Soil CEC Explained

Understanding, Measuring & Using Cation Exchange Capacity for Nutritious Crops

by Michael Astera

The exchange capacity of your soil is a measure of its ability to hold and release various elements and compounds. In agriculture we are mostly concerned with the soil's ability to hold and release plant nutrients, obviously, and the concept of exchange capacity deals with the soil's ability to hold and release positively charged nutrients. A particle that has a positive (+) charge is called a cation, pronounced *cat-eye-on*. If it has a negative charge (-) it is called an anion, pronounced *an-eye-on*. (Both words are accented on the first syllable.) The word "ion" simply means a charged particle; a positive charge is attracted to a negative charge, and vice versa.

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 that we are mainly concerned with here are calcium, magnesium, potassium and sodium. These are all alkaline cations, also called basic cations, or bases. Both types of cations may be adsorbed 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 crops or get a good rainstorm. Clay particles almost always have a negative (-) charge, so they attract and hold positively (+) charged nutrients and non-nutrients. Soil organic matter (SOM) has both positive and negative charges, so it can hold onto 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 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 container: some soils are like a big bucket (high CEC), and others are like a small pail (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, it depends on the type of clay.

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 percent base saturation of calcium, 15 percent 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.

It's still a little-known fact that the calcium-to-magnesium ratio determines how tight or loose a soil is. The more calcium a soil has, the looser it is, and 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 year's cornstalks and they are still shiny and green, you likely have a soil with an inverted calcium/magnesium ratio. On the other hand, if you get the calcium level too high, the soil will lose all its beneficial granulation and structure, and the too-high calcium will interfere with the availability of other nutrients. If you get them just right for your particular soil, you can drive over it and not have a problem with soil compaction.

Adsorb vs. Absorb

adsorb (**ad- sôrb, -zôrb**), *v.t.* Physical Chem. to gather (a gas, liquid, or dissolved substance) on a surface in a condensed layer: Charcoal will adsorb gases.

Please note the definition above, taken from my handy dictionary, flower press, and child booster seat, the real hardbound Random House second edition unabridged. It's not absorb, it's *ad*sorb, with a "d." We all know that a sponge absorbs water, a cast iron pot absorbs heat, a flat-black wall absorbs light. None of those gathers anything on the surface in a condensed layer, they soak it right in, they absorb it.

Adsorb is different, referring to a surface phenomenon. It is much like static cling, when you take a synthetic fabric shirt out of the clothes dryer and it wants to stick to you. You don't *absorb* the nylon blouse, you *adsorb* it.

BASE SATURATION

From the 1920s to the late 1940s Dr. William Albrecht experimented 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 percent calcium, 15 percent magnesium, 4 percent potassium, and 1 percent to 5 percent sodium (no, they don't add to 100 percent — 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.

Because calcium tends to loosen soil and magnesium tightens it, in a heavy clay soil you may want 70 percent calcium and 10 percent magnesium; in a loose sandy soil 60 percent Ca and 20 percent Mg might be better because it will tighten up the soil and improve water retention. If together they add to 80 percent, with about 4 percent potassium and 1-3 percent sodium, that leaves 12-15 percent of the exchange capacity free for other elements, and an interesting thing happens — 4 or 5 percent 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, and the pH of saliva and urine in a healthy human.

Thus we are looking at:

1. The cation exchange capacity;

2. The proportion of those cations in relation to each other: the percentage of base saturation (percent base saturation) and its effect on pH.

We are also looking at two old, familiar things, clay and soil organic matter, which could benefit by a bit more clarification.

HOW CLAY & HUMUS FORM

Clay particles are really tiny, so small they can't even be seen with most microscopes. When mixed in water they may take days, weeks or months to settle out, or they may never settle out and remain suspended in the water, not dissolved, but suspended. A particle that remains suspended in water like this 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*, which is also a colloid — when mixed into water it 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, and 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 to some extent; 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 recrystallize into tiny flat platelets, and become colloidal clay, made up mostly of silica and alumina. These clay particles aggregate 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. Over millions of years, the space in these expanding clays is filled back in with hydrated aluminum oxide and they lose their exchange capacity again, this time permanently.

In the southern half of the United States, the age of the clay fraction of the soil generally increases from west to east. The arid regions, from California to western Texas, are largely young soils, containing a lot of sand and gravel and some young clays without a lot of exchange capacity. The central regions, from west-central Texas and above into Oklahoma, Kansas and Nebraska, contain well-developed clays with high CEC. Moving east, rainfall increases, the soils are older, and the clays are generally aged and have lost much of their ability to exchange cations. Across Louisiana, Mississippi, Alabama and Georgia, the clays have been rained on and leached out for millions of years. Their reserves of calcium and magnesium are often long gone. The northern-tier states, from Washington in the West to Pennsylvania and New York in the East, were largely covered with glaciers as recently as 10,000 years ago, which brought them a fresh supply of minerals, and clays of high exchange capacity are common.

ORGANIC MATTER & HUMUS

Regarding soil organic matter (SOM) 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 usually breaks down faster. Moisture and oxygen being equal, colder northern areas will tend to build up more organic matter in the soil than hotter southern climates, with one extreme being found in the tropics, where organic matter breaks down and disappears very quickly, and the other being the vast, deep peat beds and "muck" soils of some Northern states. As always, there are exceptions, such as the everglades of Florida, where lack of oxygen combined with stagnant water have formed the largest peat beds in the world. The area around Sacramento California is another example: there were muck soils 100 feet deep when that delta was first farmed by European settlers.

Ordinary organic matter from the compost or manure pile, or the remains of last year's 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 it as food anymore, it has ended up as 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. The only 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. Humus and humic acids have an exchange capacity greater than even the highest CEC clays.

Now, let's pull this information together:

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, approximately:

- 65 percent Ca
- 15 percent Mg
- 4 percent K (Potassium)
- 1-3 percent 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 understanding how the plant and the soil life get those nutrients from the exchange sites, the "exchange" part of the story.

TRADING PLACES

In the same way that acid rain can leach cations from the soil, plants and soil microorganisms more or less "leach" 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, 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+, and if enough of these H+ ions are given off to surround the nutrient cation and get closer to the negatively (-) charged exchange site than the nutrient, 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 is that the plant roots expire or breathe out carbon dioxide into the soil. This carbon dioxide (CO_2) combines with water in the soil and forms carbonic acid, and the H+ hydrogen ions from the carbonic acid are what replaces the cation nutrient on the exchange site. The calcium ion that is held to the exchange site has a double-positive charge, Ca++. When enough H+ ions surround it and some of them get closer to the exchange site than the Ca++ ion, two H+ ions replace the Ca++ ion, and the plant is free to take the Ca++ up as a nutrient. Simple as that.

MEASUREMENT

Exchange capacity is measured in milligram equivalents, abbreviated ME or meq. A milligram is of course one-thousandth of a gram, and the milligram they are referring to is a milligram of H+ exchangeable hydrogen. The example that is often used to explain milligram equivalents 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 ME, or 1 meq, one milligram of hydrogen.

To rephrase: 100 grams of a soil with a CEC of 1 could have all of its negative (-) exchange sites filled up or neutralized by one-thousandth of a gram of H+ exchangeable hydrogen. If it had a CEC of 2, it would take 2 milligrams of hydrogen H+, and 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++), 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? 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 takes only half as many calcium ions to fill the (-) sites, but calcium is 40 times heavier than hydrogen, so it takes 20 times as much calcium by weight to neutralize those (-) charges, or 12 times as much magnesium (Mg++, also a double charge), or 39 times as much potassium, by weight. (Potassium's atomic weight is 39, and it has a single positive charge, K+, so it takes 39 times as much K+ to fill all the exchange sites, once again by weight. The amount of + charges, the amount of atoms of K+ or H+, is the same.)

CONCLUSION

To quickly summarize 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 (one-thousandth 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 one-thousandth of a gram of H+.

Per 100 grams of soil, 1 meq or ME =
1 milligram H+ or
20 mg of Calcium Ca++ or
12 mg of Magnesium Mg++ or
39 mg of Potassium K+ or
23 mg of Sodium Na+

In agriculture it is assumed that the top 6 to 7 inches of soil, the "plow layer," weighs 2 million pounds, thus:

1 mg H per 100 grams give a ratio of 0.00001:1.

2,000,000 lbs x 0.00001 = 20 lbs, so:
Per acre, 1 meq or ME =
20 lb Hydrogen H+ or
400 lb Calcium Ca++ or
240 lb Magnesium Mg++ or
780 lb Potassium K+ or
460 lb Sodium Na+

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