

The Exchange Capacity of your soil is a measure of its ability to hold and release various elements and compounds. We are mostly concerned with the soil's ability to hold and release plant nutrients. Both the clay particles and the organic matter have negatively charged sites that attract and hold positively charged particles. Cation Exchange Capacity is the measure of how many negatively-charged sites are available in your soil.

The Cation Exchange Capacity of your soil could be likened to a bucket: some soils are like a big bucket (high CEC), some are like a small bucket (low CEC). Generally speaking, a sandy soil with little organic matter will have a very low CEC while a clay soil with a lot of organic matter (as humus) will have a high CEC. Organic matter (as humus) always has a high CEC; with clay soils, CEC depends on the type of clay.

Organic Matter (OM)|4% — 10%|Ideally, as humus.

pH|6.0 - 6.5|Not 7.0. Balance the minerals and pH will take care of itself

Bases (cations) as % of exchange capacity

Calcium (Ca)⁺⁺

|60% — 70%|Ca & Mg together should add to 80% of exchange capacity

Magnesium (Mg)⁺⁺

|10% — 20%|Ca & Mg together should add to 80% of exchange capacity

Potassium (K)⁺

|3% — 5%|See Phosphorus (P)

Sodium (Na)⁺

|1% — 4%|See Chlorine (Cl)

Hydrogen (H)⁺

|8% — 10%|Exchangeable Hydrogen, not a cation (cat-eye-on).

Other major nutrients (anions)

Phosphorus (P)-

|Equal to Potassium (K){br}(actual P = actual K)|Needs a highly bio-active soil to keep it available

Sulfur (S)-

|1/2 of Phosphorus{br}(up to 200 ppm.)|Needed for synthesis of essential amino acids.

Chlorine (Cl)-

|1x to 2x Sodium|NaCl, of course, is table salt.

This chart reflects our current level of knowledge. It has been put together over a period of years from many sources, including a lot of personal experience. It is meant to represent an ideal balance of minerals and trace elements for growing nutritionally perfect food for people and animals, not necessarily the ideal soil for pine trees or rhododendron flowers. It is fine for lawns, though.

So notice after each nutrient there is a plus or minus sign with calcium and magnesium having double. When a plant up takes a nutrient, it exudes, releases a positive or negative charged ion which is what makes the ph go up and down. The plant knows what it wants to eat and do I think there is a variance in ph depending on life stage but it shouldn't be much. I think it goes up in veg and lowers in bloom depending on how much phosphorus is consumed.

But all of these macro elements work synergistically with each other. So if your topsoil is getting crusty it is because of too much magnesium which causes soil to bind. The calcium lime sources like calcium carbonate are preferred for that reason. This is why dolomite should not be used because the magnesium takes so long to become available and then gets overloaded in soil. That's why there is a 7:1 ca/mg or you see people with the lime combos like 50/50 cal carbonate and gypsum.

<http://www.greenhousegrower.com/video/fertilizer-nutrition/v-understanding-nutrient-antagonisms/>

[B]I thought pH wasn't important? Don't microbes regulate my pH? So why do I have to add lime to my soil?[/B]

Positively charged particles are known as cations. There are two types of cations, acidic or acid-forming cations, and basic, or alkaline-forming cations. The Hydrogen cation H^+ and the Aluminum cation Al^{+++} are acid-forming. Neither are plant nutrients. A soil with high levels of H^+ or Al^{+++} is an acid soil, with a low pH.

The positively charged nutrients are Calcium, Magnesium, Potassium and Sodium. These are all alkaline cations, also called basic cations or bases. Both types of cations (alkaline or acidic) may attach onto either a clay particle or soil organic matter (SOM). All of the nutrients in the soil need to be held there somehow, or they will just wash away when you water the garden or get a good rain storm. Clay particles generally have a negative (-) charge, so they attract and hold positively (+) charged nutrients and non-nutrients. Soil organic matter (SOM or just OM) has both positive and negative charges, so it can hold on to both cations and anions.

Both the clay particles and the organic matter have negatively charged sites that attract and hold positively charged particles. Cation Exchange Capacity (CEC) is the measure of how many negatively-charged sites are available in your soil.

Dr. William Albrecht, did a lot of experimenting with different ratios of nutrient cations, the Calcium, Magnesium, Potassium and Sodium mentioned above. He and his associates, working at the University of Missouri Agricultural Experiment Station, came to the conclusion that the strongest, healthiest, and most nutritious crops were grown in a soil where the soil's CEC was saturated to about 65% Calcium, 15% Magnesium, 4% Potassium, and 1% to 5% Sodium. (No, they don't add to 100%; we'll get to that.) This ratio not only provided luxury levels of these nutrients to the crop and to the soil life, but also strongly affected the soil texture and pH.

The percentage of the CEC that a particular cation occupies is also known as the base saturation percentage, or percent of base saturation, so another way of describing Albrecht's ideal ratio is that you want 65% base saturation of Calcium, 15% base saturation of Magnesium etc. Don't get too hung up on these percentages; they are general guidelines and can vary quite a bit depending on soil texture and other factors.

The Calcium to Magnesium ratio determines how tight or loose a soil is. The more Calcium a soil has, the looser it is; the more Magnesium, the tighter it is, up to a point. Other things being equal, a high Calcium soil will have more Oxygen, drain more freely, and support more aerobic breakdown of organic matter, while a high Magnesium soil will have less Oxygen, tend to drain slowly, and organic matter will break down poorly if at all. In a soil with Magnesium higher than Calcium, organic matter may ferment and produce alcohol and even formaldehyde, both of which are preservatives. If you till up last years corn stalks and they are still shiny and green, you may have a soil with an inverted Calcium/Magnesium ratio. On the other hand, if you get the Calcium level too high, the soil may lose its beneficial granulation and structure and the excessive Calcium will interfere with the availability of other nutrients. If you get them just right for your particular soil, you can drive over the garden and not have a problem with soil compaction.

Because Calcium tends to loosen soil and Magnesium tightens it, in a heavy clay soil you may want 70% or even 80% Calcium and 10% Magnesium; in a loose sandy soil 60% Ca and 20% Mg might be better because it will tighten up the soil and improve water retention. If together they add to 80%, with about 4% Potassium and 1-3% Sodium, that leaves 12-15% of the exchange capacity free for other elements, and an interesting thing happens. 4% or 5% of that CEC will be filled with other bases such as Copper and Zinc, Iron and Manganese, and the remainder will be occupied by exchangeable Hydrogen , H^+ .

The pH of the soil will automatically stabilize at around 6.4 , which is the "perfect soil pH" not only for organic/biological agriculture, but is also the ideal pH of sap in a healthy plant, which I will talk about later, and the pH of saliva and urine in a healthy human.

So we are looking at two new things so far:

- 1) The Cation Exchange Capacity, and
- 2) The proportion of those cations in relation to each other: the percent of base saturation (% base saturation) and their effect on pH.

We are also looking at two old familiar things, clay and soil organic matter, and these last two need a bit more clarification.

How Clay and Humus Form

Clay particles are really tiny. They are so small that they can't even be seen in most microscopes. They are so small that when mixed in water they may take days, weeks, or months to settle out, or they may never settle out and just remain suspended in the water. A particle that remains suspended in water like this, suspended but not dissolved, is known as a colloid. Organic matter, as it breaks down, also forms smaller and smaller particles, until it breaks down as far as it can go and still be organic matter. At that stage it is called humus, and humus is also a colloid; when mixed into water humus will not readily settle out or float to the top. Colloids, because they are so small, have a very large surface area per unit volume or by weight. Some clays, such as montmorillonite and vermiculite, have a surface area as high as 800 square meters per gram, over 200,000 square feet (almost five acres) per ounce! The surface area of fully developed humus is about the same or even higher. Other clays have a much lower surface area; some clays actually have a very low exchange capacity, while humus always has a high exchange capacity.

Mineral soils are formed by the breakdown of rocks, known as the parent material. Heating and cooling, freezing and thawing, wind and water erosion, acid rain (all rain is acid; carbon dioxide in the air forms carbonic acid in the rain), and biological activity all break down the parent material into finer and finer particles. Eventually the particles get so small that some of them re-form, that is they re-crystallize into tiny flat platelets and become colloidal clay, made up mostly of silica and alumina clay particles aggregated into thin, flat sheets that stack together in layers.

Clay "History"

How old a soil is usually determines how much clay it has. The more rainfall a soil gets, the faster it breaks down into clay. Arid regions are mostly sandy and rocky soil, unless they have areas of "fossil" clay. River bottoms in arid regions will often have more clay because the small clay particles wash away easily from areas without vegetation cover. As noted above, clays tend to stick together in microscopic layers. Newly formed clays will often be made up of layers of silica and alumina sandwiched with potassium or iron. On these young clays, the only available exchange sites are on the edges. As the clays age, the "filling" in the sandwich gets taken out by acid rain or soil life or plant roots, opening up more and more negatively charged exchange sites and increasing the exchange capacity. Eventually these clays become tiny layers of silica and alumina separated by a thin film of water. These are the expanding clays; when they get

wet they swell, and when they dry out they shrink and crack deeply. Because these expanding clays have exchange sites available between their layers and not just on the edges, they have a much greater exchange capacity than freshly formed clays.

Organic Matter and Humus

Regarding soil organic matter and humus, obviously any area that gets more rainfall tends to grow more vegetation, so the fraction of the soil that is made up of decaying organic matter will usually increase with more rainfall. Breakdown of organic matter is largely dependent on moisture, temperature, and availability of oxygen. As any of these increase, the organic matter will break down faster.

Ordinary organic matter from the compost or manure pile, or the remains of last years' crops, doesn't have much exchange capacity until it has been broken down into humus, and from what we know, the formation of humus seems to require the action of soil microorganisms, earthworms, fungi, and insects. When none of them can do anything with organic matter as food anymore, it has become a very small but very complex carbon structure (a colloid) that can hold and release many times its weight in water and plant nutrients. The higher the humus level of the soil, the greater the exchange capacity. One way to increase humus in your soil is by adding organic matter and having healthy soil life to break it down or to add a soil amendment such as lignite (also known as Leonardite), a type of soft coal that contains large amounts of humus and humic acids. If the mineral balance of the soil is optimal, especially with an adequate supply of Sulfur, any fresh organic matter grown in or added to the soil will tend to form stable humus. Without balanced minerals and adequate Sulfur, much of the organic matter will decompose completely and be off-gassed as ammonia and CO₂.

Variable Exchange Capacity

Humus can have an exchange capacity greater than even the highest CEC clays, but it is a variable exchange capacity that correlates with soil pH. In soils with a pH below 6 there will be an excess of H⁺ ions in the soil/water solution and many of the negative – exchange sites will be occupied by acidic cations such as Al⁺⁺⁺ and Fe⁺⁺. As soil pH increases due to added Ca, Mg, K, and Na, these Al and Fe ions will combine with negatively charged OH⁻ ions in the soil-water solution, forming insoluble Aluminum and Iron oxides and freeing up the negatively charged sites on the humus to play a role in nutrient exchange. **A high-organic-matter soil will have a low “effective” exchange capacity at low pH, because many of the negative**

exchange sites will be filled with tightly bound Al and Fe. Adding base cations, especially Calcium, will raise the pH and the Calcium⁺⁺ ions will displace the Al and Fe with "exchangeable" Ca.

OK, let's pull this information together. We have discovered that:

1) Alkaline soil nutrients, largely Calcium, Magnesium, Potassium, and Sodium, are positively charged cations (+) and are held on negatively charged (-) sites on clay and humus.

2) The amount of humus, and the amount and type of clay, determine how much Cation Exchange Capacity a given soil has.

3) We have also discussed the ideal base saturation percentages of these nutrients which according to the work of Professor Albrecht, is approximately:

65% Ca (Calcium)

15% Mg (Magnesium)

4% K (Potassium),

1-3% Na (Sodium)

4) We have talked a little about the effect of those ratios on soil texture and pH and why they are not hard and fast "rules".

The next step is to understand how the plant, and the soil life, gets those nutrients from the exchange sites, the "exchange" part of the story.

Trading + for +

In the same way that acid rain can leach cations from the soil, plants and soil microorganisms more or less "leach" the cation nutrients from their exchange sites. These alkaline nutrients are only held on the surface with a weak, static electrical charge, i.e. they are "adsorbed". They are

constantly oscillating and moving a bit, pulled and pushed this way and that by other charged particles (ions) in the soil solution around them. What the plant roots and soil microorganisms do is exude or give off Hydrogen ions, H^+ ions, and if these H^+ ions are in high enough concentration in the soil solution that some of them surround the nutrient cation and get closer to the negatively (-) charged exchange site than the nutrient cation is, the H^+ ions will fill the exchange site, neutralize the (-) charge, and the nutrient cation will be free of its static bond and can then be taken up by the plant or microorganism.

The way this works specifically with plant roots and microbes is that they expire or breathe out carbon dioxide into the soil. This carbon dioxide (CO_2) combines with water in the soil and forms carbonic acid which is in rain water (H_2CO_3); the H^+ Hydrogen ions from the carbonic acid are what replaces the cation nutrient on the exchange site. A Calcium ion that is held to the exchange site has a double-positive charge, written Ca^{++} . When enough H^+ ions surround it that some of them get closer to the exchange site than the Ca^{++} ion is, two H^+ ions replace the Ca^{++} ion and the plant or microbe is free to take the Ca^{++} up as a nutrient.

How the CEC is measured, and what to do with that information once you have it.

Exchange capacity is measured in milligram equivalents, abbreviated ME or meq. A milligram is of course 1/1000th of a gram, and the milligram being referred to is a milligram of H^+ exchangeable Hydrogen. The comparison that is used is 1 milligram of H^+ Hydrogen to 100 grams of soil. If all of the exchange sites on that 100 grams of soil could be filled by that 1 milligram of H^+ , then the soil would have a CEC of 1. One what? One ME, one milligram equivalent (meq), the ability to adsorb and hold one milligram of H^+ Hydrogen ions.

Let me repeat that: 100 grams of a soil with a CEC of 1 could have all of its negative (-) exchange sites filled up or neutralized by 1/1000th of a gram of H^+ exchangeable Hydrogen. If it had a CEC of 2, it would take 2 milligrams of Hydrogen H^+ , if its CEC was 120 it would take 120 milligrams of H^+ to fill up all of the negative (-) exchange sites on 100 grams of soil.

The "equivalent" part of ME or meq means that other positively (+) charged ions could be substituted for the Hydrogen. If all of the sites were empty in that 100 grams of soil, and that soil had a CEC of 1, 20 milligrams of Calcium (Ca^{++}), or 12 milligrams of Magnesium (Mg^{++}), or 39 milligrams of Potassium (K^+) would fill the same exchange sites as 1 milligram of Hydrogen H^+ .

Why the difference? Why does it take 20 times as much Calcium as Hydrogen, by weight? It's

because Calcium has an atomic weight of 40, while Hydrogen, the lightest element, has an atomic weight of 1. One atom of Calcium weighs forty times as much as one atom of Hydrogen. Calcium also has a double positive charge, Ca^{++} , Hydrogen a single charge, H^+ , so each Ca^{++} ion can fill two exchange sites. It only takes half as many Calcium ions to fill the (-) sites, but Calcium is 40 times as heavy as Hydrogen, so it takes 20 times as much Calcium by weight to neutralize those (-) charges, or 12 times as much Magnesium, atomic weight 24 (Mg^{++} , also a double charge), or 39 times as much Potassium⁺. (Potassium's atomic weight is 39, and it has a single positive charge, K^+ , so it takes 39 times as much K^+ as H^+ to fill all the exchange sites, once again by weight.) The amount of + charges, the quantity of atoms, of K^+ or H^+ , is the same.)

What We Have Learned

We have now learned the basics of CEC, cation exchange, in the soil. 1) Clay and organic matter have negative charges that can hold and release positively charged nutrients. (The cations are adsorbed onto the surface of the clay or humus) That static charge keeps the nutrients from being washed away, and holds them so they are available to plant roots and soil microorganisms

2) The roots and microorganisms get these nutrients by exchanging free hydrogen ions. The free hydrogen H^+ fills the (-) site and allows the cation nutrient to be absorbed by the root or microorganism.

3) The unit of measure for this exchange capacity is the milligram equivalent, ME or meq, which stands for 1 milligram (1/1000 of a gram) of exchangeable H^+ . In a soil with an exchange capacity (CEC) of 1, each 100 grams of soil contain an amount of negative (-) sites equal to the amount of positive (+) ions in 1/1000th of a gram of H^+ .