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Chemical Indicators for Soil Health

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Introduction

Soil health is gaining interest from agricultural producers as a management philosophy to address rising input costs and improve the sustainability of soil resources. The basis for the concept is to view the soil as a living and dynamic media for plant growth and manage the soil to equally optimize soil biological, chemical, and physical properties for sustainable crop production. This includes increasing nutrient cycling and availability, improving water-holding capacity, improving soil structure, and reducing compaction and erosion, while hosting a diverse set of microorganisms which can provide multiple functions that improve crop growth and yield.

To many, soils are healthy if they can support plant growth and development with inputs of fertilizers and water. While plant production and crop yield are key indicators of soil productivity and health, soil health and productivity are reliant on a complex interaction of biological, chemical, and physical interactions. Research is ongoing to support interest in improving soil health by trying to better understand the intricate set of relationships among soil properties. One approach is to identify soil health indicators by examining changes in selected biological, chemical, and physical properties. Of all the components that contribute to soil health, soil chemical indices have been, and still are, most prevalently used for crop production. For example, routine soil testing for plant nutrient application is scientifically proven to determine fertilizer needs and has been used worldwide for decades. However, routine soil testing is founded on determining only the plant-available portion of a given nutrient or set of nutrients. Not all nutrients in the soil are essential for plant growth, as many nutrients cycle from unavailable to plant-available forms in the soil. To determine how much fertilizer is needed, routine soil testing involves using an extractant that aims at determining the plant-available portion of a given nutrient.

The concept of soil health is to use management to optimize nutrient cycling and make a larger portion of the plant nutrient pool available for plant growth. Research is ongoing with practices such as tillage and cover crops as to how they affect nutrient cycling. This fact sheet addresses soil chemical properties and how they can be used for indicators of soil health.

Chemical Indices Related to Soil Health

The following sections individually address chemical parameters that directly influence soil health and productivity. The list below highlights indices that are deemed important for Mid-South production systems but is not meant to be a comprehensive list. As soil health continues to evolve, the parameters of interest may change.

Soil pH

The concept of pH is related to the concentration of hydrogen (H^+) ions in soil solution. The measurement of pH is conducted on a base-10, logarithmic scale that ranges from 0 to 14 with a neutral pH at 7. Acidic pH values are within the range of 0 to 6.9 and are characterized by the increased presence of H^+ ions in the soil solution. Soils that exhibit acidic pH levels can create a toxic soil environment that is not conducive to proper plant growth for most plant species, although some vegetables, such as radishes (*Raphanus raphanistrum* subsp. *Sativus L.*), due to tolerance mechanisms not frequently observed in cash crops, can thrive under acidic soil conditions. In many cases, acidic soil conditions can increase the availability of both essential and non-essential elements in the soil leading to increased plant uptake and potentially plant tissue concentrations that become toxic. For instance, aluminum (Al) is not a plant-essential element that is prevalent in most soils. As the soil becomes more acidic (pH < 5.0), Al that is normally insoluble will move into soil solution and the plant can suffer from Al toxicity. However, if the soil pH is maintained near the optimum range (~ pH 6.5), Al toxicity is not a concern. Similarly, manganese (Mn) is a plant-essential element that exhibits increasing availability under acidic soil conditions and can reach toxic levels if the soil pH becomes too low. Basic, or alkaline, pH levels are within the range of 7.1 to 14 and are characterized by the increased presence of hydroxide ions (OH^-) in soil solution, which can bind nutrients needed for plant development and render them unavailable for plant uptake. Some plant species that can grow in alkaline soil pH environments include cucumber (*Cucumis sativus* L.) and asparagus (*Asparagus officinalis* L.). High pH soils tend to result in decreased nutrient availability and subsequent nutrient deficiencies, whereas acidic soil conditions can result in both nutrient deficiencies and toxicities.

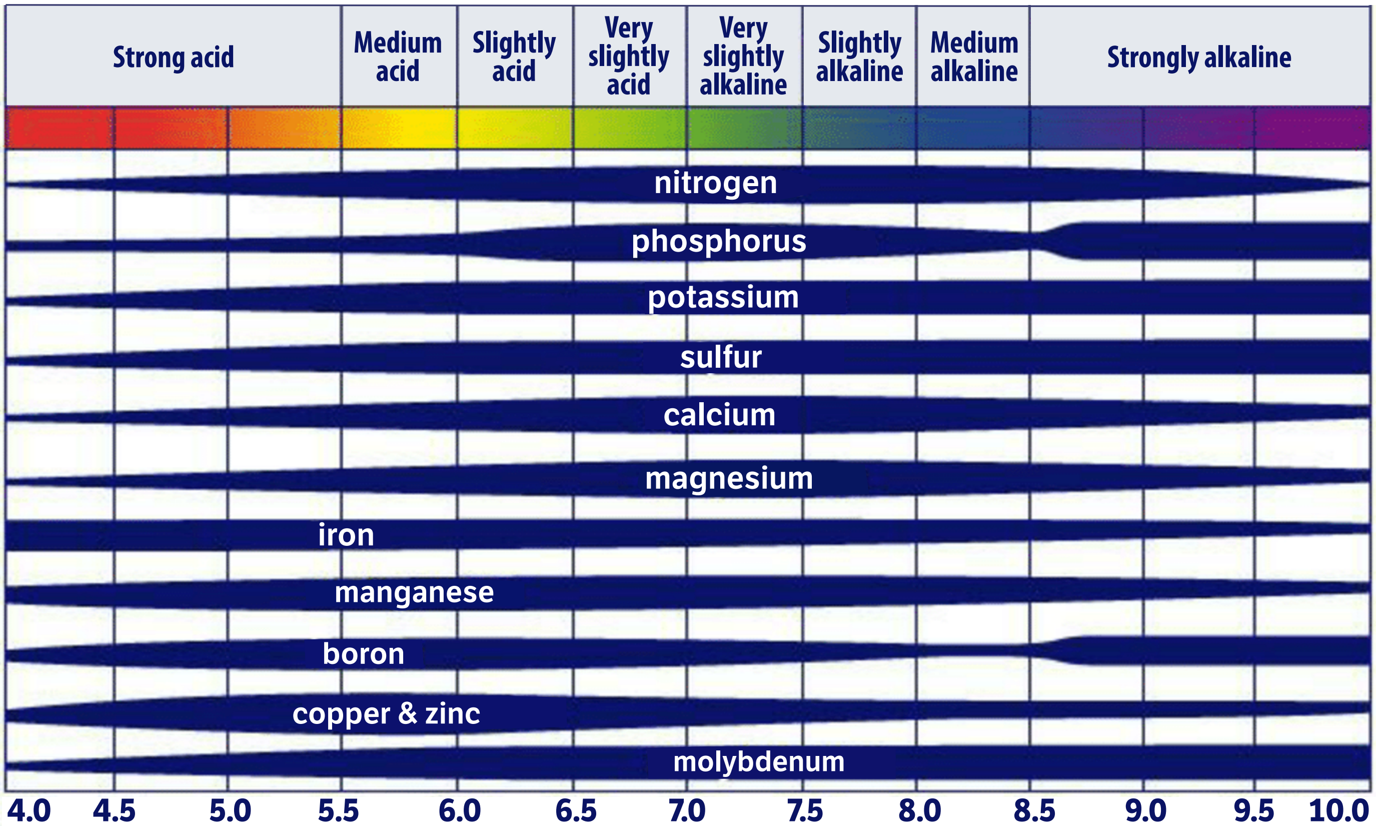
Perhaps the most important factor regarding pH is the effect that pH has on the availability of plant-essential macronutrients, such as nitrogen (N) and phosphorus (P), and many micronutrients, including zinc (Zn), iron (Fe), boron (B), and molybdenum (Mo). These nutrients are in high demand for developing row crops and any deficiencies during the growing season can result in diminished photosynthetic activity, decreased amino acid production, and drastic reduction in overall yield. Acidic soil pH conditions, with their overabundance of H+ ions, can alter the chemical behavior of N and P into forms that are not readily accessible by plant roots and root hairs. Likewise, alkaline soil pH environments can bind N and P by creating insoluble compounds highly influenced by the presence of calcium (Ca) and magnesium (Mg) ions. Soil pH also plays a large role in the microbial makeup of the soil, with fungi dominating in acidic soil conditions and bacteria dominating in alkaline soil conditions. The microbial community plays an important role in nutrient cycling and can alter the potential loss pathways of macronutrients, such as N. The optimum plant availability of N, P, and most plant-essential elements occurs at a soil pH within the 6 to 7 range (Figure 1), which makes soil testing for pH paramount for any nutrient management plan involving agricultural production. In addition, the soil and plant toxicity potential of elements such as Al and Mn decrease with increased soil pH (Delhaize and Ryan, 1995).

Routine Soil Analyses:

Nutrient Availability

For many years, the only assessment of soil chemical properties available to producers was routine soil analyses, which vary from state to state. Although extremely important for row-crop productivity, routine soil analyses capture only a portion of the chemical properties that contribute to resilient soils and plant

Figure 1. Chart showing the availability of soil nutrients at various pH levels. Image adapted from Roques et al. (2013).



productivity. In Arkansas, routine soil analyses consist of measuring soil pH and Mehlich III (M3) extractable nutrients. Current soil test reports for Arkansas provide M3 extractable nutrient concentrations for P, K, Ca, Mg, sulfate-sulfur (S), Zn, sodium (Na), Fe, copper (Cu), B, and Mn. Although all of these M3 extractable nutrient concentrations are reported, fertilizer rate recommendations based on the soil test concentrations are only provided for P, K, and Zn. Interpretations for soil pH are also provided in the report to guide lime applications and aid in the interpretation of both P and Zn fertilizer requirements. Currently, P, K, and Zn, are the only nutrients that the University of Arkansas System Division of Agriculture interprets fertilizer rate recommendations for, as these are the only nutrients with reliable and up to date correlation and calibration information.

Base Saturation and Estimated Cation Exchange Capacity (ECEC)

Using the results of the M3 extractable nutrients, the soil test lab provides a calculated estimate of base saturation (BS) and ECEC. Base saturation is a measure of the total percentage of cation exchange sites that are occupied by Ca, K, Mg, and Na. Although Na is not a plant-essential macronutrient, Na can have a profound effect on plant growth and soil physical characteristics and will be addressed in more detail below. Availability of the plant-essential Ca, K, and Mg increases with increasing BS and there is a strong and distinct relationship between BS and soil pH. The relationship between BS and soil pH will vary across soils due to differences in minerology, but generally follows an exponential increase in BS as soil pH increases. Estimated CEC is a calculation that is used to also estimate soil texture. An estimate of CEC and soil texture can aid in pesticide application and liming rate recommendations, among other things.

Salinity and Sodicity

There are many soluble compounds in the soil that can contribute to soil salinity, several of which are plant-essential elements (i.e., nitrate-N, sulfate-S, chloride, K, etc.) and some of which are not, particularly Na. As soil salinity

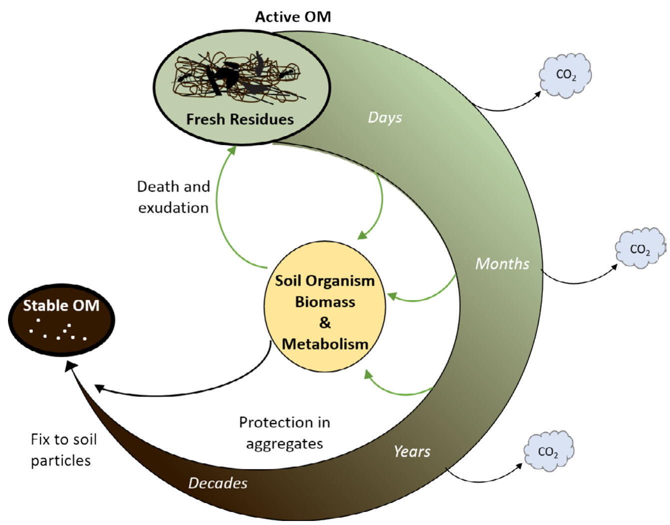


Figure 2. Diagram of soil organic matter formation. Image from UMN.

increases, plant productivity is often limited due to the inability of the plant to effectively absorb water from the soil profile. The concentration of total soluble salts in the soil is often referred to as soil salinity and is often measured in a variety of soil-to-water ratios. The standard approach, called the saturated paste extract, is often used to determine critical levels where plant growth and performance are limited by salt concentrations. Many laboratories have adopted alternative procedures that involve soil and water ratios of either 1:1 or 1:2 to speed up the analysis and increase sample throughput. Electrical conductivity (EC) is a measure of soluble salts in the saturated paste, 1:1 or 1:2 soil-water extract. As the soluble salts in the soil increase, soil EC will also generally increase proportionally. Most textbooks report a significant decrease in plant growth and performance when soil EC from a saturated paste extract is > 4 deciSiemens per meter (dS/m). Since most laboratories use a 1:2 soil-water ratio, the soil EC where plant growth becomes limited is often closer to 2 dS/m, as the increase in water content causes a dilution of the salts compared to the saturated paste extract. Laboratories that use a soil salinity method other than a saturated paste extract will typically provide equations or correction factors to calculate the saturated paste extract using the 1:1 or 1:2 soil-water-ratio methods. When assessing soil salinity, it is important to know the method implemented by the laboratory, as well as the method used by the reference material, to provide thresholds for specific crops, where the saturated paste extract is typically used as the "textbook" value. Large concentrations of specific ions in the soil, such as Na, can lead to problems with plant growth as well as soil physical properties. The measure of Na specifically in the soil is referred to as sodicity and is quantified by the exchangeable Na percentage (ESP) or the percentage of the CEC that is occupied by Na. A soil is considered sodic or problematic when the ESP is > 15%. As the soil's ESP nears or exceeds 15%, the soil will typically begin to disperse and soil structure, aggregation, and water infiltration will be negatively impacted. Problematic soils can be classified as saline (EC > 4 dS/m and ESP < 15%), sodic (EC < 4 dS/m and ESP > 15%), or saline-sodic (EC > 4 dS/m and ESP > 15%). Just because a soil is saline or salty, does not necessarily mean the soil is sodic and vice versa.

Organic Matter Concentration

Organic matter (OM) is the product of plant and animal residues or detritus decomposing on the soil surface for prolonged periods of time. These organic materials can consist of leaf litter, plant stems, crop residues, discarded fruits, and animal manure deposition. The incorporation and build-up of soil OM typically occurs within the uppermost portions of a soil profile, near the soil surface. Over time, OM can have a significant impact on soil nutrient mineralization and immobilization because of complex chemical reactions within the soil organic phase (Figure 2). The release and subsequent availability of nutrients from the OM is highly dependent on microbial activity. Soil microorganisms favorably assimilate organic materials and surface residues that have carbon (C) to nitrogen (N) ratios of < 20:1, which promote active mineralization of N and renders the N available for plant uptake.

Another vital aspect of soil OM is the formation of humus. Humus is processed organic matter that has evolved and formed over time from the deposition of surface detritus. A typical undisturbed soil will display OM enrichment in the upper soil horizons, potentially as a completely organic (O) horizon or as an OM-enriched, mineral A horizon (Figure 3). The O horizon, if present, is further differentiated according to the respective stage or level of OM decomposition. Similar to organic matter, humus is characterized by increased levels of microbial activity and chemical processes that assist in soil nutrient retention and availability. Agricultural practices, such as conservation tillage, which leaves a sizeable amount of plant material on the soil surface after harvesting, can be a driver for soil OM formation in agronomic ecosystems. Soil testing, which can provide a measurement of soil OM concentration, can aid producers and researchers by evaluating the potential to provide nutrients to developing plants, as well as OM's effects on soil health.

Soil OM typically has a large CEC per unit mass, and relatively small increases in OM can lead to significant increases in the nutrient-holding capacity of soils. In addition to nutrient retention, OM provides the energy source for soil microbes that aid in nutrient cycling. Generally, increases in soil organic matter lead to increases soil microbial populations and diversity, which enhance nutrient availability and plant growth. Increases in soil OM can also enhance soil physical properties, such as soil aggregation, water infiltration, water-holding capacity, and soil aeration, and decrease soil bulk density (i.e., a measure of the degree of soil compaction). According to the University of Arkansas System Division of Agriculture, soil OM concentrations greater than 2% are considered desirable for soil productivity.

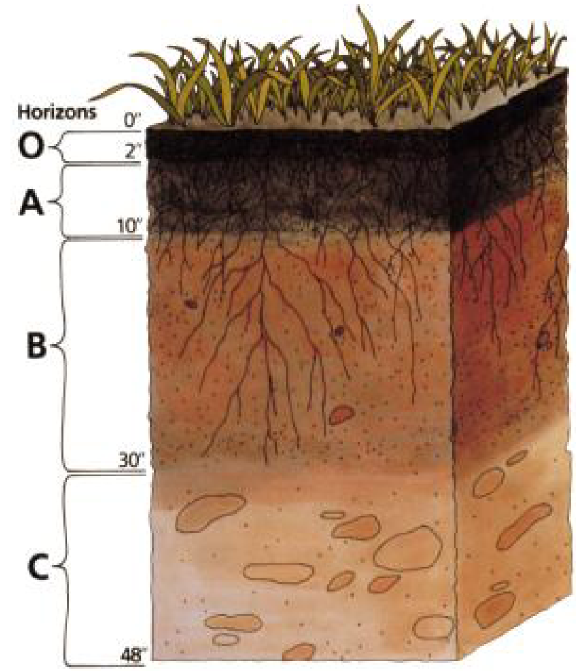


Figure 3. Diagram of soil horizons showing the organic (O) and topsoil horizons (A) containing humus. Image from the NRCS-USDA

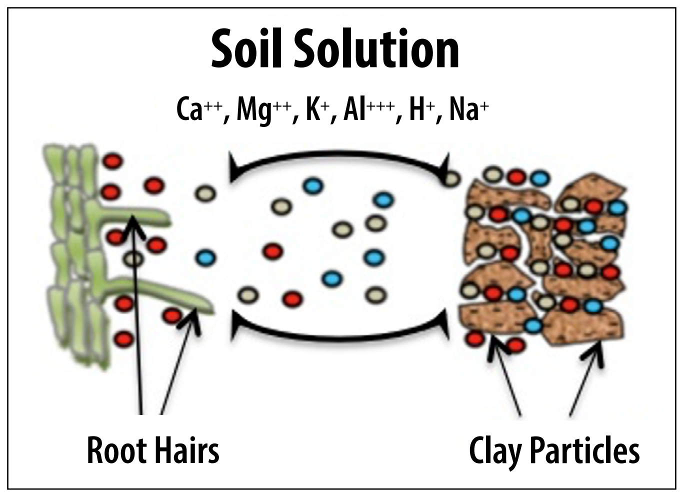


Figure 4. Diagram of soil cation exchange capacity showing cations being exchanged for anions and being made available for plant root uptake. Image from Sonon et al. (2014).

Cation Exchange Capacity

Cation exchange is the reversible process by which a cation adsorbed on the surface of soil colloids (i.e., organic compound and/or clay particle) is exchanged with another cation in the soil solution (Havlin et al., 2014). The total ability of a soil to hold or exchange cations is referred to as cation exchange capacity (CEC). Cation exchange reactions in soil are important for plant nutrient availability and retention in the soil. Clay particles have surfaces that are typically negatively charged that can attract and adsorb positively charged soil cations, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), ammonium (NH_4^+), aluminum (Al^{3+}), and hydrogen (H^+) (Figure 4). Additionally, the gradual weathering of clay and other soil minerals over time can release cations into the soil solution depending on the type of clay material and the clay's structure and arrangement, both of which can have substantial impacts regarding cation exchange and release.

Total CEC is primarily influenced by clay mineral type and clay content. Generally, as the fraction of clay in a soil increases, there will be a

Soil and Soil Components	CEC (meq/100
Clay Type	
Kaolinite	3-15
Illite	15-40
Montmorillonite	80-100
Soil Texture	
Sand	1-5
Fine Sandy Loam	5-10
Loam	5-15
Clay Loam	15-30
Clay	>30
Organic Matter	200-400

Figure 5. Chart displaying cation exchange capacity ranges from different clay mineral types and soil textures and soil organic matter. Image from Sonon et al. (2014).

proportional increase in CEC. Soils with a large percentage of 2:1 clay mineral types, such as silty clay loams and clay loams, will have a greater total CEC than soils with a large percentage of 1:1 clay minerals. Soil organic matter concentration also influences soil's bulk CEC, as small increases in OM lead to significant increases in CEC. Cation exchange capacity is significantly influenced by soil texture and OM concentration, with predominantly clay-textured soils having larger CECs and sandy-textured soils having a lower cation exchange potential (Figure 5). Nevertheless, CEC is a key indicator of the soil's ability to retain and provide nutrients to nutrient availability, along with assimilation by plants in soils that have a modest amount of clay materials without the presence of root-restrictive structures, such as clay-based hardpans.

Conclusions

Although there are additional parameters associated with the evaluation needed to comprehensively assess soil health, the chemical indicators of pH, routine nutrient analyses, soil salinity or sodicity, OM concentration, and CEC are widely regarded as being common metrics for assessing the overall productivity of a given soil. Conducting routine soil tests is an effective method to monitor soil chemical properties throughout the growing season or annually. Soil test reports often include analyses of these chemical indicators, when requested, and serve as a reliable guide when contemplating nutrient management plan development, along with land-use strategies. Further work is required to ascertain how each of these factors should be considered in the context of overall soil health.

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