A REVIEW OF SOIL HEALTH INDICATORS FOR LABORATORY USE IN THE SOUTH AFRICAN SUGAR INDUSTRY

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Abstract

To assess the health of a soil requires analysis of a short list of parameters to be quantified, with the cost and practicality of the assessment kept in mind. The aim of this paper is to assess soil parameters for possible inclusion within a reliable, yet user-friendly soil health assessment package. Soil chemical, physical and biological parameters were discussed, and the effect of common agricultural practices on soil health considered. Other areas covered include threshold values and the minimum number of soil health indicators. A short list of soil health indicators for use in the South African sugar industry was suggested.

Keywords: soil health, soil quality, chemical indicators, physical indicators, biological indicators, review

Introduction

South African sugarcane growers are generally aware of the importance of soil sustainability. Although they often optimise yields using appropriate management strategies and targeted applications of inputs, they probably require guidance on assessing the condition of soils on their farms. To achieve this, an evaluation framework is needed to identify problematic or potentially problematic soil production areas within their farming enterprises (Doran *et al*, 1998). Ideally, this package should include an index of soil quality or health (Nielsen and Winding, 2002) and cover soil chemical, physical and biological properties (Haynes and Graham, 2004).

'Soil health' and 'soil quality' are terms frequently used in the literature. They are often used synonymously without a clear distinction between them (Doran *et al*, 1996). Soil quality was defined by Doran and Parkin (1994) as, "The capacity of soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health." Doran and Safley (1997) suggested that soil health be defined as, "The continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health." For the purpose of this paper, 'soil health' will be regarded as the condition of the soil at the time of sampling. This would be analogous to the health of a patient as assessed by a medical doctor at a particular time. 'Soil quality' on the other hand, will be regarded as the condition of a soil reflecting management style and climatic conditions over an extended period of time. This could be compared with the quality of life of a patient as influenced by diet and activity. In terms of wider assessment of the condition of soils, both quality and health of soils is needed to determine agricultural sustainability (Acton and Gregorich, 1995).

The concept of soil quality and its usefulness to the sugar industry was discussed by Haynes (1997), who suggested that microbial biomass C, soil respiratory rate, soil enzyme activity and earthworm population should be included as biological indicators of soil quality. In a synthesis of world literature, Haynes and Hamilton (1999) listed the following as a result of continuous monoculture with sugarcane:

- loss of organic matter especially under a system of burning at harvest
- soil acidification mainly due to the use of nitrogenous fertilisers under dryland conditions
- lowering of K due to large amounts removed by the cane crop
- soil salinisation and sodification in low rainfall areas
- interrow soil compaction.

Although a comprehensive assessment of soil health should include a range of soil chemical, physical and biological parameters, determined in the laboratory and in-field, the processes and sampling requirements are labour intensive and possibly not achievable within a routine soil sample submission programme.

The aim of this paper is to assess soil parameters for possible inclusion within a reliable, yet user-friendly soil health assessment package. A range of soil chemical, physical and biological properties for possible inclusion in the package will be considered. In terms of biological parameters the emphasis will be on activity as apposed to biological diversity, species and analyses, which are discussed in a companion paper (van Antwerpen *et al*, 2005). The effects of common agricultural practices on soil health, methods of selecting the minimum combination of soil health indicators and critical or threshold values, will also be discussed.

Soil chemical properties

Soil testing for nutrient advisory purposes usually includes a range of discrete analyses that could be considered for soil health assessment purposes. In particular, soil samples submitted to the South African Sugarcane Research Institute (SASRI) fertiliser advisory service (FAS) laboratory are routinely analysed for a relatively large number of chemical and some physical properties (Meyer *et al*, 1989).

The current list of routine measurements included in the FAS package are pH (water), P (Truog), Zn, K, Ca, Mg, Na, S, Al (only if pH_{water} is <5.3) and total N (Meyer *et al*, 1989), titratable acidity (Thomas, 1982), cation exchange capacity (sum of titratable acidity and NH_4OAc extractable K, Ca, Mg and Na), acid saturation (titratable acidity/cation exchange capacity x 100) and organic matter (Walkley and Black, 1934).

Soil acidification is a problem in the South African (Schroeder *et al*, 1994; van Antwerpen and Meyer, 1996) and Australian (Noble *et al*, 1997) sugar industries. Noble *et al*. (1997) and Sumner (2000) have shown that pH is a sensitive indicator of soil acidity. Doran *et al*. (1996), Milton *et al*. (2002) and Haynes and Graham (2004) included pH in their lists as a soil health indicator.

Arguably, the most important parameter within any set of soil analyses for assessing soil health is organic matter or organic carbon (Gregorich *et al*, 1994; van Antwerpen and Meyer, 1996; Magdoff, 2001; Milton *et al*, 2002). It is generally recognised as an essential soil constituent for maintaining the chemical, physical and biological status of soils (Brady, 1974; Haynes and Graham, 2004). Soil organic C can be roughly divided into an active (labile, fresh) and an inactive (non-labile) pool. Active C constitutes only a small fraction of total soil C, but it is considered more sensitive than the inactive C to changes in management and land use (Milton *et al*, 2002; Haynes and Graham, 2004). Associated with the soil C is microbial biomass, which responds the most rapidly to changes in management (Haynes and Graham, 2004). As a measure of soil quality, microbial biomass is regarded as a sensitive indicator of changes in soil organic matter content (Dalal, 1998).

The active C is additionally the preferred food source for various life forms in soil, and correlates well with soil health variables such as aggregate stability, soil water infiltration rate and effective cation exchange capacity (Weil *et al*, 2003), organic N mineralisation (Wood, 1965), microbial C, N and P (Srivastava, 1992) and phosphatase activity (Jordan *et al*, 1995). The Walkley-Black (1934) method is widely used in laboratories to quantify the active C fraction and numerous modifications (Hutton and Simonson, 1942; Richardson and Bigler, 1982; Grewal *et al,* 1991; Blair *et al*, 1995; Nelson and Sommers, 1996; Islam and Weil, 1998; Weil *et al*, 2003) have been proposed for a number of reasons. One of the latest modifications is that by Weil *et al.* (2003) who suggested using 0.02 *M* $KMnO_4$ adjusted to a pH of 7.2 as the oxidising agent to quantify active C in soils. The authors claim that their suggested method is more sensitive to management-induced soil changes, and allows the investigator to detect these changes consistently. They claim that it is also more closely related to biologically mediated soil properties than other measures of soil C, such as total soil organic C and C oxidisable by the 0.333 *M* $KMnO_4$ method of Blair *et al.* (1995).

Soil physical properties

Although a substantial list of soil physical parameters (such as dispersion, linear shrinkage, modal breaking strength, penetration resistance, and various levels of water holding capacity) can be compiled, only those that in the literature are considered to be important to soil health and those that are less time consuming in measurement, will be considered here.

On collecting samples for soil health assessment, depth of the soil should be considered, as it is an indicator of the soil's productivity potential (Doran *et al*, 1996). In shallow soils, root penetration is restricted and water and nutrient reserve capacities are limited. Water drainage is also reduced, and soil erosion is often a problem (Doran *et al*, 1996).

One of the indicators showing little or no change with soil quality (and health) is soil texture (Dang *et al*, 2002). However, soil texture needs to be determined, as it is an important basic soil property used to describe soils. Good relationships exist between soil texture and parameters affecting soil health, such as porosity, aeration and water and nutrient retention (Dang *et al*, 2002).

Bulk density measurement reflects the history of management practices, and affects numerous physical, chemical and biological properties of soils (Carter, 1985). Shukla *et al.* (2004) identified bulk density as the second most important soil quality property for the rehabilitation of overburden associated with mining activities in south eastern Ohio.

Aggregate stability is regarded as one of the most sensitive physical measurements of soil quality (and health). This was recently confirmed by Shukla *et al.* (2004) who found that it was the dominant parameter used for determining the condition of rehabilitated mine dumps. Seybold *et al.* (2002) reported that an on-farm aggregate stability test was useful in highlighting differences in soil condition as influenced by the use of a cover crop versus a bare fallow. It therefore shows potential for use in determining changes in soil quality.

Biological properties

Soil biological diversity, species and methods of analysis have been discussed in a companion paper (van Antwerpen *et al*, 2005) and only trends associated with biological activity will be discussed here. Forms of biological life in soils include bacteria, fungi, protozoa, nematodes and earthworms (Haynes and Graham, 2004). Enzymes are important mediators in numerous soil processes, and are protein catalysts produced mainly by microorganisms, roots and soil fauna. Jordan *et al*. (1995) found that enzymatic activity was highly correlated to soil organic matter and was a potential soil health indicator (Lui *et al*, 2002). Two factors characterising the ability of soil microbes to decompose organic substances are dehydrogenase activity and soil respiration activity (Tesarová *et al*, 1998). Neher (2001) suggested that the composition of nematode communities might be used as bioindicators of soil health, because their composition correlates well with nitrogen cycling and decomposition, two critical ecological processes in soil.

Factors affecting microbial values are the presence of soil organic matter (Costantini and Segat, 1994), soil type and geographic region (Brejda *et al*, 2000), soil temperature (Alvarez *et al*, 1995), season of the year (Díaz-Raviña *et al*, 1995), soil water content (Acea and Carballas, 1990, reported by Díaz-Raviña *et al*, 1995) and various nutrients (Díaz-Raviña *et al*, 1995).

Alvarez *et al*. (1995) in Argentina collected samples to a depth of 0-100 mm from a soil containing 20% clay, 66% silt and 2.15% organic C, and found a highly correlated (r^2=0.90) inverse power relationship between microbial C and soil temperature. Thus, microbial C values are higher in winter than in summer. However, metabolic quotient (*in situ* respiration/ microbial C ratio) increased exponentially (r^2=0.89) with an increase in soil temperature, due to higher maintenance energy requirement at higher temperatures. A weaker but still meaningful linear relationship between microbial biomass C and soil water content was obtained when the data of Alvarez *et al*. (1995) was recalculated (r^2=0.49). The reason is best explained by the fact that all samples were reportedly collected from wet soils (Alvarez *et al*, 1995).

In Spain, Díaz-Raviña *et al*. (1995) found the highest microbial biomass in winter and spring (787 to 880 ug C/g soil) and the lowest in summer and autumn (589 to 560 ug C/g soil) despite the fact that the highest temperature is reached in summer (July to August) and the lowest in winter (December to February). However, seasonal variability was largely explained by soil type (71%; sampling depth 150 mm) and time of year (18%). Acea and Carballas (1990), according to Díaz-Raviña *et al*. (1995), suggested that lack of water rather than temperature limits microbial biomass, since lower rainfall and lower microbe numbers were observed in summer than in winter. Rainfall distribution for the sample area was 38, 28, 24 and 10% for winter, spring, autumn and summer respectively. The relatively high level of microbial biomass in spring may have been due to a sudden increase in available substrate derived from roots, which favoured the proliferation of microorganisms. The increase in microbial biomass in winter may have been due to a larger proportion of fungi, which are particularly favoured by high humidity.

Microbial activity follows the trend of organic matter in being highest near the soil surface, and decreasing with depth (Kaiser and Heinemeyer, 1993; Haynes and Graham, 2004). The depth of sampling, however, should not be restricted to the surface, as assessing the health of soils should represent the most practical and active depth. Depending on the objectives of the project, sampling depths reported in literature are 100 mm (Alvarez *et al*, 1995; Jordan *et al*, 1995; Wander *et al*, 1994), 150 mm (Díaz-Raviña *et al*, 1995; Nicolardot *et al*, 1994), 200mm (Costantini and Segat, 1994; Houot and Chaussod, 1995; Lui *et al*, 2002), 300 mm (Kaiser and Heinemeyer, 1993) and 400 mm (Dang *et al*, 2002). This implies that the objectives of a project should be taken into account when deciding on the depth of sampling.

The effect of common agricultural practices on soil health

One of the most common and routine management practices used in agriculture is the application of nutrients using inorganic fertilisers. van Antwerpen and Meyer (1998) showed that the use of inorganic fertiliser without the return of organic matter resulted in some degree of dispersion (mainly due to K) of the profile to a depth of at least 500 mm, compared with where no fertiliser had been applied. The addition of organic matter (cane trash) was effective to counter this dispersion from the use of inorganic fertiliser to a depth of 100 mm on a vertisol. The least amount of dispersion was found where no inorganic fertiliser was used and all residual organic matter (cane trash) was retained. Similar results were reported for soil aggregate stability and penetration resistance by van Antwerpen and Meyer (1998). This trend was confirmed for other soils in the South African sugar industry (van Antwerpen *et al*, 2003).

Graham *et al*. (2001, 2002) found that the microbial community was significantly enhanced where organic matter (cane trash) was retained on a conventionally fertilised field. Houot and Chaussod (1995) showed that microbial biomass was correlated with total organic C in soil and decreased with soil treatments in the order of farmyard manure > mineral NPK > unfertilised control.

Another common agriculture activity is in-field vehicle movement. This includes seedbed preparation, planting, fertilisation, spraying and harvesting. In-field traffic unavoidably leads to soil compaction and therefore reduced hydraulic conductivity and nitrogen availability (Rahman *et al*., 1999), reduced pore volume and increased soil strength (Hill and Meza-Montalvo, 1990) and reduced cane growth and yield (Meyer *et al*., 1996). Dick *et al*. (1988) reported that compaction had a negative effect on soil microbial enzyme activity, biomass C, organic C and total N. Carter (1985) studied the effects where no wheels were allowed within 750 mm of the crop row. Results indicated that this led to increased water infiltration on the row, increased volume of soil available for root exploitation, increased rooting density, and reduced tillage energy required. Pathogenic fungal populations were altered and yields increased in two years out of four. The history of a field must therefore be considered where a soil health assessment is needed.

Indicators of soil health

An important debate in the literature is the selection of soil parameters as indicators of soil health. Many soil parameters may be used as indicators of terrestrial health, but would be very costly. The challenge is to find the minimum combination of parameters that will reveal a comprehensive view of the soil's condition. Lists of parameters have been suggested by Doran *et al*. (1996), Kurakov *et al*. (1998), Santana *et al*. (1998), Nielsen and Winding (2002), Milton *et al*. (2002), Morón and Sawchik, (2002) and Haynes and Graham (2004).

Consideration should be given to understanding what a healthy soil really is and how it will be recognised. Magdoff (2001) listed the following ten characteristics to be expected from high quality soils:

1. a sufficient, but not excess, supply of nutrients
2. good structure (tilth)
3. sufficient depth for drainage and rooting
4. good internal drainage
5. low populations of plant diseases and parasitic organisms
6. high populations of organisms that promote plant growth
7. low weed pressure
8. no chemicals that might harm the plant
9. resistance to being degraded
10. resilience following an episode of degradation.

Ideally, indicators of soil health should cover all of these characteristics. However, analyses associated with the latter three are potentially expensive and/or time consuming.

Although the list of soil factors to be used as health indicators is potentially long, not all factors are of equal value (Kurakov *et al*, 1998). The value of a factor is determined by the purpose of the soil health index, i.e. whether it is to gauge the condition of polluted soils, mine dumps or agricultural soils. It is possible that this distinction could be split further into regions and soil types. In their assessment of possible biological soil health indicators in lead-polluted soils Kurakov *et al*. (1998) analysed for 35 components, most of which were rated as having low or medium sensitivity. Only four factors were rated as being highly sensitive, and six as having medium to high sensitivity.

Palojärvi *et al*. (2002) used eight chemical, seven biological and three physical soil measurements to compare the condition of 10 fields (all organic versus conventional management). Significant differences were obtained for only three chemical (electrical conductivity, inorganic N and exchangeable P) and two biological properties (microbial biomass and basal respiration).

Dang *et al*. (2002) found that long-term crop yield of tea reflected the change in soil quality, with reductions in crop yield being attributed to soil degradation. In terms of crop productivity, the most important soil quality indicators were soil organic C, available K, $pH_{(water)}$, penetration resistance, bulk density, total porosity, plant available water capacity (PAWC) and earthworm population. Indicators showing little or no change with soil quality were effective cation exchange capacity (ECEC), Fe and Al oxide content, total Cd and soil texture (Dang *et al*, 2002).

Numerous workers showed that biological components such as nematodes (Neher, 2001), microbial biomass (Nkem *et al*, 2002; Tesarová *et al*, 1998), basal respiration (Nkem *et al*, 2002), *Actinomycetes* spp (Tesarová *et al*, 1998), *Azotobacter* spp, dehydrogenase, urease and respiration (Kurakov *et al*, 1998; Filip, 1998; Liu *et al*, 2002) were sensitive to anthropogenic disturbance of soil and can be used as indicators of soil health.

Methods to select the minimum combination of soil health indicators

As the number of parameters as indicators of soil health is large, suitable criteria are needed to ensure that those used are the most appropriate. Ideally, the minimum combination of soil health indicators should include parameters from the chemical, physical and microbial disciplines.

Kurakov *et al.* (1998) published the following list of 11 criteria to be used to evaluate biological methods for soil quality assessment:

1. sensitivity of the method to detect health differences between soils
2. acceptable variability of the data according to coefficient of variation and standard deviation (repeatability)
3. indicator combination must be specific to the type of pollution or soil disturbance
4. the data obtained should have an integral value or characterise a specific organism or soil function
5. the analysis method gives direct or indirect values of a soil property
6. the analysis is performed in natural soil conditions (field or laboratory) or in artificial standardised conditions
7. the ability to apply the method on various types of soils (universality of method)
8. duration of the analysis
9. complexity of performance
10. necessity to have advanced experience or skills
11. cost of the method and equipment.

Milton *et al.* (2002) used similar but fewer criteria to compile a list of potential soil quality indicators (Table 1). For most indicators, these authors listed a sensitivity rating which represents the estimated minimum number of years required for a method to detect significant differences between management options (treatments on a six year old field trial) assessed on a grey clay soil (Australian Sodosol). Most of the soil biological/biochemical indices were responsive to changes in management practice within a five year period (Table 1).

Cameron *et al.* (1998) suggested a simple scoring approach, which they used to either accept or reject potential soil health indicators for use in a soil degradation (i.e. pollution) situation:

$$A = \Sigma\,(S\ U\ M\ I\ R)$$

Where
A = acceptance score for indicator
S = sensitivity of indicator to degradation or remediation processes
U = ease of understanding of indicator value
M = ease and/or cost effectiveness of measurement
I = predictable influence of property on soil, plant, animal health and productivity (this may vary for a single property due to interaction effects between pollutants)
R = relationship to ecosystem processes (especially those reflecting wider aspects of environmental quality and sustainability).

Each parameter in the equation is given a score of 1 to 5, based on knowledge and experience (both subjective and objective). The sum of the individual scores gave the level of acceptance score (A), which could then be ranked in comparison to other potential indicators.

Critical levels or threshold values

Threshold values for chemical and physical soil properties analysed routinely by FAS are well established in the South African sugar industry. The advantage of using chemical properties for the assessment of soil quality and health is that the results give absolute values of the concentration of contaminants in soils; however, they cannot provide criteria for the determination of permissible concentrations of pollutants in soils (Kurakov *et* al, 1998).

Although threshold values for biological factors could exist for specific situations, none were found in peer reviewed scientific papers. Nielsen and Winding (2002) suggest that baseline information must be built up within the first years of repeatedly monitoring sites in order to define threshold values. The lack of threshold values did not discourage the use of microbial indicators to assess the condition of soils. In fact, microbial factors have increased in importance as indicators of environmental health. According to Nielsen and Winding (2002), microorganisms possess the ability to give an integrated measure of soil health, an aspect that cannot be obtained with physical/chemical measures and/or analyses of diversity of higher organisms.

Table 1. Potential soil health indicators for field and laboratory assessment and their sensitivity to detect changes in land use (after Milton *et al*, 2002).

Indicator	Laboratory or field assessment	Sensitivity*
Biological/Biochemical:		
Cotton strip assay (cellulase)	Lab	6.5
Mycorrhizal bioassay	Lab	2.6
Microbial biomass C	Lab	4.2
Potentially mineralisable N (anaerobic)	Lab	2.8
Phosphatase (P)	Lab	3.3
B-Glucosidase ©	Lab	3.9
Arylsulphatase (N)	Lab	3.4
Hot water extractable C	Lab	2.7
Light fraction organic matter	Lab	5.7
Permanganate oxidisable organic C	Lab	
Total organic C	Lab	6.7
Total organic N	Lab	4.7
Chemical:		
PH	Lab	8.1
Electrical conductivity	Lab	5.1
N	Lab	
P	Lab	
K	Lab	
S	Lab	
MED test for non-wetting	Lab	
Physical:		
Bulk density	Lab	
Aggregate stability	Lab/Field	
Porosity	Lab	
Plant available water capacity	Lab	7.8
Gravimetric water content	Lab	
Penetration resistance	Field	
Soil texture	Field	
Soil depth	Field	

*Sensitivity = Estimated minimum number of years required for a method to detect significant differences between management options assessed on grey clay soils (Australian Sodosol) (after Milton *et al*, 2002).

Soil microbial factors in particular are affected by seasonal changes (Alvarez *et al*, 1995; Díaz-Raviña *et al*, 1995; Kaiser and Heinemeyer, 1993) and it is doubtful whether a simple threshold value guideline for the interpretation of data could be developed. This is further complicated by the fact that microbial factors may vary for different soil types and regions, since indicators vary due to climate, topography, parent material, crop choice and land use practices (Milton *et al*, 2002; Nielsen and Winding, 2002).

Minimum threshold values to sustain the economical production of tea was determined as 1.2% for organic C, 6.02 mg available P/kg, 1.0% total K and 94 mm/m plant available water capacity (Dang *et* al, 2002). However, threshold values for one soil often do not apply to another, especially where the textural rating is different (Doran *et al*, 1996). This point is illustrated in the following example: the threshold value whereafter root distribution was affected was 1.3 Mg/m^3 for a Fluvisol with 30% clay in the topsoil, and 1.2 Mg/m^3 for a Vertisol where the clay content was at least 55%. To overcome this problem, Hartemink (1998) found that an increase of 0.2 Mg/m^3 was sufficient to be critical for both soil types.

A good indicator of sustainable land management is crop yield (Hartemink, 1998). However, crop yield will not necessarily be affected by a significant decrease in the soil condition where the individual health parameters have not reached threshold values for sugarcane. Hartemink (1998) further suggests that a surrogate, but more quantitative, method of investigating whether threshold values were reached, is the analysis of sugarcane tissue samples reflecting nutrient availability.

Conclusion

Of all the soil properties reviewed, soil organic carbon (labile fraction) was undoubtedly the parameter with the most significant impact on soil chemical, physical and biological properties, and is therefore regarded as the most import indicator of soil quality and health. Microbial biomass was regarded as a sensitive indicator of changes in soil organic carbon content (Dalal, 1998).

The most sensitive soil physical parameter to reflect the health of soils is aggregate stability. Other than soil organic carbon in terms of soil chemical properties, pH is regarded as a useful measurement because it is easy to measure, and affects both microbial community and nutrient availability.

It was clear from the literature cited (Doran *et al*, 1996; Kurakov *et al*, 1998; Santana *et al*, 1998; Nielsen and Winding, 2002; Milton *et al*, 2002; Morón and Sawchik, 2002; Haynes and Graham, 2004) that the globe's scientists are still seeking a recipe to formulate the combination of criteria to be used as indicators of soil condition.

The literature is not prescriptive regarding the depth of sampling, but implies that the objectives of a project should be used as a guide. However, the surface layer is the most active zone of biological activity, which decreases with depth. Shallower rather than deep sampling is therefore advised.

Due to the fact that a long list of factors is affecting the level of microbial properties in soils (Milton *et al*, 2002; Nielsen and Winding, 2002) and that threshold values are lacking, Haynes and Graham (2004) suggested that microbial properties must be seen as a unit with chemical and physical properties and that these properties are all interlinked, interdependent and of equal value.

The parameters discussed in this paper and others shown in lists by Doran *et al.* (1996), Kurakov *et al.* (1998), Santana *et al.* (1998), Nielsen and Winding (2002), Milton *et al.* (2002), Morón and Sawchik, (2002) and Haynes and Graham (2004), were considered to compile the minimum data set (MDS) shown in Table 2. This MDS represents possible parameters that can be analysed on samples submitted to the laboratory and for which only the information provided on the sample label is available for interpretation of the results. The final number of parameters to be included in a list for any soil health assessment package will to a large extent be determined by the cost.

Only a few of the cited references mentioned that crop yield could be affected by degradation of soil health (Doran *et al*, 1996; Dang *et* al, 2002; Hartemink, 1998), probably due to the lack of quality data to illustrate this. Hartemink (1998) gave another possible reason, explaining that sugarcane yield would not be affected where individual health parameters had not reached their threshold values. This means that a soil could be in a state of degradation relative to virgin land, but, as long as no threshold values have been crossed, it is unlikely to have a negative impact on yield.

Table 2. Suggested list of soil health indicators from which a minimum set, for use in the South African sugar industry, should be selected. All indicator values must be time and cost effective and obtainable from laboratory assessments.

Chemical	Physical	Biological
FAS routine (soil)	Texture	Microbial biomass C
Mineralisable C	Dispersion index	Microbial biomass N
Mineralisable N	Aggregate stability	Basal respiration
Labile C	Plant available water capacity	Dehydrogenase activity
Total C	Soil colour	Bacteria to Fungal ratio
		Nematodes

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