What is an Essential Element?

The number of elements considered essential for the growth of higher plants now varies from 16 to 20 or more, depending upon the definition of essentiality. The authors of this book are aware that Arnon* limits essentiality to only those elements that are needed for higher plants to complete all life functions and that the deficiency can be corrected by the application *only of this specific element causing the deficiency.* Other scientists such as Nicholas believe that an element should be considered essential if its addition enhances plant growth even though it merely substitutes for one of the 16 elements that Arnon declares to be essential. For example, because sodium can substitute in plant nutrition for some potassium, and vanadium for some molybdenum, Nicholas would consider both sodium and vanadium as essential, but Arnon would not. On the basis of the criteria used, Arnon specifies 16 elements and Nicholas 20 elements as being essential for the growth of higher plants such as cotton and corn. Three other debated nutrients are nickel (urea transformations), cobalt (N2 fixation), and silicon. (See Chapter 8 for further information on essential elements for plants.)

D. I. Arnon, "Mineral Nutrition of Plants," Annual Review of Biochemistry, 12 (1943), pp. 493-528.
D. J. D. Nicholas, "Minor Mineral Elements," Annual Review of Plant Physiology, 12 (1961), pp. 63-90.

1. Essential Nutrients and Ionic Forms

From soil, water, and air

Carbon	$C0_3^{-2}$, HCO_3^{-}, CO_2
Hydrogen	H^{+}, OH
Oxygen	O_2, OH^{-}

Primarily from soil: macro or major, secondary, and micrometabolic or trace elements

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^{+2}, Fe^{+3}
Copper	Cu^{+2}, Cu^{+}
Zinc	Zn^{+2}
Manganese	Mn^{+2}, MnO_4^{-}
Molybdenum	$HMoO_4^{-}$, MoO_4^{-2}
Boron	H_3BO_3, $B_4O_7^{-2}$
Chlorine	Cl^{-}

See Table 1 for list of 92 naturally occurring elements. Also, see pp 12-13 of text for additional information on other elements and definitions of the term "essential".

Table 1. List of Naturally Occurring Element.

Element	Symbol	Atomic No.	Atomic weight	Element	Symbol	Atomic No.	Atomic weight
Hydrogen*	**H**	**1**	**1.008**	Silver	Ag	47	107.87
Helium	He	2	4.003	Cadmium	Cd	48	112.4
Lithium	Li	3	6.94	Indium	In	49	114.82
Beryllium	Be	4	9.012	Tin	Sn	50	118.7
Boron	**B**	**5**	**10.81**	Antimony	Sb	51	121.75
Carbon	**C**	**6**	**12.01**	Tellurium	Te	52	127.6
Nitrogen	**N**	**7**	**14.007**	Iodine	I	53	126.9
Oxygen	**O**	**8**	**15.999**	Xenon	Xe	54	131.3
Fluorine	F	9	18.998	Cesium	Cs	55	132.91
Neon	Ne	10	20.179	Barium	Ba	56	137.34
Sodium	Na	11	22.99	Lanthanum	La	57	138.91
Magnesium	**Mg**	**12**	**24.305**	Cerium	Ce	58	140.12
Aluminum	Al	13	26.98	Praseodymium	Pr	59	140.91
Silicon	Si	14	28.08	Neodymium	Nd	60	144.24
Phosphorus	**P**	**15**	**30.97**	Promethium	Pm	61	[145.]**
Sulfur	**S**	**16**	**32.06**	Samarium	Sm	62	150.4
Chlorine	**Cl**	**17**	**35.45**	Europium	Eu	63	151.96
Argon	A	18	39.948	Gadolinium	Gd	64	157.25
Potassium	**K**	**19**	**39.102**	Terbium	Tb	65	158.9
Calcium	**Ca**	**20**	**40.08**	Dysprosium	Dy	66	162.5
Scandium	Sc	21	44.96	Holmium	Ho	67	164.93
Titanium	Ti	22	47.9	Erbium	Er	68	167.26
Vanadium	V	23	50.94	Thulium	Tin	69	168.9
Chromium	Cr	24	51.996	Ytterbium	Yb	70	173.04
Manganese	**Mn**	**25**	**54.94**	Lutetium	Lu	71	174.97
Iron	**Fe**	**26**	**55.85**	Hafnium	Hf	72	178.49
Cobalt	Co	27	58.93	Tantalum	Ta	73	180.94
Nickel	Ni	28	58.71	Tungsten	W	74	183.85
Copper	**Cu**	**29**	**63.55**	Rhenium	Re	75	186.2
Zinc	**Zn**	**30**	**65.37**	Osmium	Os	76	190.2
Gallium	Ga	31	69.72	Iridium	Ir	77	192.2
Germanium	Ge	32	72.6	Platinum	Pt	78	195.09
Arsenic	As	33	74.92	Gold	Au	79	197
Selenium	Se	34	78.96	Mercury	Hg	80	200.59
Bromine	Br	35	79.904	Thallium	Ti	81	204.37
Krypton	Kr	36	83.8	Lead	Pb	82	207.2
Rubidium	Rb	37	85.47	Bismuth	Bi	83	209
Strontium	Sr	38	87.62	Polonium	Po	84	[209]
Yttrium	Y	39	88.91	Astatine	At	85	[210]
Zirconium	Zr	40	91.22	Radon	Rn	86	[222]
Niobium	Nb	41	92.91	Francium	Fr	87	[223]
Molybdenum	**Mo**	**42**	**95.94**	Radium	Ra	88	226.03
Technetium	Tc	43	98.91	Actinium	Ac	89	[227]
Ruthenium	Ru	44	101.07	Thorium	Th	90	232.04
Rhodium	Rh	45	102.91	Protactinium	Pa	91	231
Palladium	Pd	46	106.4	Uranium	U	92	238.03

* Elements in bold type essential to plants (see p 12, text). ** Values in brackets are mass nos. of most stable known isotope.

Elemental abundance in plant tissue.

Average elemental composition of corn tissue (silage). From Troeh, Frederick and L. M. Thompson. 1993. Soils and soil fertility. Oxford University Press. New York.

Element	Corn silage ppm, dry wt.	%, dry wt.
oxygen	450,000	45
carbon	440,000	44
hydrogen	63,000	6.3
nitrogen	13,000	1.3
silicon	12,000	1.2
potassium	9,000	0.9
calcium	2,500	0.25
phosphorus	1,600	0.16
magnesium	1,600	0.16
sulfur	1,500	0.15
chlorine	1,500	0.15
aluminum	1,100	0.11
sodium	300	0.03
iron	90	0.009
manganese	60	0.006
zinc	30	0.003
boron	10	0.001
copper	5	0.0005
molybdenum	1	0.0001

Be aware that elemental concentrations in plant tissue can vary widely for a given crop depending on the stage of growth and environmental conditions and for different crops, yet plants can still appear normal and healthy. For some elements the range of sufficiency is wide and for others the range is narrow. A good deal of caution needs to be exercised in diagnosing mineral deficiencies based only on plant tissue analysis.

Sufficiency Ranges

Following tables are based on data presented in Soil *Testing and Plant Analysis* Edited by Leo M. Walsh and James D. Beaton, published by Soil Science Society of America, Madison, Wisconsin, 1973.

Sufficiency ranges for soybean leaves, based on data from Ohio State University Plant Analysis Laboratory, 1971.

Element	Sufficiency range
N, %	4.26-5.50
P, %	0.26-0.50
K, %	1.71-2.50
Ca, %	0.36-2.00
Mg, %	0.26-1.00
Mn, ppm	21-100
Fe, ppm	51-350
B, ppm	21-55
Cu, ppm	10-30
Zn, ppm	21-50
Mo, ppm	1-5

Sufficiency ranges reported for corn:

Element	Sufficiency range
N, %	2.6-5.0
P, %	0.25-0.8
K, %	1.7-5.0
Ca, %	0.21-1.6
Mg, %	0.21-0.8
S, %	0.2-0.5
Al, ppm	0-200
B, ppm	6-20
Cu, ppm	6-20
Fe, ppm	21-300
Mn, ppm	20-200
Mo, ppm	0.6-1.0
Zn, ppm	20-150

Sufficiency ranges reported for small grains:

Element	Sufficiency range
N, %	1.25-3.0
P, %	0.15-0.50
K, %	1.25-3.0
Ca, %	0.2-1.2
Mg, %	0.15-0.50
S, %	0.15-0.40
Cu, ppm	5-25
Mn, ppm	5-100
Zn, ppm	15-70

Sufficiency ranges reported for cotton:

Element	Sufficiency range
N, %	3.0-4.5
P, %	0.30-0.65
K, %	0.90-3.0
Ca, %	1.90-3.50
Mg, %	0.30-0.90
B, ppm	20-60
Cu, ppm	8-20
Fe, ppm	30-300
Mn, ppm	30-350
Zn, ppm	20-100

2. Cation Exchange

Soil colloids, clay minerals and soil organic matter account for cation exchange properties of soils. See Chapter 5 of text for discussion of soil colloids, structural features, and other characteristics of soil colloids. Soil organic matter means the organic fraction of the soil but **does not include** undecayed plant and animal residues. Estimates of the average age of the carbon in soil organic matter, based on radiocarbon dating, varies from a few hundred years to more than 25,000 years. (See page 217 in text.) Soil organic matter does not consist primarily of recent crop residues. It is a recalcitrant mixture of organic "residuals" that resist decomposition. Generally, it takes many years to change the organic matter content of a soil from its current "equilibrium" value. Tillage is the major agronomic practice that affects soil organic matter content. Reducing tillage is the most effective way to maintain or attempt to build back organic matter content that has been severely depressed due to intensive or non-conserving agricultural practices. However, climate exerts a natural control or limit as to the amount of soil organic matter that can be achieved and sustained.

Cation exchange capacity (CEC)

The CEC of a soil depends upon the amount and type of soil colloids present. The clay content, the type of clay minerals present, and the organic matter content determine a soil's CEC.

Colloid	CEC, cmol(+) /kg*
kaolinite	3-15
illite	20-40
montmorillonite	60-100
soil organic matter, humus, etc.	100-300

- Unit is centimole of charge per kilogram of colloid; another common unit for expressing CEC is me/100g (milliequivalents/100 grams). Note that 1me/100g = 1$cmol_c$ /kg.

Kaolinite is the dominant clay mineral in soils of this region, but some soils contain significant amounts of montmorillonite, a clay mineral of the smectite group.

CEC for various soils: a typical range of CEC for soils in the state and the region is 3-5 me/100 g. See page 147 of text for a range of CEC for a variety of soils from various regions of the U. S. You may encounter a CEC expressed as "sum of the bases" (Ca+Mg+K+Na) or a CEC based on "sum of the bases and exchangeable acidity" (H+Al). For soils such as those in the Piedmont there is usually a large difference. Generally CEC is not used directly to manage soils and their fertility. The effect of CEC and its significance in managing soils is incorporated into management of pH and lime requirement. The larger the CEC the more buffering capacity a soil will have and the more lime that will be required to raise the soil pH by a specific amount, for example, from 5.5 to 6.5. By the same token soils with a large CEC will have more K supplying power for a given degree of K saturation. Following proven soil test methods and fertilizer recommendations is the best way to manage plant nutrient supplies.

Conversion of me/100 grams to pounds/acre and other facts relating to acreage:

element	factor	example
Ca	400	1 me Ca/100 grams = 400 lbs /acre
K	780	1 me K/100 grams = 780 lbs/acre
Mg	240	1 me Mg/100 grams = 240 lbs/acre
Na	460	1 me Na/100 grams= 460 lbs/acre

These conversions are based on an estimate that the surface 6 inch layer of soil over the area of an acre weighs 2,000,000 pounds. The actual weight depends upon the soil bulk density which commonly varies from about 1.3 to 1.7 g/cc. For example, a cubic foot of water weighs 62.4 lbs. If the bulk density of a soil were 1.3 g/cc (1.3 times heavier than water) then the soil would weight 62.4 x 1.3 or 81.1 lbs/cu. ft. on a dry weight basis. Soil properties such as clay content and gravimetric water content are always expressed on a soil dry weight basis.

Other useful numbers to remember and examples of how to use them:

-1 acre = 43,560 sq ft;

the weight of an acre foot of soil with a bulk density of 1.47

= 43,560 sq ft x 1 ft x 62.4 lbs/cu ft x 1.47 = 4,000,000 lbs

-1 part per million (ppm) nitrate-N in the top 12 inches of this soil = 4 lbs/acre

-If you had a row spacing of 36 inches, one row 14,520 feet long would be an acre

(43,560 ft^2/3 ft); if the row spacing were 40 inches, the row would be 13,068 feet long (43,560/(40/36) or 43,560/3.333).

- 454 grams = 1 pound; 1 ounce = 28.4 grams
- 1 acre inch of water = 3,630 cu ft = 27,154 gallons = 226,512 pounds
- 1 cu ft weighs 62.4 pounds

Base saturation

The figure "Base Saturation" is based on data published in Soil *Testing and Plant Analysis,* Edited by Leo M. Walsh and James D. Beaton and published by the Soil Science Society of America, Madison, Wisconsin in 1973. The original data was developed by A. Mehlich and published in 1943.

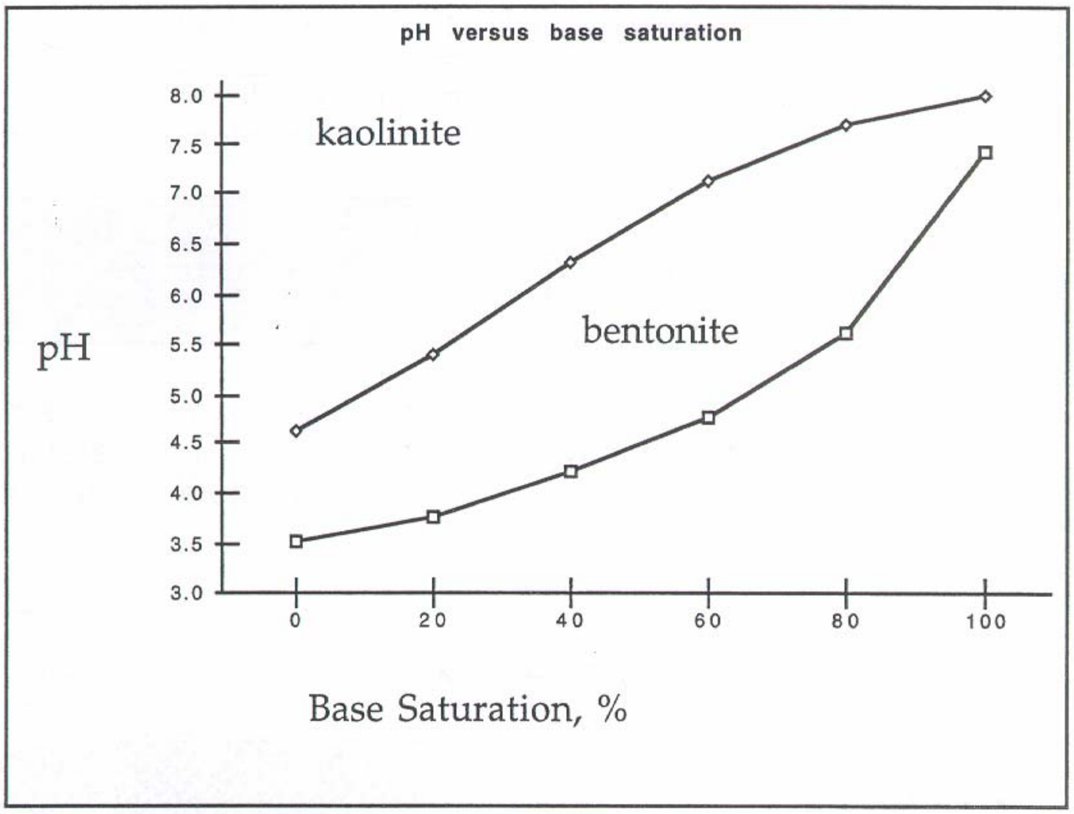
Base saturation is the amount of the CEC that is occupied by the basic cations such as Ca, K, Mg, and Na. The portion of the CEC that is occupied by acidic cations, primarily H, Al, and Fe, is called the "**exchangeable acidity**". Note differences in base saturation of kaolinite and bentonite over the pH range 5.5 to 6.5. Humic acid and illite have pH-base saturation relationships similar to bentonite.

Unless one knows some specific characteristics about a soil such as the dominant clay minerals, the amount of clay in the soil, and the amount of organic matter, **soil pH will not tell how much is the lime requirement.** The pH is a measure of the amount of hydrogen ion in solution. As is true of all cationic species, acidic as well as bases, only a small amount of the total exchangeable ions are present in the soil solution at one time.

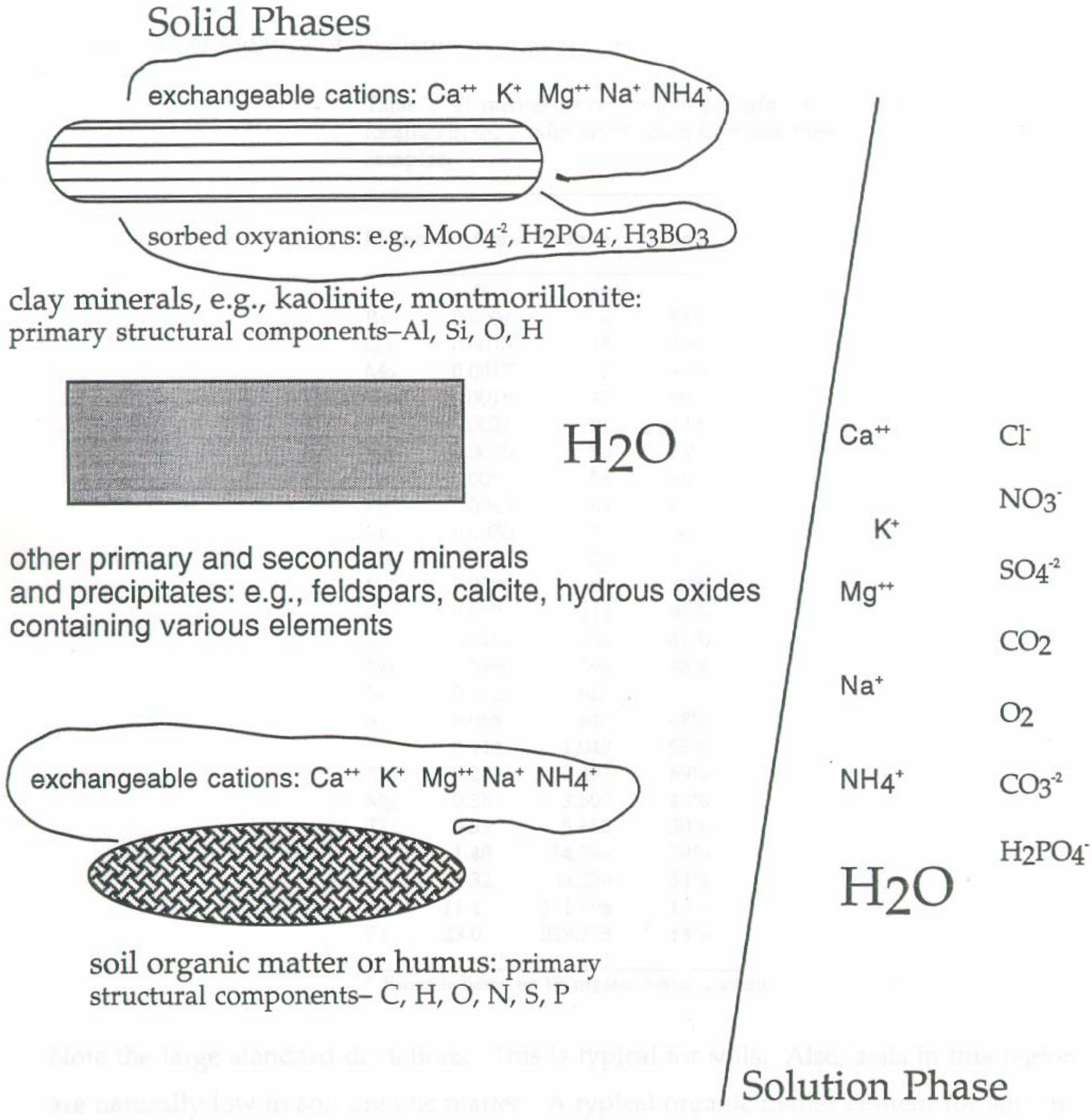
Soil test methods that have been developed to quickly measure exchangeable acidity must be relied upon to estimate the amount of lime required to raise the soil pH to a desired range.

<u>3. Soil Solution</u>

For most elements only a very small fraction of that present in soil is available to plants or other biological organisms. The soil solution, that is the water surrounding the soil particles which contains dissolved minerals and salts, typically contains only a few parts per million of the various elements. The



Note differences in base saturation of kaolinite and bentonite over the pH range 5.5 to 6.5. Humic acid and illite have pH-base saturation relationships similar to bentonite.


Solid Phases
exchangeable cations: Ca^{++} K^{+} Mg^{++} Na^{+} NH_4^{+}
sorbed oxyanions: e.g., MoO_4^{-2}, $H_2PO_4^{-}$, H_3BO_3
clay minerals, e.g., kaolinite, montmorillonite:
primary structural components–Al, Si, O, H
H_2O
other primary and secondary minerals
and precipitates: e.g., feldspars, calcite, hydrous oxides
containing various elements
exchangeable cations: Ca^{++} K^{+} Mg^{++} Na^{+} NH_4^{+}
soil organic matter or humus: primary
structural components– C, H, O, N, S, P
Ca^{++}
K^{+}
Mg^{++}
Na^{+}
NH_4^{+}
Cl^{-}
NO_3^{-}
SO_4^{-2}
CO_2
O_2
CO_3^{-2}
$H_2PO_4^{-}$
H_2O
Solution Phase

natural abundance of elements in a surface soil is presented in Table 2.

Table 2. Elemental concentrations of surface soil from a location in the Piedmont of South Carolina; means of 33 samples.

Element	Concentration %	PPM	st. dev.
Br	0.0004	4	54%
Ga	0.0015	15	29%
Mo	0.0017	17	52%
Cu	0.0018	18	50%
Ni	0.0021	21	43%
Rb	0.0050	50	25%
Cr	0.0059	59	48%
Pb	0.0069	69	60%
Sr	0.0070	70	106%
Zn	0.0093	93	81 %
V	0.0099	99	37%
Cl	0.012	114	58%
Zr	0.0282	282	41%
Mb	0.0390	390	48%
N *	0.0625	625	
S	0.065	645	48%
P	0.114	1,043	55%
Ca	0.25	2,493	69%
Mg	0.35	3,507	43%
Ti	0.59	5,852	30%
K	1.48	14,799	39%
Fe	3.32	33,220	34%
Al	11.1	111,498	19%
Si	23.0	229,773	14%

* Estimate based on 1% organic matter content.

Note the large standard deviations. This is typical for soils. Also, soils in this region are naturally low in soil organic matter. A typical organic matter content for soils in South Carolina is 1%. Soils with a higher organic matter content would have a correspondingly higher total nitrogen content and higher nitrogen supplying power than most soils of the Southeast.

Nutrients are distributed between solid and liquid or water phases. The major portion of the various elements are part of the structure of amorphous and crystalline minerals, clay minerals, and organic matter. They are not available to plants or microorganisms except through dissolution and weathering processes. Exchangeable ions are held close to the colloidal surfaces. They are not free to move about as are ions or solutes in the soil solution but they can be replaced as a result of an ion exchange reaction.

The concentration of nutrients in the soil solution is constantly changing as a result of many reactions proceeding simultaneously, including growth cycles of soil microorganisms, decomposition of crop residues, dissolution and precipitation of solid phases, uptake of ions by plant roots, respiration of plant roots and release of metabolic products such as carbon dioxide and organic acids, and the cycling of ions between the various phases as a result of these reactions.

Measurement of the amount of nutrients in soil which are available to plants has been the subject of extensive research over the past 100 years. Most estimates are based on extraction of the soil with various solutions including acids, salts, and chelating agents. The amounts extracted are then compared with the amount which can be taken up by plants. The plant is the authority on what is available. Some plants are able to extract more nutrients from soil than other plants.

4. Supply of Nutrients to Plant Roots: References: text, page 282

There are three main processes by which nutrients are supplied to plant roots:
1. **Mass flow** of soil solution to the plant root as a result of water uptake.
2. **Diffusion** of ions from solid phases or regions of high concentration towards the plant root as concentrations become depleted due to nutrient absorption.
3. **Root interception** as a result of the root growing and occupying more space.

The table below shows the relative amounts of several nutrients supplied to corn roots by the three processes.

Nutrient	Total Uptake	Root Interception kg/ha	Mass-Flow	Diffusion
Ca	23	66	175	
Mg	28	16	105	
K	135	4	35	96
P	39	1	2	36
M n	0.23	0.10	0.05	0.08
Zn	0.23	0.10	0.53	
Cu	0.16	0.01	0.35	
B	0.07	0.02	0.70	
Fe	0.80	0.10	0.53	0.17

From: Soil Testing and Plant Analysis. 1973. Editors, Leo M. Walsh and James D. Beaton. Soil Science Society of America. Madison, Wisconsin.

5. Nutrient Availability and Mobility

See pages 261-274, 279-287, and 291-297 of the text for discussion of reactions that affect plant availability of N, P, and K in soil.

A. General mechanisms that affect availability of various elements and relevant terms.

Note: check the Glossary in the text for concise definitions of the terms discussed below.

Adsorption-desorption or ion exchange; Note: adsorption refers to an attraction to a surface while absorption refers to being incorporated into something. See diagram on page 144 of the text.

Mineralization: organic ---> inorganic

Precipitation-dissolution: when dissolved substances form solids (solid phases) and drop out of solution, the process is called "precipitation"; it is not the same as adsorption; dissolution is the opposite process whereby solids go into the solution phase and become "solutes".

Fixation: elements or certain ions such as NH_4 become physically and chemically bound in a nonexchangeable form. An example is the entrapment of potassium between silica layers of clay minerals. Some clays also fix ammonium in the same way. Phosphorus can also become "fixed" in unavailable forms but the mechanism is different than ammonium or potassium fixation. Phosphorus is fixed by being bound chemically to iron and aluminum compounds.

Denitrification: biochemical reduction of nitrate or nitrite to gaseous nitrogen

Mineralization: conversion of an organic form of an element into an inorganic form.

B. Nitrogen

Most of the nitrogen in soil is present as soil organic matter and is unavailable to plants. Organic matter is about 50% carbon and 5% nitrogen, thus it has a carbon/nitrogen ratio of about 10. Nitrogen is released very slowly from soil organic matter as a result of soil microbial activity. This process is affected by moisture, temperature, tillage or any physical disturbance such as soil wetting and drying. The amount of nitrogen released by this process is also dependent on the soil organic matter content. A soil with 1% organic matter will supply much less plant available nitrogen than one that is 5% organic matter, under similar conditions.

The decomposition of crop residues is usually limited by the C/N ratio of the residue as well as environmental conditions. Soil microorganisms have first choice of available nitrogen. Higher plants get what is left over. Alfalfa will decompose more quickly in soil than corn stalks because of its higher nitrogen content (lower C/N ratio).

Nitrate, being an anion, is the most mobile form of N in soil; it moves within the water as water percolates through soil and is easily lost through this leaching process. Ammonium and ammonia forms are cationic and held by cation exchange sites. However, ammonium and ammonia forms are converted to nitrate by soil microorganisms. The reaction is fast in warm moist soils. The reaction rate becomes slower as the soil becomes more acidic. From spring through fall most ammonium fertilizer is converted to nitrate within a few days to a week or two. Urea nitrogen is hydrolyzed to ammonium nitrogen by a soil enzyme and then quickly converted to nitrate provided conditions are right.

C. Phosphorus

Phosphorus is strongly held by soil clays and iron and aluminum compounds associated with soil clays; also, phosphorus forms very sparingly soluble compounds, precipitates, in soil. These reactions proceed rapidly after fertilizer is applied. Most phosphorus in soil is precipitated, fixed, or adsorbed. These solid phases form phosphate reserves that can replenish the soil solution when phosphorus is taken up by plants, but the reaction is slow. Only small amounts of phosphorus are present in the soil solution. Because of these reactions with soil, P is very immobile, not subject to significant leaching losses. However, P is readily lost through erosion of surface soil and the associated P.

D. Potassium

Potassium exists as exchangeable K and in K-bearing minerals. In soils that contain mica-type clay minerals and vermiculate some K exists as “fixed” K within the clay mineral structure. Fixed K is not exchangeable.