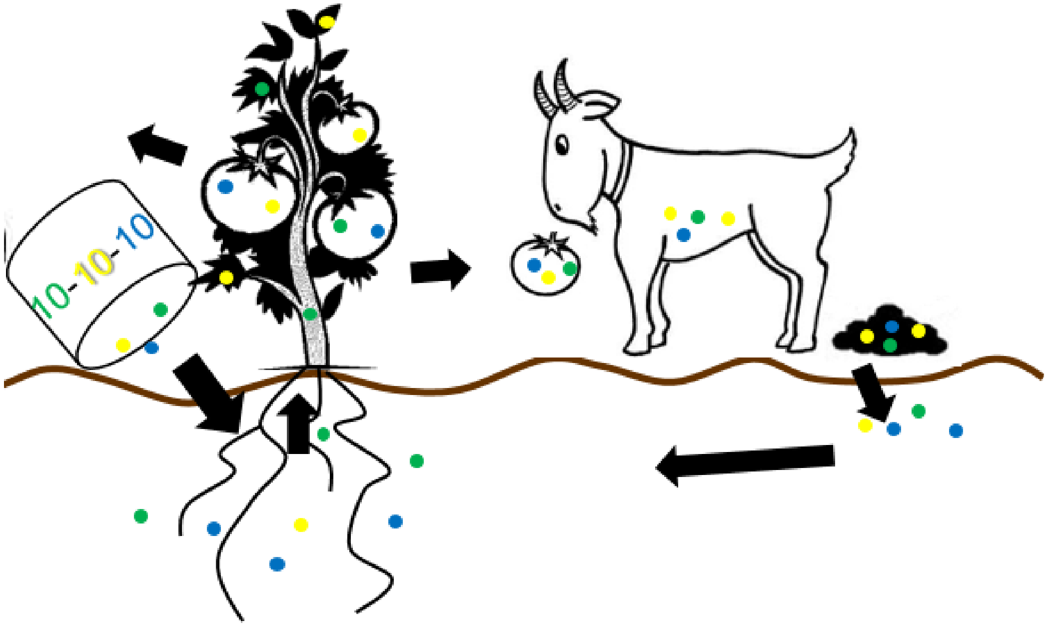
- water
- below-ground aeration
- atmospheric CO_2
- temperature
- mechanical support
- nutrients ⟵ ‘Basic Soil Fertility’
- disease/pest pressure
- symbioses

Pepper plants growing poorly.
Image credit: Neith Little, UMD Extension

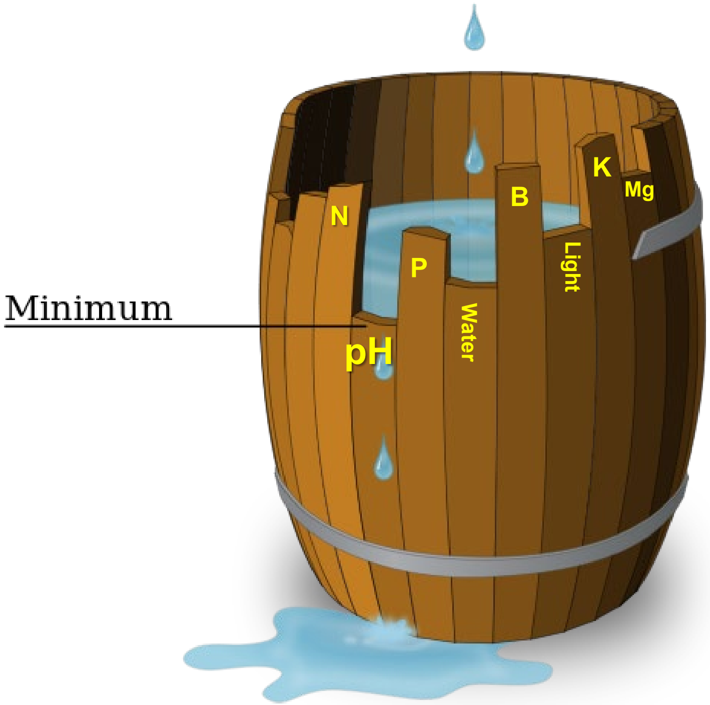
Definition of a nutrient

- Required for life-cycle completion

- Exogenous
  - plants can’t generate them
  - obtained from environment



Liebig-Sprengel law of the minimum



Growth is dictated by the nutrient present in the most limiting amount.

Assumes no interaction between nutrients.

Plant-Essential Nutrients (Tables 4-1 & 4-2, pp. 55-56, MANMH)

Non-Mineral	Mineral*		
	Macronutrients		Micronutrients
	Primary	Secondary	
carbon (CO_2)** oxygen (O_2)*,** hydrogen (H_2O)*	nitrogen (NO_3^-, NH_4^+) phosphorus (HPO_4^{2-}, $H_2PO_4^-$) potassium (K^+)	calcium (Ca^{2+}) magnesium (Mg^{2+}) sulfur (SO_4^{2-})	iron (Fe^{3+}, Fe^{2+}) nickel (Ni^{2+}) zinc (Zn^{2+}) chlorine (Cl^-) manganese (Mn^{2+}, Mn^{4+}) boron (H_3BO_4, $H_2BO_4^-$, $B_4O_7^{2-}$) copper (Cu^{2+}) cobalt (Co^{2+}) molybdenum (Mo^{2+})

*uptake (typically) via roots; **uptake via leaves

‘Holding charge is holding nutrients’

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‘Holding charge is holding nutrients’

A useful mnemonic for essential plant nutrients (Courtesy, R. Weil, UMCP)

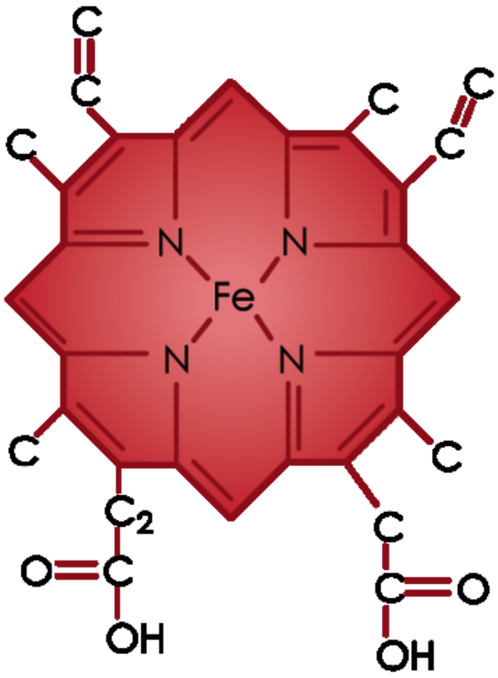
C. B. Hopkins Café Co.
Closed Monday Morning & Night.
See you Zoon, the Mgmt.

C. B. HOPKiNS CaFé Co.
Closed Monday Morning & Night.
See you Zoon, the Mgmt.

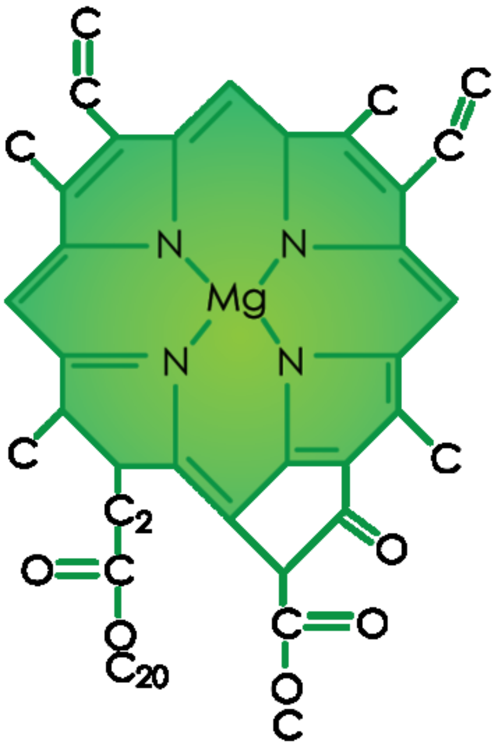
What do plants do with nutrients?

Indispensable roles in the machinery of cell function.

Nitrogen	Protein
Phosphorus	Energy delivery; DNA structure
Potassium	Salt balance between roots and soil
Magnesium	Essential element in chlorophyll



Human Blood
Hemoglobin



Plant Chlorophyll

Three main questions to answer

- Why are some soils better at supplying nutrients than others?

- How do soils lose nutrient content; and how can you tell?

- What can be done to maintain fertility?

Why are some soils better at supplying nutrients than others?

All things being equal why is it that some soils are more fertile than others?

The beginning of the answer:

Some soils contain more nutrients anyway

Some soils can hold on to nutrients better

Q. Why do some soils inherently contain more nutrients?

A. Because soils develop from different geologies

Mineral	**Formula**
Quartz, quartzite	SiO_2
Olivene	$(Ca,Mg)_2SiO_4$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Muscovite	$KAl_2(AlSi_3O_{10})(FOH)_2$
Montmorillonite	$(Na,Ca)_{0\text{-}3}(Al,Mg)_2Si_4O_{10}(OH)_2 \bullet n(H_2O)$
Limestone	$(Ca,Mg)CO_3$

…. and some geologies contain more nutrients!

Q. Why do some soils hold more nutrients?

A. Because soils differ in

Organic matter content

Relative amount of sand, silt and clay ('soil texture')

Relative amount of different types of clays

pH

Soil component	Relative ability to hold positive charge
Organic matter	100-550
Vermiculite clay	120-150
Montmorillonite clay	80-120
Illite clay	15-40
Kaolinite clay	3-15
iron oxide clays (at pH 7)	0-2
silts	0
sands	0

Increasing surface area ↑

Soils with more **clay**, more **OM** and more of **certain clays** will hold more positive charge.

'Holding charge is holding nutrients'

Because all soils typically have a distribution of sand, silt, clay and organic matter, all soils have some ability to hold nutrients

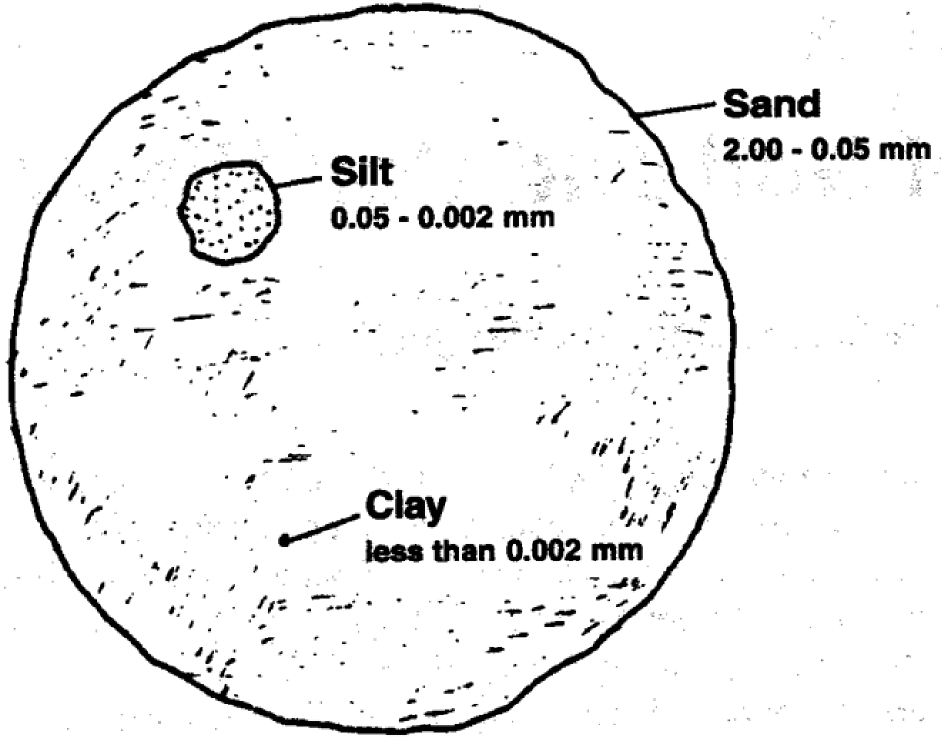
Soil Textural Class	Amount of charged held per unit weight of soil (cmoles+/kg) or (meq*+/100g)
sands	1-5
fine sandy loams	5-10
loams and silt loams	5-15
clay loams	15-30
clays	>30

*meq = ‘milliequivalents’

Texture

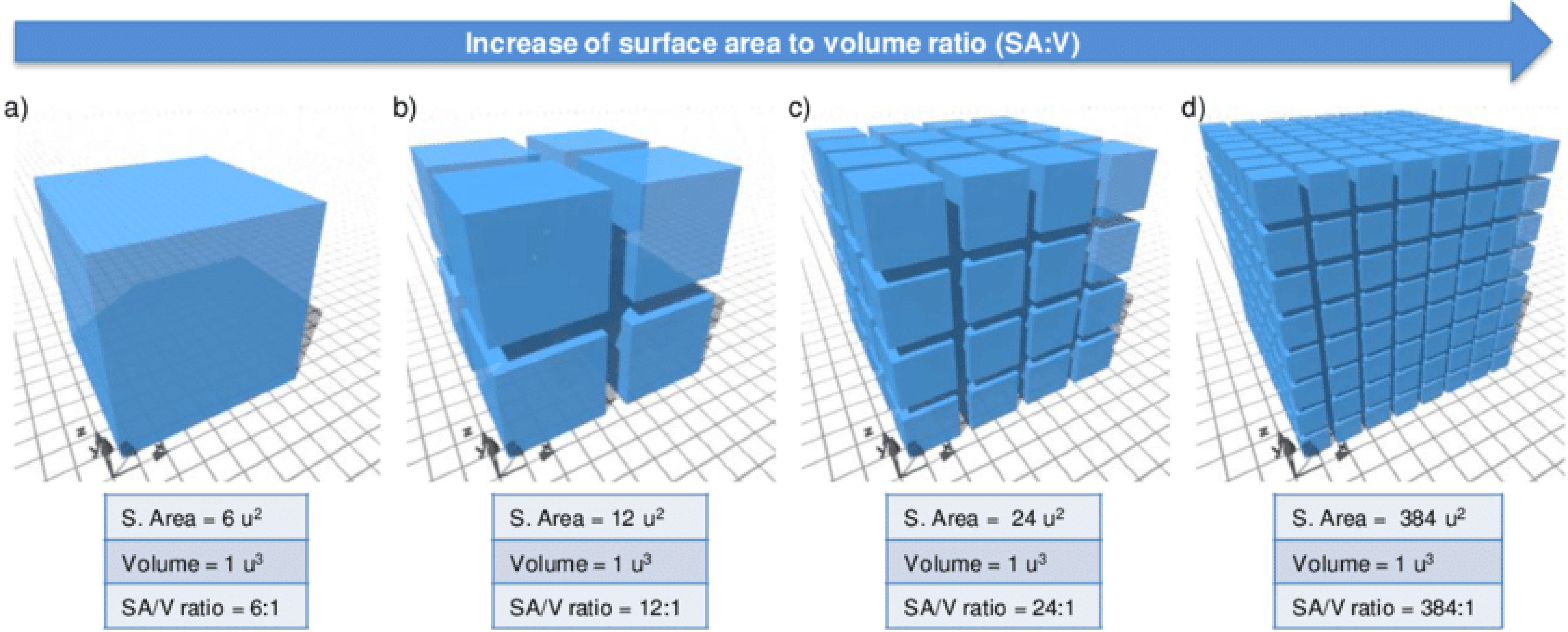
Soil texture is like family.

You get what you get,
and you're stuck with it
unless you move away.



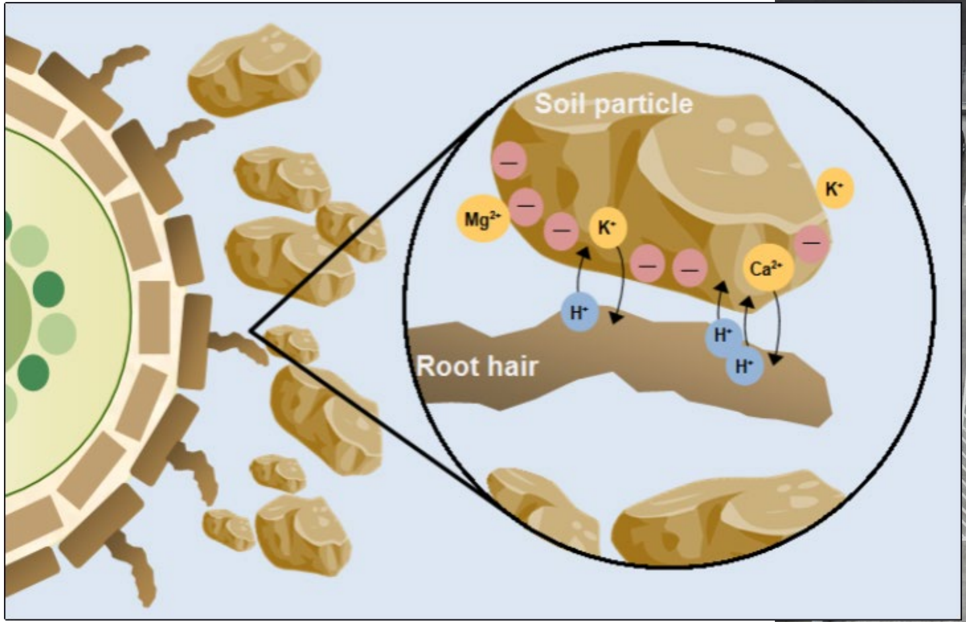
Why does texture affect ability to hold charge?

Surface area to volume ratio



Graphic from Fig. 2.3 of Functionalization of Metal Oxide Nanostructures via Self-Assembly. Implications and Applications by Portilla (2017).

Higher surface area to volume ratio (SA/V) = Larger ion exchange capacity



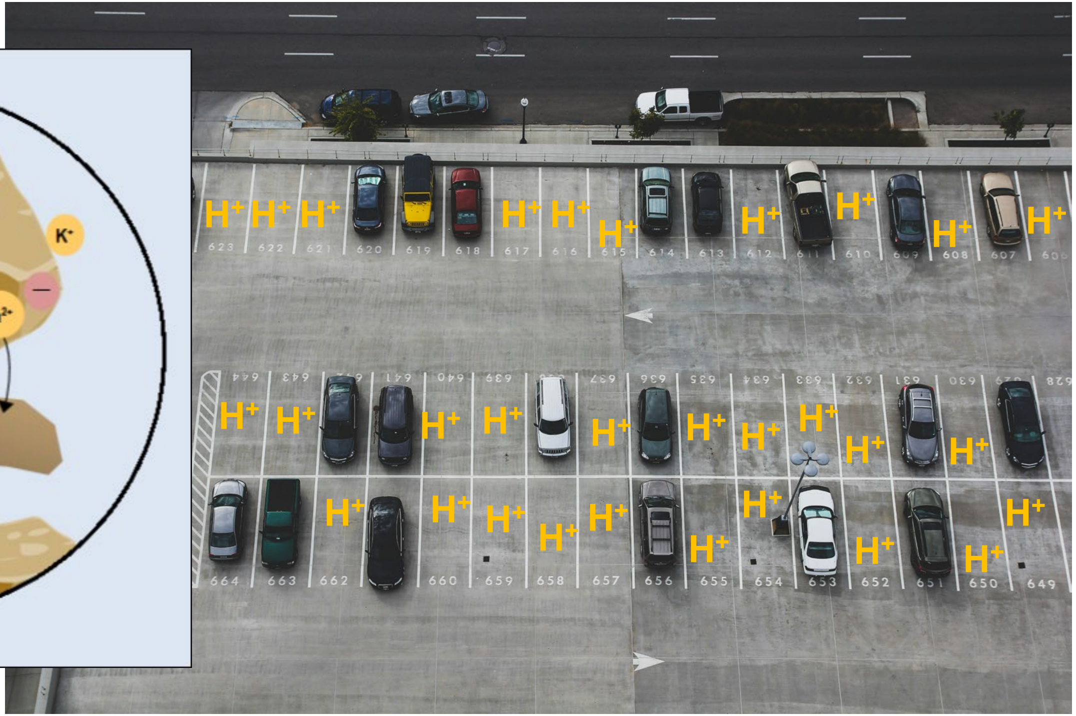
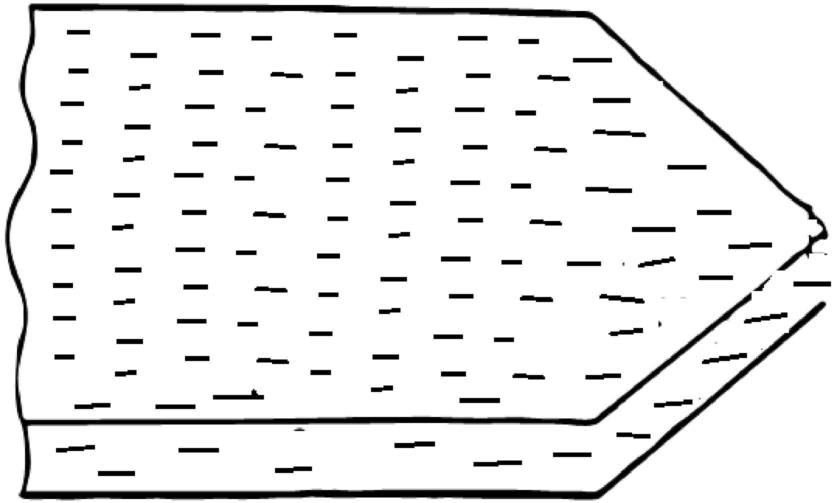
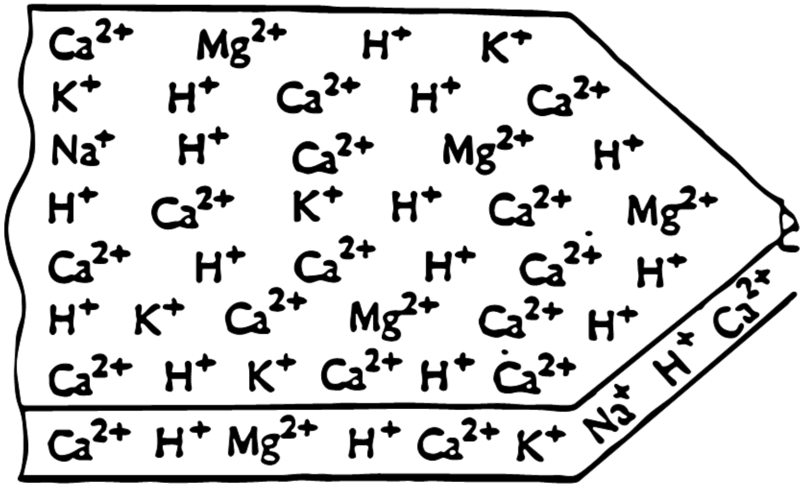


Image credits: Left, LSU College of Agriculture's Louisiana Home Lawn Series; Right, photo by John Matychuk on Unsplash.



Clays attract positive ions because negative charge is *built into* them when they are formed. ‘isomorphic substitution’



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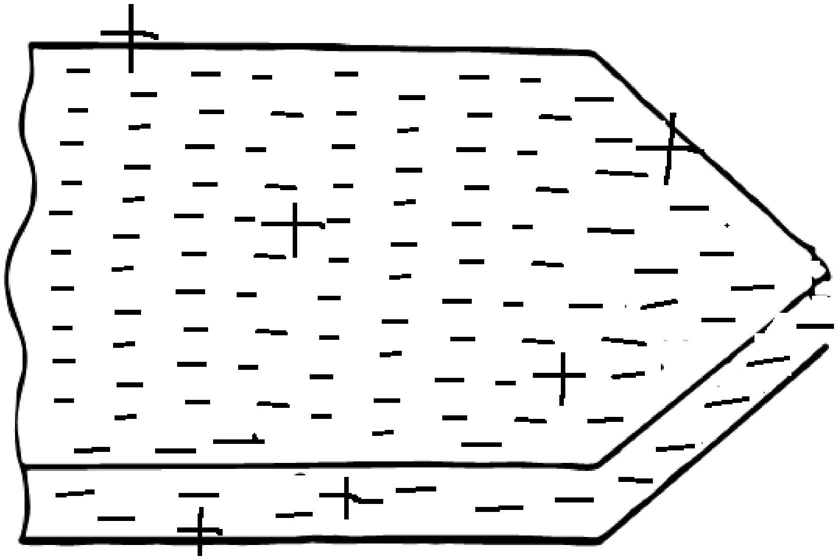
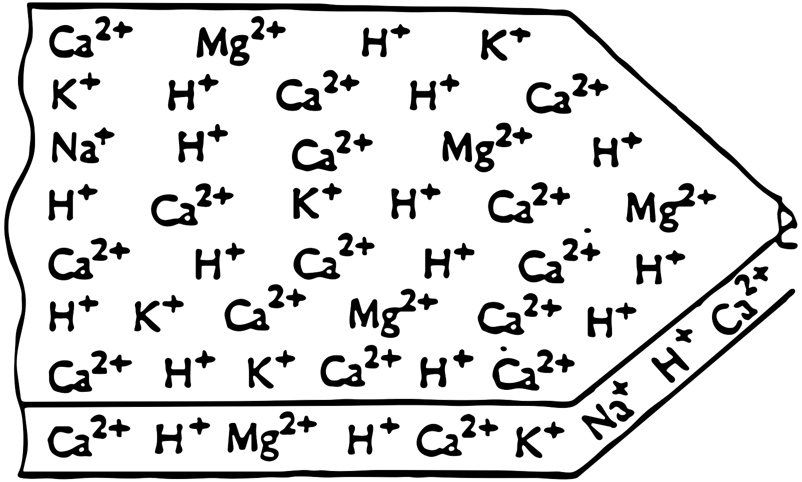


Positive charges (which attract negative ions) are rarer in clays

(except for iron oxides)

Ability of soils to hold charge: 'ion exchange capacity'

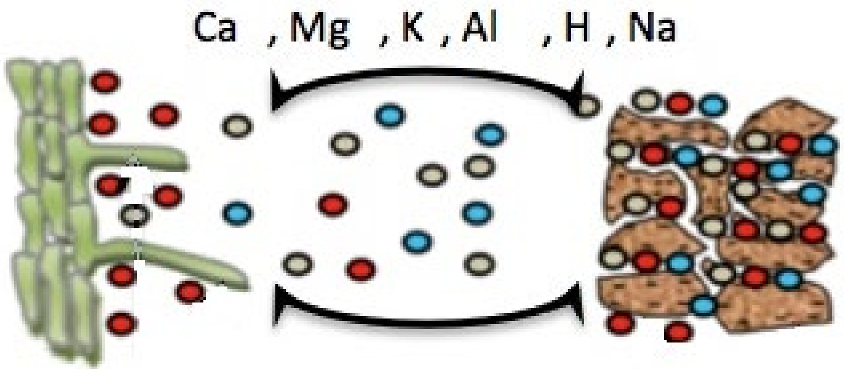
<table>
<tr><td rowspan="2">Amount of charge that can be retained by a certain amount of soil mass</td><td rowspan="2">centimoles of charge per kg of soil ('cmoles/kg')
=
'Milliequivalents' of charge per 100g of soil ('meq/100g')</td><td>'Cation Exchange Capacity'
(CEC; ability to hold cations, e.g. Ca^{2+})</td><td>OM and most clays</td></tr>
<tr><td>'Anion Exchange Capacity'
(AEC; ability to hold anions, e.g. Cl^{-})</td><td>Iron oxide clays</td></tr>
</table>



Clinging ions came from the soil water and can go back to it.

So we have a special term for the ability of the soil to hold charge:

'Exchange Capacity'
(EC)



Sonon, Saha and Kissell, Extension.uga.edu, Circular 1040.

	Soil H_2O (plant available)	Soil Solids (fertility tests)
Cations	Dissolved cations	Cations adsorbed to soil 'Cation Exchange Capacity' (CEC)
Anions	Dissolved anions	Anions adsorbed to soil 'Anion Exchange Capacity' (AEC)
H^+	Dissolved H^+ 'Active acidity' pH of soil/water slurry	H^+ adsorbed to soil 'Reserve acidity' pH of buffer test

CEC>AEC

Exchange Capacity >> dissolved ion content

‘Exchange Capacity’

- routine analysis by some soil testing labs
- **Example**: exchangeable positive charge was extracted and measured on per kg basis by a soil testing lab

3 cmoles of + from H

What is the CEC of this soil?

12 cmoles of + from Ca

5 cmoles of + from Mg

1 cmole of + from Na

4 cmole of + from K

'Exchange Capacity'

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1 cmole of + from Na

4 cmole of + from K

What is the CEC of this soil?

CEC = 3+12+5+1+4
=25 cmole of + / kg soil
=25 meq of + / 100g soil

While nutrient content can be tested we can also evaluate the share of the ion exchange capacity occupied by certain elements.

There is particular interest in the share of adsorbed elements that are not acidic.

Acid cations	**Basic cations**
H^{+}	Ca^{2+}
Al^{3+}	Mg^{2+}
Fe^{3+}	Na^{+}
Mn^{4+}	K^{+}

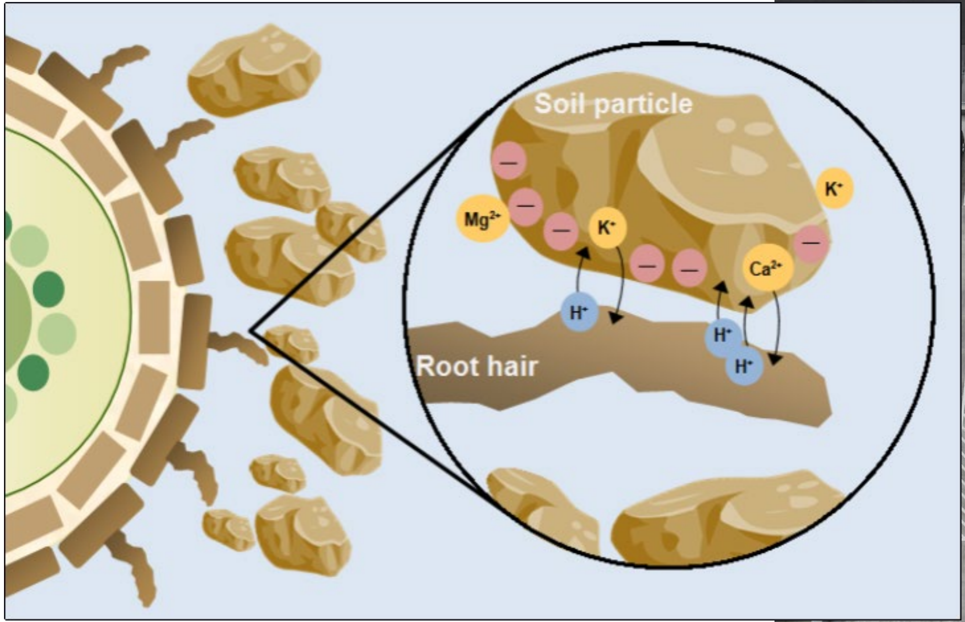
‘Base Saturation’

= share of CEC provided by ‘basic’ cations

$$= \frac{\text{cmol + charge / kg due to Mg, Ca, Na, K}}{\text{CEC}}$$

a means of gauging soil fertility.

Higher surface area to volume ratio (SA/V) = Larger ion exchange capacity



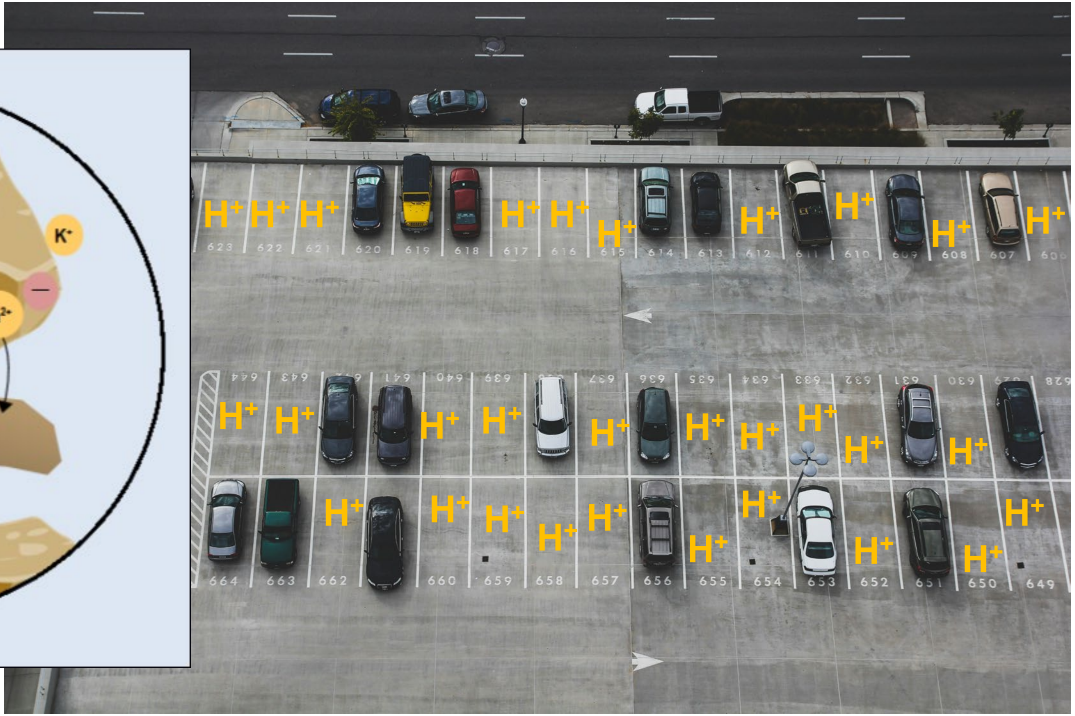


Image credits: Left, LSU College of Agriculture's Louisiana Home Lawn Series; Right, photo by John Matychuk on Unsplash.

Base Saturation

Example: exchangeable positive charge was extracted and measured

3 cmoles of + per kg from H

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What is the base saturation?

Base Saturation

Example: exchangeable positive charge was extracted and measured

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Acid cations	**Basic cations**
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Al^{3+}	Mg^{2+}
Fe^{3+}	Na^{+}
Mn^{4+}	K^{+}

What is the CEC of this soil?

CEC = 3+12+5+1+4

=25 cmole of + / kg

=25 meq of + / 100g

What is the base saturation?

BS=cmol of + due to 'Base' cations / CEC

(12+5+1+4)/25

(22/25) = 0.88 = 88%

Multiply decimal base saturation by 100 to get % base saturation

Review:

- Soils with more OM, and clays hold more nutrients – a function of
  - geology (clays) and
  - Management (OM content and loss of upper soil layers)
- Nutrient holding capacity = Exchange Capacity
  - CEC > AEC
- Snapshot of nutrients held = Base Saturation (BS)
- pH = $-\log_{10}$ (H+); more abundant H^+ means
  - Lower pH
  - Less abundant OH^- (H^+ and OH^- play a zero-sum game)
  - Lower CEC and lower BS

pH

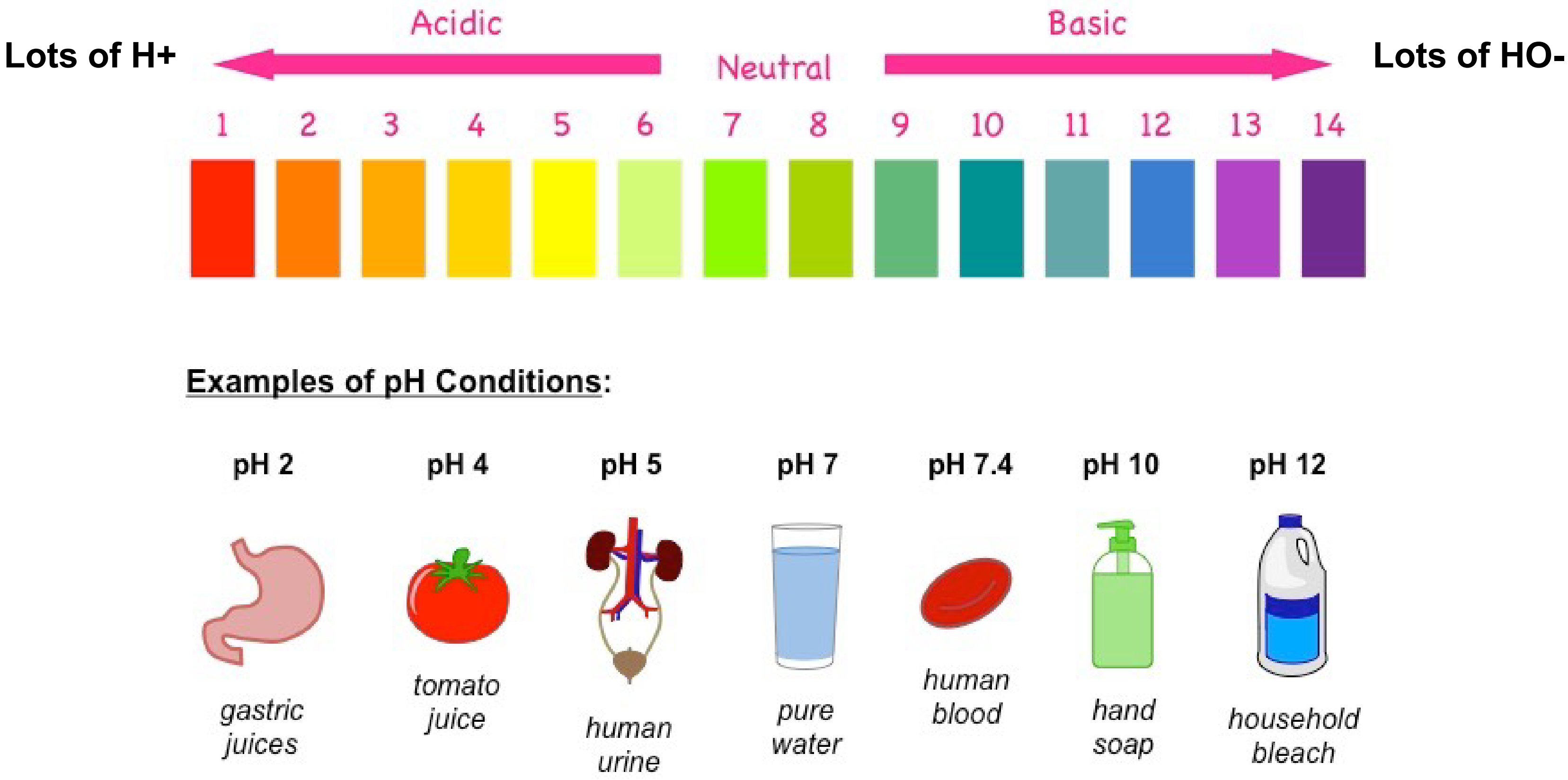
What is pH?

- measure of acidity ← → alkalinity
- shorthand for the number of dissolved H^+ ions in soil water

	Acidic	Alkaline
More abundant	H^+	OH^-
Less abundant	OH^-	H^+

H^+ and OH^- play a zero sum game

What is pH?


Lots of H+
Acidic
Neutral
Basic
Lots of HO-
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Examples of pH Conditions:
pH 2
gastric juices
pH 4
tomato juice
pH 5
human urine
pH 7
pure water
pH 7.4
human blood
pH 10
hand soap
pH 12
household bleach

pH = -log [H^+]; ‘a logarithm is an exponent’

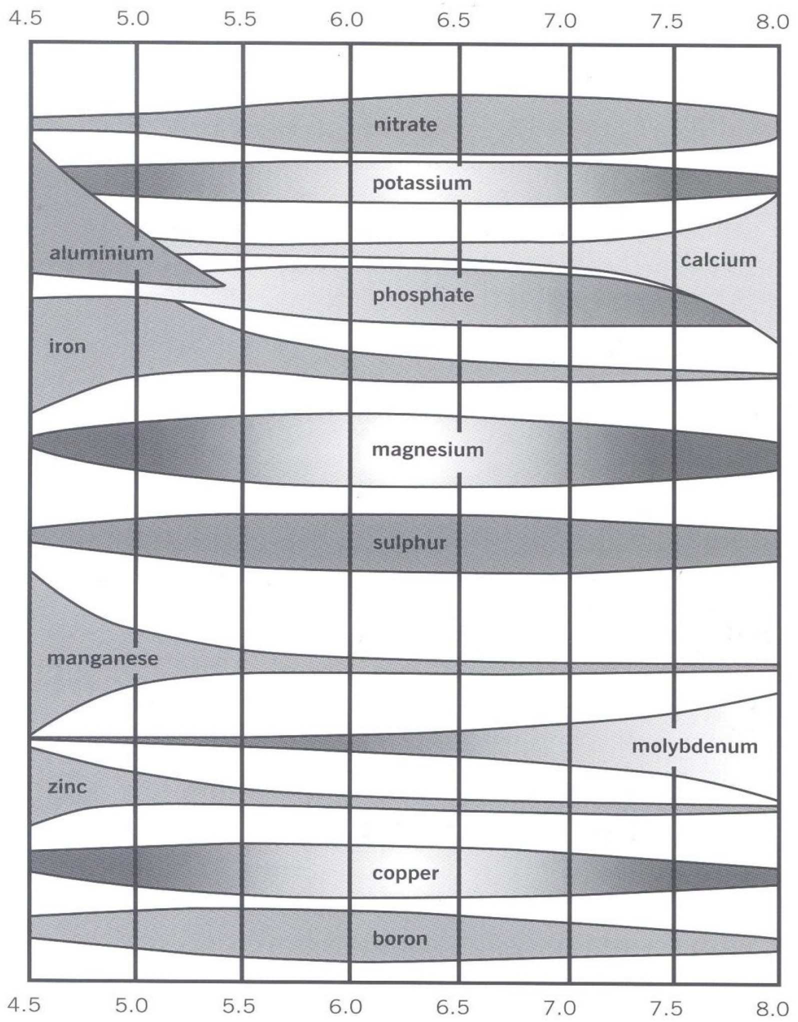
[H^+] (moles/L)	[H^+] (moles/L)	pH
.1	10^{-1}	1
.01	10^{-2}	2
.001	10^{-3}	3
.0001	10^{-4}	4
.00001	10^{-5}	5
.000001	10^{-6}	6
.0000001	10^{-7}	7
.00000001	10^{-8}	8
.000000001	10^{-9}	9

[OH^-]
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}

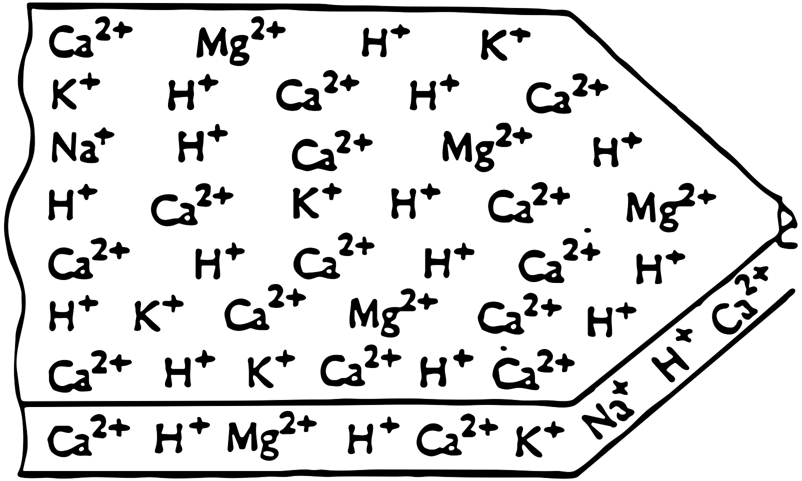
H^+ and OH^- play a zero sum game

You can’t manage nutrients without managing pH; notice a ‘sweet spot’ between pH 6 & 6.5 for most ag crops

*Nitrogen fixation in legumes is facilitated by slightly acidic to neutral pH.



pH affects not only nutrient availability (see previous slide) but also CEC (and AEC).



Increasing acidity lowers CEC and BS; the more H+s there are the fewer spaces remain for other cations.

Target pH in Maryland

- pH 7.0
  - alfalfa establishment
- pH 5.6
  - tobacco
- pH 5.2
  - potatoes, sweet potatoes, blueberries
- pH 6.5
  - most other agronomic and horticultural crops

pH review

- Most crops have a target pH around 6.5
- pH = $-\log_{10}$ (H+)
- more abundant H^+ means
  - Lower pH
  - Less abundant OH^- (H^+ and OH^- play a zero-sum game)
  - Lower CEC and lower BS

How is soil fertility lost?


Evin Thayler, NPR

(Other than erosion)

How is it that soils lose their ability to supply nutrients?

Note that soil-based nutrients are ionic

Non-Mineral	Mineral*		
	Macronutrients		Micronutrients
	Primary	Secondary	
carbon (CO_2)** oxygen (O_2)*,** hydrogen (H_2O)*	nitrogen (NO_3^-, NH_4^+ phosphorus (HPO_4^{2-}, $H_2PO_4^-$) potassium (K^+)	calcium (Ca^{2+}) magnesium (Mg^{2+}) sulfur (SO_4^{2-})	iron (Fe^{3+}, Fe^{2+}) nickel (Ni^{2+}) zinc (Zn^{2+}) chlorine (Cl^-) manganese (Mn^{2+}, Mn^{4+}) boron (H_3BO_4, $H_2BO_4^-$, $B_4O_7^{2-}$) copper (Cu^{2+}) cobalt (Co^{2+}) molybdenum (Mo^{2+})

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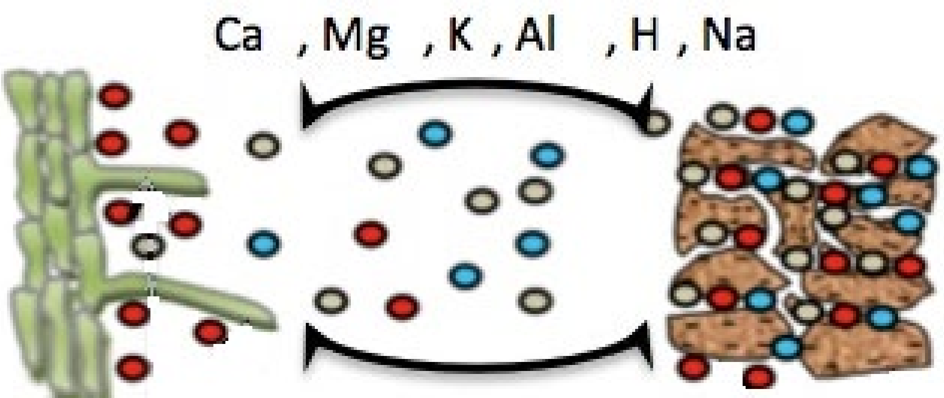


Ions (nutrients) dissolve in water or stick to the charges in the soil.

	Dissolve in water	Stick to charges in the soil
The good	Roots pull nutrient out of the soil water – dissolution of nutrients is exactly what makes them plant-available.	Nutrients can be held by the soil to be made available to plants later
The bad	Dissolved nutrients can be leached out of the root zone. This may be the fate of up to 50% of applied N	Some nutrients can be held so strongly that they are never made plant-available again.

NO_3^-

PO_4^{3-}

PO_4^{3-}

Nutrients can change from (plant-available) ionic forms to gaseous forms that volatilize out of the soil.

Because of waterlogging, NO_3^- is transformed to N_2, & N_2O gasses. If plants are not killed by a lack of oxygen in the soil the survivors develop an N-deficiency.

Nutrients can interfere with each other’s uptake, or form insoluble compounds

Nutrient in Excess	Induced Deficiency	mechanism
NH_4^+, Ca^{2+}, Mg^{2+}	K^+	Within-plant competition or uptake competition
K^+ or Ca^{2+}	Mg^{2+}	
Cl^-	NO_3^- and SO_4^{2-}	
Ca^{2+}	Mg^{2+}	
Mg^{2+}	Ca^{2+}	
Mo^{2+}	Cu^{2+}	
Fe	Mn	
Mn	Fe	
Ca	B	
PO_4^{3-}	Fe, Mn, Zn^{2+}, Cu^{2+}	Formation of insoluble compounds inhibiting uptake

https://www.maximumyield.com/how-nutrient-antagonism-leads-to-nutrient-deficiency-in-plants/2/2092

Over time, soils in humid environments become increasingly acidic thereby taking you out of the ‘sweet spot’.

Where/How does soil acidity originate?

- nitrification (oxidation) of ammonium
  - most fertilizers and all organic sources
- organic acids produced by plant roots and microbes
- rainfall
  - carbonic acid, nitric acid, sulfuric acid
- transformation of geologic minerals to soil minerals
  - 3 H^+ per 1 Al^{+3}
- oxidation of sulfur
  - 2 H^+ per 1 S

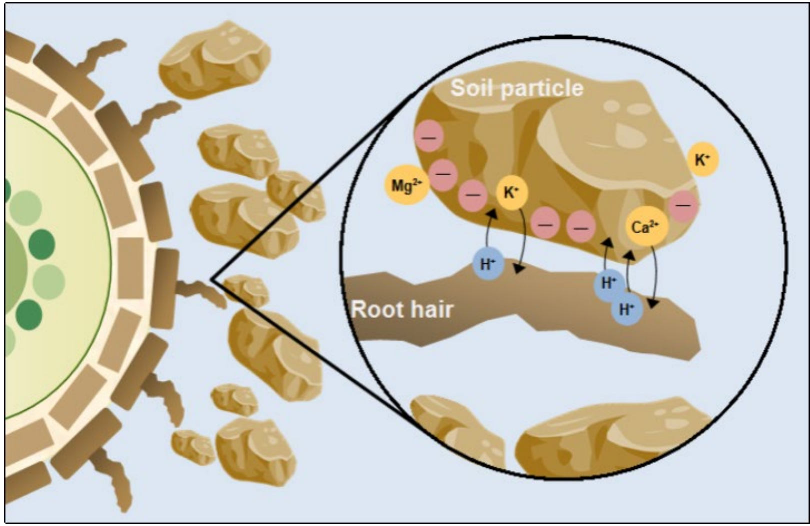
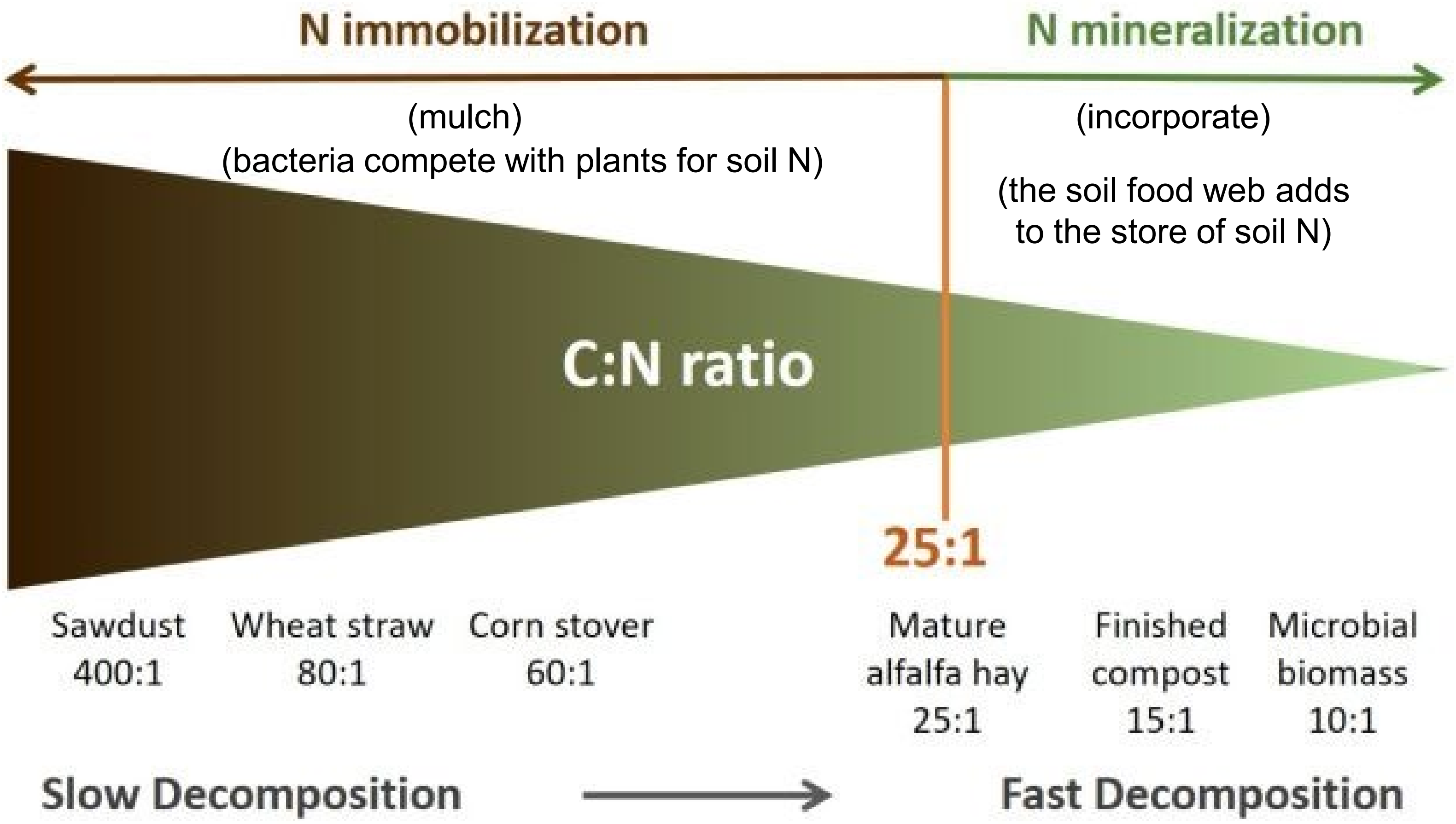


Image credits: LSU College of Agriculture's Louisiana Home Lawn Series

Soil material too high in C can rob plants of N

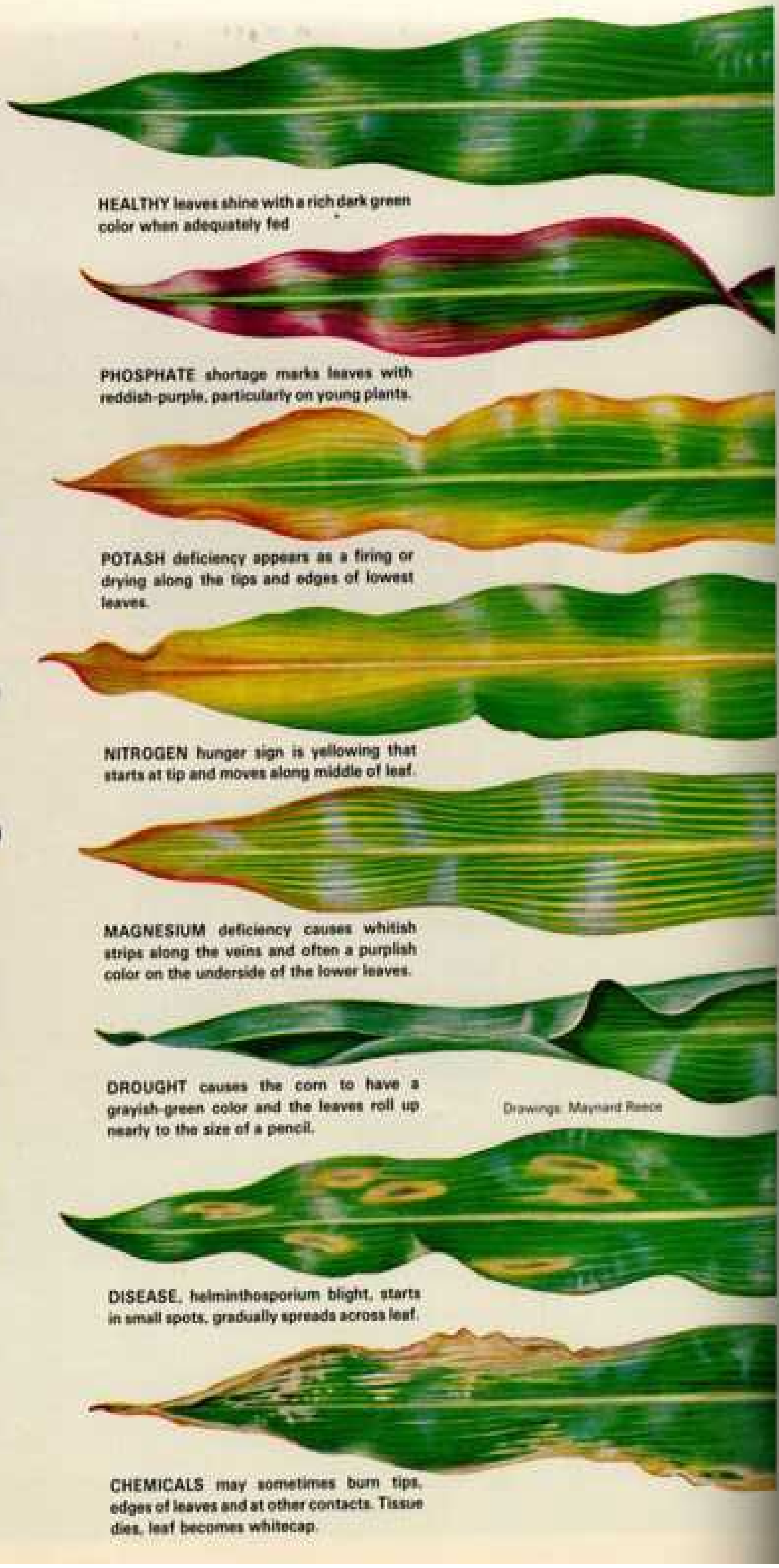


UMN Extension

How can nutrient deficiencies be determined?

Plate IV
Figure 31

Guide to Nutrient Deficiency Symptoms



Mobile nutrients Immobile nutrients

Nutrient deficiency symptoms occur as yellowing of leaves, interveinal yellowing of leaves, shortened internodes, or abnormal coloration such as red, purple, or bronze leaves. These symptoms appear on different plant parts as a result of nutrient mobility in the plant.

Symptoms caused by nutrients mobile in the plant occur on the lower, older leaves.

Potassium deficiency in corn, lower leaves

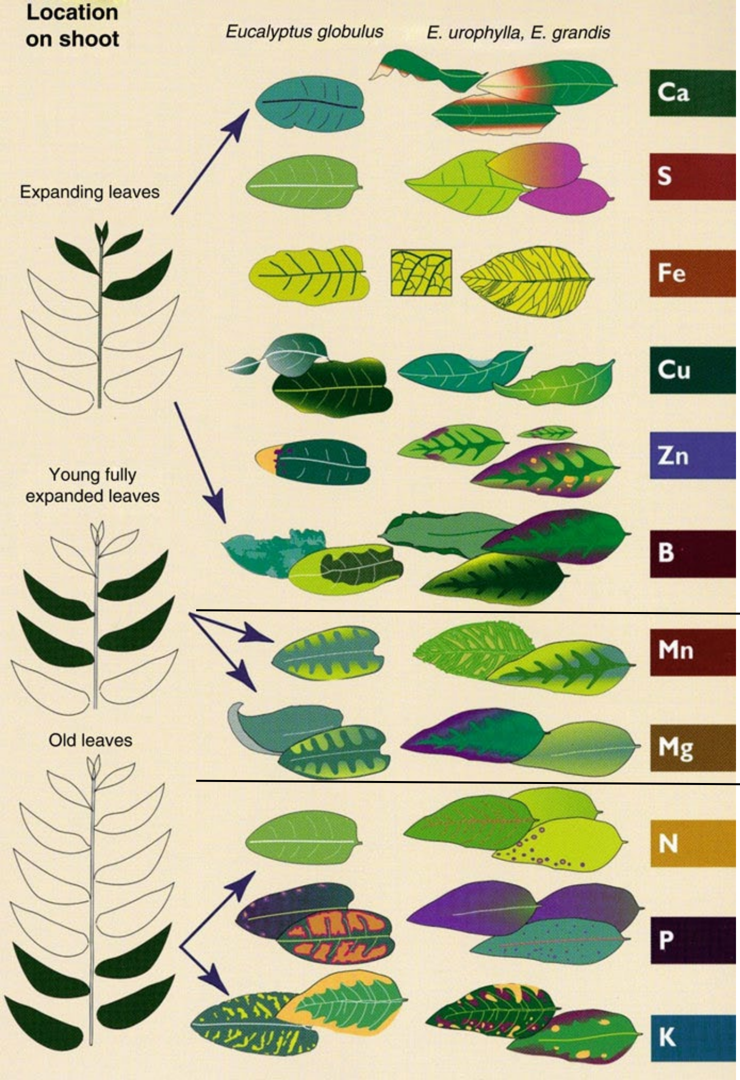
Symptoms caused by nutrients immobile in the plant occur on the upper, younger leaves.

Iron deficiency in soybean, upper leaves

Deficiency on Older Leaves

Deficiency on Younger Leaves

Sawyer, Iowa State Ext., 2004

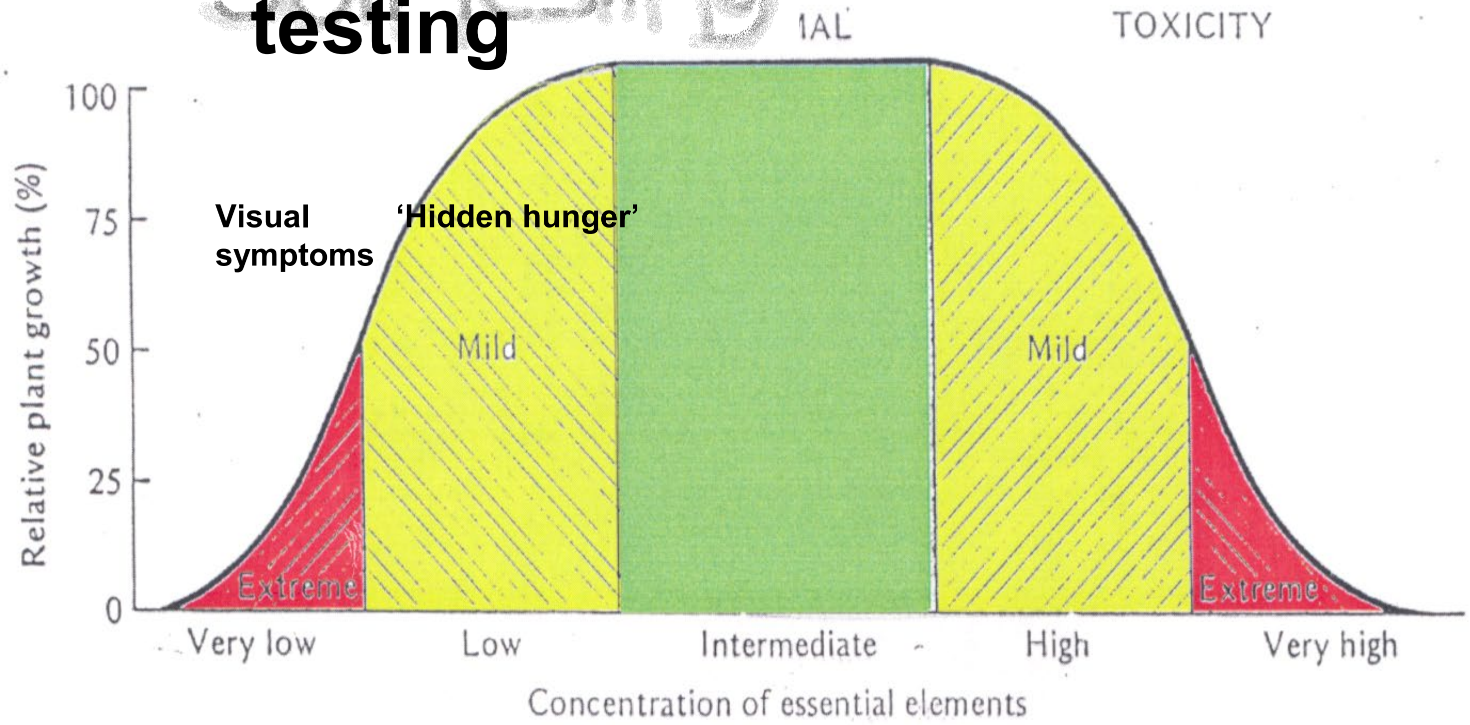


immobile

mobile

http://www.nue.okstate.edu/Spatial_N_Variability.htm

Foliar testing



Relationship between plant growth and concentration in the soil of elements that are essential to the plant.

Can the concentration of a nutrient be too high?

Yes

- toxicity is only a problem with some nutrients, but…
  - In soil water nutrients are ionic. If they are too abundant the soil water may be too salty.
    - High concentrations of one nutrient can interfere with another.

Deficiencies and toxicities can occur even if soil test levels are ‘good’ or ‘optimal’

Source	Effects		
drought	Slower nutrient flow to roots	Possible salinity problems	
waterlogging	Lack of O_2 to roots	Induced nutrient loss	Induced nutrient toxicities
temperature	Cold soil may restrict below-ground growth		
pH	Crop-inappropriate pH makes deficiencies/toxicities more likely	Low pH reduces capacity of CEC to hold nutrients	

https://www.slideshare.net/viticulture/grapevine-micronutrient-use-deficiency-symptoms-in-the-sjv-of-california

Early-season deficiencies often sort themselves out.

As I mentioned, the **unfavorable conditions for crop growth this spring mean that observing some deficiency symptoms in young corn plants should not be cause for immediate alarm**. However, **if deficiencies continue** after growing season conditions improve, it is important to **confirm any deficiency before trying to correct the problem**. **Since the visual symptoms** are sometimes **not clear-cut**, it could be beneficial to **collect affected plants and conduct tissue nutrient analysis**.—

Fabián G. Fernández, UMN Extension

http://bulletin.ipm.illinois.edu/print.php?id=1163

What can be done to maintain fertility?

‘What factors limit Crop Production?’ or ‘Soil Fertility writ Large’

- water
- below-ground aeration, atmospheric CO_2
- temperature
- mechanical support
- nutrients ⟵ ‘Basic Soil Fertility’
- disease/pest pressure
- symbioses

What be done to maintain fertility?

Optimize pH (stay in the sweet spot)

Maintain soil organic matter levels!

(maximize Exchange Capacity)*

Follow your nutrient management plan!

(make it unlikely that crop growth will be nutrient limited)*

What be done to maintain fertility?

Make use of cover crops
(retrieve nutrients from lower soil layers; cover the soil to avoid erosion)

Occasionally utilize animal manures
(to maintain secondary and micro nutrients, but beware of getting P to excessive levels)

Questions

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