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Soil health – What should the doctor order?

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Abstract

The concept of soil health has been extensively reviewed in the scientific literature, but there is only patchy and inconsistent information available to farmers and growers who are concerned about the declining condition of their soils and are looking for appropriate test methods and management interventions to help reverse it. Although there are well-established laboratory methods for soil chemical analysis, and a range of laboratory and field methods for measuring soil physical properties, only now are methods starting to emerge for soil biological analysis. This study provides an overview of the methods that are currently available commercially (or are close to commercialization) for farmers and growers in the UK. We examine the science underpinning the methods, the value of the information provided and how farmers and advisors can use results from such assessments for informed decision-making in relation to soil management.

Keywords: soil health, soil pH, soil nutrients, soil organic matter, soil structure, soil biology

Introduction

Healthy soil is fundamental to the sustainability and profitability of agriculture and horticulture worldwide (Jones *et al*., 2012; FAO & ITPS, 2015). The scientific basis underlying the concept of soil health has been thoroughly reviewed in the USA (Doran *et al*., 1996) and in the UK (Kibblewhite *et al*., 2008) with broad agreement on what is meant by the term 'soil health', but no clear direction in terms of what to measure. Whilst Doran *et al*. (1996) are prepared to use the terms 'soil quality' and 'soil health' synonymously, they state a preference for 'soil health' as it conveys the idea of soil as a living system and with it come useful analogies with human health (e.g. soil respiration and breathing). From our own experience, based on the delivery of knowledge exchange activities over the past decade, the concept of soil health has traction with those who work the land. Although there are well-established methods available to farmers and growers for analysis and interpretation of soil chemical analysis (e.g. Defra, 2010) several new methods for testing soils are now being offered to farmers and growers that broaden the range of properties being evaluated, such as electromagnetic induction techniques (Doolittle & Brevik, 2014), and include those, for example, soil respiration (Haney *et al*., 2008) that address biological aspects.

Our aim in this paper was to provide an overview of the methods for assessing soil health that are currently available commercially (or are close to commercialization) for farmers and growers in the UK. We explore the science underpinning the methods, the value of the information provided and how the methods can inform decision-making by farmers and advisors in relation to soil management.

Soil health – interdisciplinary soil science into practice

There is no doubt that many farmers and growers in the UK are concerned about the current health of their soils (compared with say 30 or 40 years ago), and some of these concerns are supported by soil analysis data collected over the same period, for example, a general decline in soil organic matter (Webb *et al*., 2001; Bellamy *et al*., 2005). So how do farmers and growers currently acquire information on the health of their soils? They will have an idea of the texture of the soil in each part of a field (e.g. light sand, heavy clay, silt) and how easily the soil is cultivated (e.g. during ploughing and seedbed formation), how rain and irrigation infiltrates the soil (water-logging and runoff indicating potential soil structural problems) and where weed problems are most severe. Every three or 4 years they receive the results of soil analysis for a field, normally pH, phosphorus (P), potassium (K), magnesium (Mg) together

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with estimated requirements for fertiliser use (provided by a commercial soil analysis laboratory), and they take note of crop yield and quality. They may also note the number of earthworms in the soil during cultivation either directly, or by the number of seagulls following cultivation equipment as it makes its way across a field.

This combination of standardized laboratory chemical analysis together with informal observation of soil physical and biological properties provides a general indication of soil health. Our view is that if test methods are going to provide useful information on soil health then the methods should be universally applicable to all farming systems, they should be quantitative and relatively simple and, of course, cheap to use. What about organic farming systems? Although the management of soil fertility in organic farming systems is distinctly different from that in other farming systems, there is no evidence that the processes involved in nutrient cycling in soil managed according to the principles of organic farming differ fundamentally from soil managed under conventional farming systems (Stockdale *et al*., 2002); therefore, methods for assessing soil health should be equally applicable to organic and to conventional production systems.

It is clear in general terms that the continued ability of soils to support agricultural and horticultural production depends upon the integrated and balanced interaction of physical, chemical and biological properties and functions of soil. This contrasts to the approach widely taken around the world over the past 70 years or so in which the soil has been viewed largely as a physical medium to support the plant via its roots and provide a platform to absorb, to a greater or lesser extent, chemical fertilisers and pesticides. Selman Waksman commented on this almost 100 years ago (Waksman & Starkey, 1924):

> A soil composed of little else than quartz sand with available elements essential to plant growth may support plants temporarily and still lack any abundant microbial flora. In such cases the microbiological activities .... may be better considered as forecasting the future possibilities of the soils. .... an abundant microbial life may better be considered to indicate that the soil has been built up to a state of fertility which is more permanent than when the microbial activity is considerably less.

By introducing the concept of biological activity (Waksman, for example, proposed soil respiration as a useful measurement) alongside soil chemical analysis the idea of soil health takes onboard the concept of sustainable soil fertility in contrast to short-term soil fertility. This chimes with the old adage that as a farmer you should leave the land in a far better condition than you found it (Henderson, 1943).

In the light of all this it seems reasonable to assume that an assessment of soil health should include elements of the three major scientific disciplines of chemistry, biology and physics; in fact, just what soil science should be doing (Wild, 1989). But although we understand a good deal of the scientific principles underpinning the properties and functioning of soils, we have not been able to come up with a definitive set of measurements that allow us to claim with confidence 'this is how to measure the health of soil'. This uncertainty is compounded by the lack of agreement over methods to be adopted in carrying out well-established standard soil tests (e.g. Jordan-Meille *et al*., 2012).

Soil analysis for soil health assessment – rationale and standard soil tests

To be of value to farmers and growers, methods for assessing soil health should not only measure something, but should also provide information that can be used to form the basis on which recommendations can be made for management interventions. This can be broken down into three parts:

1. A quantitative method to analyse soil that is universal to all soil types;
2. A method for categorizing the results of the analysis such that a management action may be assigned to each category;
3. A soil management scheme with distinct actions attributed to each category.

A further requirement of a soil analysis method is that the result should relate to the area of land being sampled (a field for example); this normally involves taking a number of subsamples (around 25) systematically from the field (avoiding unrepresentative areas), bulking and mixing the subsamples and then taking a subsample of an appropriate size suitable for analysis (Defra, 2010). More intensive sampling and analysis may be employed, for example, to quantify the spatial relationships between subsample values (Frogbrook & Oliver, 2001) for the purposes of precision management of soil nutrients (Oliver, 2013).

Soil pH can be considered to be a 'master variable', that is a parameter with influence on a range of other soil properties such as nutrient availability (Rowell, 1994) and microbial populations (Wood, 1995). Soil pH can be measured, and on the basis of the result a recommendation can be made for the amount of lime that should be applied to neutralize the acidity indicated by the pH value of the soil sample. For field crops, the measurement is not an end in itself but a call for action, in this case the application of lime (Rowell, 1994). However, there is no universal method of measurement for pH. In England and Wales, pH is normally measured in a suspension of soil and water (Defra, 2010), whereas in Scotland a suspension of soil and 0.01 M $CaCl_2$ is used, and to compare results with values obtained in water 0.6 are added to the value obtained in $CaCl_2$ (Edwards *et al*., 2016).

The principle of soil analysis linked to soil management practices is illustrated by the methodology used for managing soil P. This can be considered in terms of three steps: (i) measurement of the available P in soil, (ii) interpretation of the results of this measurement in terms of the sufficiency of P availability in soil for the crop(s) to be grown, (iii) estimation of a recommended application of P as inorganic or organic fertiliser (Jordan-Meille *et al*., 2012). Once again there is no universal method of measurement: in England, Wales and Northern Ireland the Olsen P method is used (Johnston *et al*., 2013), whereas in Scotland the Modified Morgans method is used (Edwards *et al*., 2016), largely because of differences in the levels of calcium ions in the soils that were derived from basic or acidic rocks. There is an even greater diversity in methods used across continental Europe (Jordan-Meille *et al*., 2012) prompting these authors to conclude that '...the chemical methods in common use and their utilization in global P fertilizer strategies have a poor theoretical background and are lacking any scientific rationale'.

In the UK, there is scientific evidence to support the schemes used to manage soil P, although up until recently neither system has taken into account the sorption of P to soil surfaces and how this might influence the response by crops to P fertiliser in any particular soil. The latest recommendations for Scotland (Sinclair *et al*., 2015) now include consideration of the capacity of soil to adsorb P by linking in to farm-level soil information.

In England, Wales and Northern Ireland the results of the Olsen P test method are grouped into nine categories (soil index values), although for managing P requirements the 9 are reduced to 5 categories (0, 1, 2, 3, ≥4) (Defra, 2010). The general P management recommendation for arable crops and grassland, based on these categories, is to maintain soil P at a target index of 2, which relates to a range of Olsen P values from 16 to 25 mg/L (Johnston *et al*., 2013).

A recent analysis of historical data for two experimental sites in Suffolk and Hertfordshire, England by Johnston *et al*. (2013) indicates that for winter wheat, for example, grown from 1978 to 1986 on a sandy clay loam soil the critical values of Olsen P which minimize the likelihood of yield reductions due to limitations in the supply of available P varied from 6 to 33 mg/kg. Assuming a bulk density for the soil when prepared for analysis of 1 g/cm^3 (Rowell, 1994) this is equivalent to a range of P index values from 0 to 3. So even with what appears to be a sophisticated soil management intervention scheme based on measurement of Olsen P and an associated P index, there is a good deal of uncertainty in being able to predict responses to P fertiliser for a specific crop growing in a particular soil.

One thing that is clear, however, is that if soil is in good physical condition allowing better root growth and exploration of the soil then there will be a better chance of ensuring that a crop will not be limited in its growth by supply of a major nutrient such as P (Johnston, 1986). Furthermore, as described later, empirical relationships exist between soil physical properties, such as aggregate stability and the organic matter content of a soil (Greenland *et al*., 1975).

An alternative interpretation of soil chemical analysis has emerged from the ideas of US soil scientist William Albrecht who, late in his career, became interested in the nutrition of plants and animals based on ratios of exchangeable cations (Marshall, 1977). The concept of ideal ratios of nutrients such as Ca and Mg in soil has been around for over 100 years, but the evidence directly relating specific cation ratios to crop productivity are inconsistent (Kopittke & Menzies, 2007; Johnston, 2011). In the 1940s, scientists (e.g. Bear & Toth, 1948) defined what they considered the ideal soil in terms of the balance of exchangeable Ca, Mg, K and H ions. This notion, which emphasized the importance of the ratio of cationic nutrients rather than the total amounts present, was formalized as the 'Base Cation Saturation Ratio System' and became associated with the name of Albrecht (Kopittke & Menzies, 2007).

However, the evidence from research is that plants thrive over a range of cation ratios, providing the amounts of K, Ca and Mg supplied by the soil are sufficient (Johnston, 2011). There is no evidence that the balance between cations has any significant impact on soil biology such as earthworm activity or on weeds (Kopittke & Menzies, 2007). Standard soil tests for cations in the UK measure the exchangeable K and Mg and express this as a Soil Index (England and Wales) or Soil Status (Scotland). There are some specific situations where the ratios of cations are important: for example The Fertiliser Manual (RB209) (Defra, 2010) highlights the importance of K:Mg ratios in fruit, vines and hops (the recommendation is that the ratio of exchangeable K to exchangeable Mg should not be >3:1 to avoid the risk of Mg deficiency).

Soil organic matter and architecture – the foundation of soil health

Soil organic matter is a key factor in determining soil health (Johnston, 1986), and there are several different approaches towards measuring the amount of organic matter in soil; for example, by the stoichiometric loss of carbon during wet oxidation or the weight loss following combustion of a soil sample at 500 °C (loss-on-ignition). Frogbrook & Oliver (2001) intensively sampled soil from two arable fields, a clay loam soil and a sandy loam soil (160 and 100 samples, respectively, at 20 m grid spacing) and analysed them for organic matter using these two methods. Values for organic carbon (C) were converted to organic matter using the standard multiplier of 1.74. The mean vales for organic matter (expressed as percentage by mass in air-dry soil) in the clay loam soil were 2.7% and 4.5% when measured by wet oxidation and loss-on-ignition, respectively, and the corresponding values for the sandy loam soil were 2.6% and 4.0%, respectively. The loss-on-ignition method gave higher values than the wet oxidation method for all soil samples, as reported by Ball (1964), but there were consistent relationships between the two sets of measurements, although these relationships were different for the two soil types. Weight-loss-on-ignition is the preferred standard laboratory test method because it is simple, rapid and cheap to use. However, these data indicate that caution should be exercised in using this method to obtain absolute measures of soil organic matter content. It may be better used for monitoring relative changes in soil organic matter content following management practices applied over several years.

Soil organic matter analysis can be taken a stage further by separating it into a number of different fractions based on size and density of the individual particles. Particles of low density (<1.7 g/cm^3, termed the 'light fraction') include the physical remains of plants and animals, root fragments and fungal hyphae (Diochon *et al.*, 2016). Both the light fraction and the sand-size fraction of organic matter are decomposed relatively rapidly, and therefore offer a potentially useful method for measuring the labile pool of organic matter. Analysis of light fraction organic C and N has been shown to clearly differentiate land under contrasting agricultural management when compared with a range of other biochemical and microbial indicators of soil health (Bending *et al.*, 2004).

Concern about the deteriorating structure of UK soils in the late 1960s prompted a government review of the structural problems of different soil types across the country (Strutt, 1970). The nature of good soil structure and what might be considered to be the ideal architecture of soil has been succinctly described by Tisdall & Oades (1982): 'Good structure for crop growth depends on the presence of aggregates of soil particles 1–10 mm diameter which remain stable when wetted. Such water-stable aggregates should be porous (pores > 75 μm diameter) so that they remain aerobic, and yet possess sufficient numbers of pores 30–0.2 μm diameter to retain water for the growth of plants. The pores between the aggregates should be large enough to allow rapid infiltration and drainage of water'.

Measurement of the stability of aggregates (based on their resistance to slaking and dispersion when immersed in water) from 180 locations in England and Wales by Greenland *et al.* (1975) indicted a general critical level of soil organic matter, corresponding to 2% organic C, below which soils were liable to structural deterioration. However, Loveland & Webb (2003) were unable to find further evidence to support this critical value more widely for agricultural soils of temperate regions. Target values for soil organic matter in different soil types remain elusive.

Assessing soil structural problems in the field

Soil compaction is associated with weak soil structure together with heavy traffic movements across a field (Batey, 2009) and may be manifested, for example, by localized surface water. It is a major challenge for soils in modern farming systems. Whereas soil cores will provide an indication of the problem, the direct symptoms of compaction are best observed *in situ* following the excavation of a soil pit, and include increased soil bulk density and decreased porosity, leading to localized water-logging and associated anoxia (Batey & McKenzie, 2006). If compaction is observed then a variety of mechanical interventions may be used, depending on the nature of the problem, for example, the depth of the compacted layer (Spoor, 2006).

To provide a semi-quantitative estimate of the extent of structural problems, a number of schemes have been developed as follows: the Landcare visual soil assessment (VSA) includes soil structure, colour, porosity and earthworm count; the Peerlkamp method is based on an estimate of visual porosity and distribution throughout the soil profile (Newell-Price *et al.*, 2013). Newell-Price *et al.* (2013) compared these visual soil assessment methods with laboratory measurements such as bulk density, and shear strength for 300 grassland soils on 150 farms in England and Wales. Larger VSA scores were associated with greater soil organic matter content and with greater sand content, but there were weak relationships with shear strength and bulk density. The advantage of this approach is the possibility of describing the overall structural condition of a block of soil by using a relatively simple scoring system. However, there remains a place for other measurements such as rate of water infiltration (Evanylo & McGuinn, 2009), which can also provide a visually engaging demonstration of structural problems.

Assessing the biological component of soil health

Deep-burrowing (anecic) earthworms such as *Lumbricus terrestris* play an important role in soil health, creating large channels (macropores) which allow rapid transport of air and water through the soil profile (Stroud *et al.*, 2016). The population of these earthworms is strongly influenced by soil cultivation; for example, ploughing causes a significant decrease compared with reduced tillage (Edwards & Lofty, 1982; Chan, 2001). Stroud *et al.* (2016) have shown that surface-applied straw can significantly increase the population of *L. terrestris* as measured by midden (cast) counts, which were validated by extraction of worms using mustard. Earthworm counts, when used as part of a visual soil assessment, can provide useful information therefore and can indicate the need for specific management interventions.

Progress has been made in the use of respiration as a tool to measure soil biological activity both in the laboratory (Haney *et al*., 2008) using sophisticated and simple methods for measuring CO_2 evolution from soil samples and in the field (Liebig *et al*., 1996). The flush of CO_2 from a soil sample that has been dried and re-wetted is associated with a flush in mineralization of N and P (Birch, 1958). Standardization of this procedure together with the availability of simple and cheap tools to measure carbon dioxide offers the prospect of readily quantifying the potential supply of N and P to crops from the labile pool of soil organic matter (Haney *et al*., 2008). Furthermore, the flush of CO_2 from soil following drying and re-wetting provides an estimate of the soil microbial biomass (Jenkinson & Powlson, 1976; Powlson & Jenkinson, 1976), and this has been shown to be a more sensitive predictor of changes in soil organic matter than is a direct determination (Powlson *et al*., 1987). More recently, using the techniques of molecular biology, Placella *et al*. (2012) have shown that this flush of CO_2 and N mineralization is associated with the rapid and sequential revival of distinct, phylogenetically clustered groups of microorganisms over a range of timescales (minutes, hours, days).

In the USA, to assist with the assessment of soil health, a set of indicators comprising measurements of chemical, biological and physical properties of soil together with information sheets has been developed (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/health/assessment/?cid=stelprdb1237387; accessed 21/11/16). Some of the measurements are suitable for use in the field, for example, soil pH, earthworm count, water infiltration rate and soil respiration rate. These tests, when used as a field test kit, compared well with standard laboratory methods (Liebig *et al*., 1996) and identified differences between soil management treatments (mineral fertiliser, farmyard manure, incorporated cover crop) (Evanylo & McGuinn, 2009). Results from the soil respiration measurements were grouped into categories, which were linked to management interventions. One laboratory in the UK is now using soil respiration measurements as part of a soil health analytical package (http://www.nrm.uk.com/services.php?service=soil-health; accessed 21/11/16).

Another approach to assessing the biological component of soil is based on detailed studies carried out originally on prairie soils in the USA (Hunt *et al*., 1987). In addition to providing fundamental ecological knowledge on the types of organisms involved in nutrient cycling and the ways in which these organisms interact (a soil-food-web), the information has prompted the introduction of soil analysis services to quantify selected key functional groups of organisms (http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/biology/?cid=nrcs142p2_053865; accessed 21/11/16). These groups of organisms clearly play important roles in the functioning of soil (Wood, 1991), but we lack an understanding of all the factors that control the complex biological communities found in soil at different spatial and temporal scales (Bardgett & van der Putten, 2014). Without this information appropriate management interventions cannot be implemented.

Alongside well-established techniques for measuring the abundance, diversity and activity of soil microorganisms, techniques based on molecular biology, for example, DNA fingerprinting, are now being used to estimate the structure of microbial communities (Philippot *et al*., 2012). However, the apparent microbial diversity measured using any nucleic acid analysis procedure is highly dependent on the method used to extract DNA from soil (Delmont *et al*., 2011). Although this approach shows much promise in terms of improving our understanding of soil biology, it does not yet provide information that can form the basis of soil management decisions.

A role for field-scale, remotely sensed information

Progress has been made in the use of electromagnetic induction (EMI) for taking ground-level measurements to better understand the spatial variability of soils and soil properties at the field scale. EMI is easy to use, rapid, relatively low-cost and generates a large volume of data that can be particularly useful when linked to information gained simultaneously from global-positioning systems (GPS) (Doolittle & Brevik, 2014). EMI sensors measure changes in the apparent electrical conductivity (EC_a) of the land subsurface without direct contact with the soil. EC_a is increased by increases in soluble salt content, water content, clay content and temperature (Doolittle & Brevik, 2014), and provides an average conductivity measurement of a column of soil to a specific depth. The EM38 meter, the most widely used EMI meter in agriculture, has a depth of investigation of either 0.75 m (horizontal dipole orientation) or 1.5 m depth (vertical dipole orientation). Interpretation of results tends to be site-specific and is not always straightforward, with complex interactions between soil properties sometimes leading to ambiguous or inconsistent results. However, for example in soils that have low salt contents, EC_a is strongly influenced by variations in clay and moisture content, the former a constant soil variable, the latter a fluctuating variable. Although not a replacement for traditional soil analysis techniques, when combined with in-field sampling and measurement, the combination of approaches offers significant possibilities for characterizing soils at the field-scale (Doolittle & Brevik, 2014).

Increasingly farmers and growers are accessing Google Maps to gain information on the variability in crop and soil across a field. It is easy to use, universally available and free at the point of use, but could be made into a richer user experience if linked with other sources of information, such as soil survey databases. A Soil-Web application has been developed in the USA as a web-app and an iPhone app; these provide a simple and rapid means of accessing soils information for a wide range of potential users (Beaudette & O'Geen, 2009, 2010). Similar schemes are starting to emerge in England and Scotland.

Future developments

From our experience based on knowledge exchange activities in England, Scotland and Wales, the concept of soil health captures the interest of farmers and advisors, whereas soil quality is a less engaging concept. The indications in 2016 were that programmes for the assessment and improvement of soil health were high on the political agenda. In June 2016, the UK Government's Environmental Audit Committee published a report on Soil Health (http://www.parliament.uk/business/committees/committees-a-z/commons-select/environmental-audit-committee/news-parliament-2015/soil-health-report-published-16-17/; accessed 30/1/17), which called for a new national approach to monitor soil health in the UK, and described the current rules regulating soil health linked to farm subsidy payments as 'too weak, too loosely enforced'. In December 2016 in the USA, the Obama Administration announced a series of actions to promote the long-term health and sustainable use of soil (https://obamawhitehouse.archives.gov/blog/2016/12/05/obama-administration-announces-new-steps-maintain-and-create-healthy-soils; accessed 30/1/17). One action, for example, involved the improvement of soil health practices on leased or rented agricultural land, something which is a challenge in the USA and the UK. Political agendas have subsequently changed dramatically; however, we believe that the soil health paradigm will continue to exert traction with farmers and advisors and will provide a useful framework within which soil scientists around the world can support the sustainable management of our most undervalued natural resource.

Conclusions

This overview of approaches to the assessment of properties that contribute to the overall health of soil has indicated a range of methods; some limited to the laboratory, some suitable for field use, each of which provides some useful information, but none of them, even the most sophisticated, without uncertainty. No single method can provide adequate information on which to base an assessment of soil health; therefore, a combination of approaches is most appropriate. Where possible, these should include field-based assessments, although not to the exclusion of laboratory analysis. It is essential that any measurement made can be linked to practical soil management interventions to be of value to farmers and growers.

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