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# The soil health tool—Theory and initial broad-scale application

Richard L. Haney[a], Elizabeth B. Haney[b,*], Douglas R. Smith[a], R. Daren Harmel[a], Mike J. White[a]

[a] USDA-ARS, Grassland, Soil and Water Research Laboratory, 808 East Blackland Road, Temple, TX 76502, USA
[b] Texas A&M University, Texas AgriLife Research and Extension Center, 720 E. Blackland Road, Temple, TX 76502, USA

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ABSTRACT

Soil health has traditionally been judged in terms of production; however, it recently has gained a wider focus with a global audience, as soil condition is becoming an environmental quality, human health, and political issue. A crucial initial step in evaluating soil health is properly assessing the condition of the soil. Currently most laboratory soil analyses treat soils as non-living, non-integrated systems. Plant available nutrients have traditionally been estimated with methods that utilize harsh chemical extractants in testing soil for inorganic N, P, K, and micronutrients. Complementary methods, including soil texture, pH, and total soil organic matter, also do not evaluate biological soil aspects. In this paper we introduce and describe the theory behind the Soil Health Tool, focusing on two objectives: 1) to estimate plant available N, P, and K; and 2) to provide an indication of soil health with respect to nutrient and C cycling. The Soil Health Tool is an integrative soil testing approach that measures inorganic N, P, and K with a soil extractant comprised of organic acids. It also estimates potentially mineralizable N and P as influenced by water extractable organic C and N and microbial soil respiration. The Soil Health Tool was designed for use in commercial soil testing laboratories and uses rapid, cost-effective procedures. The tool also offers insight into the complex interactions between soil chemistry and biology and providing additional value to producers through improved plant available nutrient estimates as well as an indication of the soil health status as related to C, N, and P cycling.

## 1. Introduction

Soil health is normally viewed in terms of production, which could be biomass production (McBratney et al., 2012) or productivity indices relative to fundamental soil properties. As early as the 1930s, studies were conducted with regards to the fitness of soils for crop production based on increasing yields from a profit standpoint. In recent years, soil quality is beginning to have a wider focus with a global audience, as soil condition is becoming an environmental quality, human health, and political issue. Soil is the keystone of food security, water security, climate change mitigation, and biodiversity protection (McBratney et al., 2014).

Soil health or quality has been defined in many ways that usually include various aspects of physical and chemical soil properties and some biological indicators. The Food and Agriculture Organization of the United Nations (FAO) describes soil health as the "capacity of soil to function as a living system, with ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production" (FAO, 2008). Simply put, the soil is a living ecosystem deserving of equivalent analyses as animal or plant habitats.

From an agricultural standpoint we have long focused solely on the soil physical and chemical properties that relate to plant production, neglecting the inherent biological components of soil that contribute to its overall health. In 1 $m^3$ of agricultural soil there is between 1200 and 1700 kg of soil containing approximately 2.3%–2.6% of the soil's carbon in the microbial biomass (Anderson and Domsch, 1989). Throughout their life cycle, the microbial biomass (bacteria and fungi) immobilize N during growth and release plant-available N and P upon their death. Microbial nutrient cycling can provide enough N and P to produce a crop without the addition of fertilizers. When the agricultural community accepts the fact that the soil is a biological system and manages it accordingly, it will be able to restore and build soil health while concurrently reducing input costs and maintaining or improving crop yields (Stika, 2013). Additionally, producers have the potential to significantly reduce the negative environmental effects of modern farming practices by managing the soil as a living ecosystem and

* Corresponding author.
*E-mail address:* lhaney@brc.tamus.edu (E.B. Haney).

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enhancing its inherent nutrient cycling ability.

An important initial step in improving soil health is properly assessing the current soil condition. In most current laboratory analyses, soils are treated as non-living, non-integrated systems, and traditional soil testing methods include harsh chemical to extract inorganic N, P, and K and sometimes micronutrients. These chemical extractants (e.g., sulfuric, hydrochloric, nitric, phosphoric, diethylenetriaminepentaacetic, and ethylenediametetraacetic acids) do not occur in nature. Traditional methods also determine soil texture, pH, and total soil organic matter (SOM); however, organic matter provides a gross indication of soil biological function at best. In this paper we introduce a new method to estimate plant available N, P, and K; and provide an indication of soil health focused on nutrient and C cycling. The Soil Health Tool integrates several measurements soil biological and chemical properties utilizing methods designed for commercial soil testing laboratories.

This paper serves as an introduction to the Soil Health Tool developed by USDA Agricultural Research Service (USDA-ARS) scientists in Temple, TX, as the culmination of more than 15 years of soil testing research. The Soil Health Tool analyzes soil nutrient dynamics recognizing soil is a living, highly-integrated, and evolved system. In contrast to soil fertility research and practice in the past, it utilizes an integrated approach that synthesizes both the Newtonian and Darwinian approaches to science, as viewed by physicists and ecologists. As it relates to soil fertility, the Newtonian scientific approach views soil in ever increasing simplistic components that dictate a reliable pattern or law (Harte, 2002); therefore, concentrations of N, P, and K are determined chemically and used to determine a predicted production response. This simplistic “component” view does not account for the biological, or more broadly, ecological nature of the soil. In contrast, the Darwinian scientific approach views each component of a particular habitat or species as ever increasingly complex and seeks to understand the complex interactions. The Soil Health Tool combines both scientific viewpoints in the examination of the chemical and biological sources of soil fertility. In this paper we will: (1) describe the theory and methods behind the Soil Health Tool; and (2) present results of soils under corn, wheat, and soybean production when analyzed with the Soil Health Tool.

## 2. Materials and methods

### 2.1. Sample procurement

More than 21,000 soil samples from throughout the contiguous United States have been analyzed with the Soil Health Tool at the Grassland, Soil and Water Research Laboratory, Temple, TX. Hundreds of thousands samples have been analyzed using the Soil Health Tool by commercial laboratories. The data used in this preliminary analysis are comprised of 432 soil samples obtained from the top 15 cm of the upper soil profile from 26 states collected in 2014 (Table 3). These samples were chosen because they had corresponding yield data on major crops (corn, wheat, soybean) and management information for a variety of practices including cultivated and no-till cropland, pasture land, and land with and without cover crops. Plant available N and P in the soil, fertilizer additions, soil health scores, and crop yields were analyzed for each of these crops. Statistical analyses (linear regression and descriptive statistics) were performed using SigmaPlot 12.0 (Systat Software, Inc.).

### 2.2. Soil C, N, and P analysis

The Soil Health Tool integrates measurements of water extractable organic C; water extractable total N; water and H3A extractable $NO_3$-N, $NH_4$-N, and $PO_4$-P; H3A extractable Al, Fe, Ca, P, and K; and $CO_2$-C evolution after 24 h incubation (Haney et al., 2008a, 2010a) to estimate plant available N, P, and K, and provide an indication of soil health as related to nutrient and C cycling.

Microbial food sources, namely organic N and C, also strongly influence soil microbial activity and nutrient cycling; however, traditional soil tests typically only estimate one form of plant available N ($NO_3$-N and ignore other plant available inorganic and organic forms (e.g., $NH_4$-N). In fact, some laboratories do not test for N, which ignores the fact that soils do contribute inorganic and organic N to plants. The soil organic N pool, which is highly related to the water extractable organic C pool, contains potentially mineralizable N that can be released to the soil in inorganic N forms that are readily plant available (Haney et al., 2008b, 2012).

Traditional tests often use the SOM test and a simple, universal conversion factor to estimate soil C, but the soil C pool is large and mostly inactive, so it provides little information related to soil nutrient cycling. In contrast, water extractable organic C (WEOC) reflects the quality of soil organic C as it provides the energy source for soil microbial activity (Haney et al., 2012). The contrast in soil C forms can be clearly seen with the following example. A soil with 3% SOM when measured with the combustion method and a 0–7.6 cm sampling depth represents a soil C concentration of 20,000 mg C/kg soil. In contrast, water extractable C from the same soil typically ranges from 100 to 500 mg C/kg soil for cropland and 250 to 1000 mg C/kg soil for grassland; therefore, the Soil Health Tool estimates this active pool of soil C. Similarly, the Soil Health Tool uses the water extractable organic C: N (not the total soil C: N) because it is a more sensitive indicator and better respects active soil pools (Haney et al., 2012).

Traditional soil tests typically utilize extractants including Mehlich 3 (Mehlich, 1984) and Olsen (Olsen et al., 1954), which were designed for certain soil pH ranges; however, these extractants are often applied outside their intended pH range because of the benefits of uniform procedures and rapid analysis. This produces inaccurate predictions of plant available P because of the influence of soil pH on soil-solution chemistry (Nelson et al., 1953; Menon et al., 1988) and P solubility (Golterman, 1998; Sharpley, 1993). Thus, the Soil Health Tool uses the H3A extractant (Haney et al., 2006, 2010a), which is composed of weak organic acids that mimic plant root exudates. H3A has been shown to closely match results from the “gold standard” plant available P test that uses FeAlO strip results (Haney et al., 2016).

Each soil sample was dried at 50 °C (Haney et al., 2004), ground to pass a 2-mm sieve, and weighed into two 50-ml centrifuge tubes (4 g each). One 4-g sample was extracted with 40 ml of DI water, and the other was extracted with H3A (Haney et al., 2006, 2010a). The water and H3A extracts were analyzed on a Seal Analytical rapid flow analyzer (RFA) for $NO_3$-N, $PO_4$-P, and $NH_4$-N. The water extract was also analyzed on a Teledyne-Tekmar Apollo 9000C:N analyzer for water extractable organic C and total water extractable N (WEN). The H3A extract was also analyzed on a Varian ICP for Ca, Fe, Al, P, and K.

### 2.3. $CO_2$ respiration

Soil research utilized steady state conditions for estimating soil microbial activity (i.e., constant temperature, oxygen, and water content). This was an understandable initial approach for the laboratory; however, the drying/rewetting cycle that occurs with rainfall and irrigation events creates a highly dynamic, microbial-driven nutrient cycling mechanism in nature and agricultural fields (Haney and Haney, 2010). Thus the Soil Health Tool utilizes the natural drying-rewetting cycle in the soil in its estimates of soil microbial activity and plant available N and P.

Almost 100 years ago, researchers recognized that $CO_2$ respiration is an indicator of soil fertility (Gainey, 1919; Lebedjantzev, 1924; Birch, 1960). The microbial biomass plays the leading role in organic matter decomposition and nutrient cycling and is highly related to active pools of potential C and N mineralization (Franzluebbers et al., 1999, 2000). The microbial population oxidizes organic compounds from SOM and generates $CO_2$. This release of $CO_2$ is coupled with energy production,