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Integrated Assessment of Soil Quality for Landscape and Urban Management

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Abstract

Approaches to measuring air and water quality are well established, but soil quality assessment protocols to be used in landscape monitoring efforts are largely non-existent. The concept of soil quality and health represents the integration of the physical, biological and chemical aspects of soils. Limited attention has been given to the holistic assessment of soil quality in landscape and urban planning, as it is typically being addressed only through chemical analyses. This paper describes the process used for the selection of soil quality indicators that are being offered as part of the new Cornell Soil Health Test. Over 1500 samples were collected from agricultural landscapes, including controlled experiments, and analyzed for 39 potential soil quality indicators. Four physical and four biological soil indicators were selected based on sensitivity to management, relevance to functional soil processes, ease and cost of sampling, and cost of analysis. Seven chemical indicators were selected as they constitute the standard soil fertility test. For potentially contaminated sites, additional chemical indicators are considered through a total elemental analysis. Test reports were developed to allow for overall soil quality assessment as well as the identification of specific soil constraints that may be remedied through management practices. The use of the new soil quality test is exemplified for two landscape scenarios in New York State: A vegetable farm, a town park, and a vacant urban lot. The protocol provides an integrated assessment of the soil's ability to perform critical environmental processes at a relatively modest cost, and helps target management and remediation approaches.

1. Introduction

1.1. Landscapes and Soils

Landscapes are regionally cohesive spatial units that are composed of interacting land uses and common landforms, soils, hydrology, climate, biota and human influences (after Gregorich et al. 2001). A healthy landscape is a multifunctional and safe environment capable of supporting diverse and high quality life forms. The three fundamental resources that support such life processes are air, water and soil. Approaches to measuring air and water quality are generally well established and have largely been standardized around the world (Riley, 2001). Soil quality, however, was only recently considered and standard protocols for extensive monitoring are largely non-existent. Soil additionally poses greater sampling challenges as, unlike water and air, the medium does not flow or mix and has high spatial and temporal variability (van Es et al., 1999).

Soil quality degradation is manifest in the pressing problems of land and water contamination from erosion, compaction, acidification, organic matter losses, desertification and chemical contamination, which have reduced agricultural production capacity and food security. It has also contributed to reduced ecosystem functioning through altered regional water balances and lower diversity and richness of plant and animal species. In addition, global climate change is dramatically increasing the variability of weather conditions worldwide, and soil is a critical buffer medium for hydrologic and biogeochemical processes and therefore can mitigate the effects of extreme weather conditions and uncertainty in the availability of water resources (Larson and Pierce 1991).

1.1 Soil Quality and Health

Doran and Parkin (1994) defined soil quality as “the capacity of a soil to function, within ecosystem and land use boundaries, to sustain productivity, maintain environmental quality, and promote plant and animal health”. It includes an inherent and a dynamic component (Carter, 2002; Larson and Pierce, 1991). The former is an expression of the soil forming factors (Brady and Weil, 2002), often documented by soil surveys (Soil Survey Division Staff, 1993). Dynamic soil quality, on the other hand, generally refers to the condition of soil that is changeable in a short period of time by human impact (Carter, 2002; Karlen et al., 1997; Mausbach and Seybold, 1998; Wienhold et al., 2004). With farmer and lay audiences, the term “soil health” is often preferred when referring to this dynamic soil quality concept as it connotes a holistic approach to soil management (Idowu et al., 2007).

Soil quality integrates physical, chemical and biological components and processes and the interactions between them (Karlen et al., 2001; Dexter, 2004a). The physical structure of soil plays an integral role in controlling chemical and biological processes (Dexter and Czyz, 2000; Dexter, 2004b), and also affects infiltration, aeration and drainage (Kemper and Rosenau, 1986), as well as better root penetration and proliferation (Czyz, 2004). Alternatively, biological and chemical processes, such as root growth, organic matter input, macro fauna activity and bacterial and fungal proliferation influence pore size distribution, density and stability of the soil’s structure (Wright and Upadhyaya, 1998; Magdoff and van Es, 2000). Soil-impacting practices such as tillage, traffic, plant cover systems, and organic and inorganic inputs (accidental or deliberate) strongly influence all components of soil quality and thus ecological functioning (Doran and Parkin, 1996; Guérif et al., 2001).

1.2 Soil Quality Assessment and Indicators

New regulations have catalyzed the proliferation of various indicators and "environmental report cards" for assessing vulnerability and improvement towards sustainability (Riley, 2001). There are several criteria by which the suitability of indicators can be judged, for example relevance, accessibility to users, and measurability (Nambiar et al., 2001). Once relevant indicators are identified, it is assumed that the researcher can set criteria and thresholds by which to assess the environment and the level of performance relative to a justifiable standard (Manhoudt et al., 2005). In a review of eleven agricultural case studies using six different types of environmental assessment, Payraudeau and van der Werf (2005) concluded that the most powerful indicators consider the effects of productivity and on the environment.

Indicators can be used to represent complex processes, and many have been developed for ecological and environmental analyses, e.g., for nutrient loss potential on fields (Lemunyon and Gilbert, 1993; Williams and Kissel, 1991) and the environmental impact of different land use mosaics (e.g., Medvedev, 1994). Soil quality cannot be measured directly, but soil properties that are sensitive to changes in management can be used as indicators (Brejda et al., 2000). Methods for measuring individual indicators and minimum data sets (da Silva et al., 1997; Dexter, 2004c) and for calculating indices from groups of indicators (Karlen and Stott 1994, Andrews et al. 2004) are being developed for the purposes of monitoring soil quality over time and evaluating the sustainability of agricultural and land management practices. However, such tests must not be too costly as that would prevent widespread adoption beyond the research domain.

Limited experience exists with the use of inexpensive methods (other than for standard agricultural soil tests) that might be widely adopted by governments, farmers, and consultants for integrated soil quality assessment. The standard agricultural soil tests focus on a limited number of soil chemical indicators that are critical to crop nutrition. They have provided farmers and consultants around the world with relevant information for nutrient and lime management. In a more holistic soil quality paradigm, soil tests are needed to provide an integrative assessment of the triad of soil quality domains (physical, biological and chemical). Such a soil test would need to involve soil quality indicators that represent soil processes relevant to soil functions, and also provide information that is useful for practical soil management. In this context, soil quality is best assessed through soil properties that are sensitive to changes in management (Andrews and Carroll, 2001; Brejda et al., 2000; Doran and Parkin, 1994; Larson and Pierce, 1991).

Sojka and Upchurch (1999) argued that the optimization of processes may require different interpretations of soil quality indicators for the different soil functions. Our approach gets around that issue by placing the emphasis on the value of the information itself, rather than the broader interpretation within an evaluation framework. It identifies soil constraints and aids the selection of management solutions (Idowu et al., 2007). The interpretation of the test results thus requires professional judgment and placement into the context of the land use objectives. For example, soil health test results from a dairy farm require different interpretations and management approaches than for a viticulture operation (White, 2003) or an urban park.

The objective of this paper is to discuss the process of the selection of key soil quality indicators, as implemented through the new Cornell Soil Health Test, and to highlight the utility of the test through three example cases.

2. Cornell Soil Health Test Development

2.1 Approach

The development of the Cornell Soil Health Test involved a triage process for potential soil quality indicators and streamlining of methodologies. The new three-faceted soil quality test was envisioned to provide critical quantitative information that would allow for better management and protection of soil resources in rural and urban areas. Specifically, the test was developed for the following reasons:

- Improved soil inventory assessment: Evaluation of dynamic soil quality in addition to the traditional genetic (inherent) soil quality as reported in soil surveys.
- Land valuation: Effective quantification of soil quality allows for better assessment of the monetary value of land for purchasing and rental transactions, thereby facilitating monetary rewards for good land management.
- Targeting management practices: Measured soil constraints can be addressed with high likelihood for positive results, while no investments are needed in unsubstantiated problems.
- Quantifying soil degradation or aggradation from management: Agencies, farmers, consultants, and applied researchers can evaluate the soil quality benefits resulting from changes in management practices. Governments can link green payments to soil quality improvements.
- Education: Site-specific soil quality information facilitates discussion on soil management and care.

Thirty-nine potential soil health indicators were evaluated (Table 1). The suitability of the soil properties as quality indicators was evaluated through samples from (i) long-term, replicated research experiments related to tillage, rotation and cover cropping studies, (ii) commercial farms that provided real-world perspective under the range of soil management conditions in

New York State, and (iii) selected non-agricultural sites. The commercial farms included samples from grain, dairy, vegetable, and fruit operations, and a wide range of soil types. In total, over 1500 samples were included in the evaluation, although not all 39 properties were measured on all. For the controlled experiments, soil samples were collected four times over the course of the 2004 growing season to evaluate within-season variability.

2.2 Sampling and Analysis

For all management units, two undisturbed soil core samples were collected from the 5 to 66-mm depth using stainless steel rings (61 mm height, 72 mm ID, 1.5 mm wall thickness). Disturbed samples were collected from the 5 to 150 mm depth using trowels. All samples were stored at 2^oC until analysis.

The physical tests were based on standard methodology, as discussed in detail by Moebius (2006), except for wet aggregate stability which involved the application of simulated rainfall of known energy (Ogden et al., 1997) to aggregates on sieves (van Es et al., 2006). The biological test also mostly involved established methods: The decomposition rate was based on loss of filter paper volume after 3-week soil incubation. The active carbon test involved a $KMnO_4$ oxidation procedure based on work by Weil et al. (2003). The root health assessment involved a bioassay method where snap bean seeds are planted in the sampled soil material and root damage is rated based on root morphological features (Abawi and Widmer, 2000).

Analysis of the chemical indicators was based on the standard soil fertility test offered by the Cornell Nutrient Analysis Laboratory. The available nutrients are extracted with Morgan’s solution, a sodium acetate/acetic acid solution, buffered at pH 4.8. The extraction slurry is filtered and analyzed for K, Ca, Mg, Fe, Al, Mn, and Zn on an inductively-coupled plasma spectrometer (ICP) and plant-available PO_4-P is measured using an automated rapid flow analyzer. pH is determined from a 1:1 soil:water mix using a standard pH meter and electrodes. Some samples with potential chemical contamination concerns were additionally subjected to an elemental analysis using complete HNO_3 digestion, combined with ICP analysis.

2.2 Indicator Selection

The general criteria used for physical and biological indicator selection into the test included (Moebius, 2006):

- Sensitivity to management, i.e., frequency of significant treatment effects in the controlled experiments and directional consistency of these effects.
- Precision of measurement method, i.e, residual errors from analyses of variance.
- Relevance to important functional soil processes such as aeration, water infiltration/transmission, water retention, root proliferation, nitrogen mineralization, development of root diseases, etc.
- Ease and cost of sampling
- Cost of analysis.

Qualitative ratings for sensitivity to sampling error and ability to represent soil functional processes were assigned using relationships established in the literature (Andrews et al., 2004; Larson and Pierce, 1991; Luxmoore, 1981), as well as experience from this study. Quantitative data were obtained from experimental analyses (e.g. consistency of treatment effects and reproducibility) and sample processing (e.g. cost of labor, equipment and supplies). Many of the soil physical properties were rejected as suitable indicators due to the requirement for undisturbed samples, or due to high variability. Many soil biological indicators were rejected due to the high cost of analysis, often associated with labor intensity.

The nine soil chemical indicators were all adopted in the integrated soil quality test as they are part of a well-established standard soil fertility analysis procedures that is widely used at reasonable cost. The elemental analysis based on HNO_3 digestion was included in the standard test for samples where contamination was expected. It is currently handled separately in the interpretation of the soil quality test as it is an additional expense that is not desirable for the majority of soils.

2.3 Selected Test Indicators

Table 2 shows the physical, biological and chemical indicators that have been selected for the soil health test (Idowu et al., 2007). These soil measurements can be considered as indicators of critical soil processes (e.g., aeration, infiltration, water and nutrient retention, root proliferation, N mineralization, toxicity prevention, pest suppression, etc.), which in turn relate to soil functions such as plant production, landscape water partitioning, habitat support, etc. The standard soil health test thereby evaluates the soil's ability to accommodate ecosystem functioning within landscapes. The optional elemental analysis additionally provides information on human, animal and plant toxicity concerns. Soil texture is an integrative property and provides the basis for results interpretation through scoring functions (discussed below). Root health assessment is an integrative biological measurement related to overall pressure from soil-borne disease organisms (Abawi and Widmer, 2000). The minor elements of the chemical analysis were grouped to prevent a bias of the soil health assessment in favor of chemical quality.

The indicators are measured based on a composited disturbed sample, which we recommend to be obtained from two locations nested within five sites on a land unit (field, lot, etc.; Gugino et al. 2007). The test also includes penetrometer measurements as the only in-field assessment. Although it is widely regarded as an important physical indicator, bulk density was not included because it was found to be imprecise (Moebius et al, 2007) and generally strongly correlated with other physical indicators in the test (and therefore mostly redundant). Moreover, the use of ring samplers for bulk density proved to be a serious obstacle with field practitioners and technicians, and therefore the reliability of the results was questionable due to frequent improper sampling, especially with soils containing coarse fragments. Based on an economic analysis (Moebius et al., 2007), the standard test can be offered for less than US $50. The optional elemental analysis adds approximately $15 to 20 to the cost.

It is strongly recommended that samples only be collected during the early spring (15 April to 1 June), preferably prior to tillage. Some indicators were shown to have significant within-season variability (Moebius, 2007), and soil management practices can be a confounding influence for soil physical and biological indicators. Also, spring sampling is facilitated by favorable soil water conditions (generally near field capacity), and biological assessments benefit from the more uniform conditions following over-wintering.

2.4 Data Interpretation and Scoring Curves

Effective use of soil health test results requires the development of an interpretive framework for the measured data. The general approach of Andrews et al. (2004) was applied for this purpose, and scoring functions were developed for all soil indicators (except texture) to rate test results. Different scoring functions were developed for the three main textural classes, sand, silt, and clay, hence the necessity to determine soil texture during the testing procedure (which is done by the rapid "feel method"; Brady and Weil, 2002).

The scoring functions were defined in the simple linear-plateau framework, as no justification existed for curvilinear functions. Three types of scoring functions were considered (Fig. 1), "more is better", "less is better", and "optimum". The critical cutoff values for the highest and lowest curves were developed based on the frequency distribution of data generated from the indicators selection process. The 25th and 75th percentile of the distribution curve were generally taken as the extreme values for the linear model where scores increase from 1 to 10. i.e., test results with values less than the 25th percentile were given scores of 1, and greater than the 75th percentile were given scores of 10. This approach was evaluated relative to literature reports and in some cases minor modifications were made.

The scoring curves for active carbon (Fig. 2) are examples of the "more is better" relationship. A low score of 1 is assigned to results of less than 450, 500 and 500 mg kg^{-1} for sand, silt and clay soils, respectively. Respective aggregate stability values of greater than 800, 800 and 900 mg kg^{-1} are scored as 10, and intermediate values are linearly interpolated. Scoring curves for other indicators are reported in Gugino et al. (2007).

2.5 Soil Health Test Report

The standard soil health test report was designed for practitioner audiences, and facilitates both integrative assessment and targeted identification of soil constraints. This is accomplished through the combined use of quantitative data and color coding (Fig. 3). The physical, biological and chemical indicators are grouped by blue, green, and yellow colors, respectively. For each indicator, the measured value is reported as well as the associated score (using a scoring function). The latter is interpreted with colors in that scores of less than three receive a red code, scores greater than 8 a green code, and those in between are coded yellow. This provides for an intuitive overview of the test report. If results are coded red, the associated soil constraints are additionally listed (Fig. 3). Finally, the percentile rating is shown for each indicator, based on the sample's ranking in the database of soil indicator measurements (Fig. 3). An overall soil health score is provided at the bottom of the report, which is standardized to a scale from 1 to 100. It is noted that the interpretation of the test results are generalized for agricultural systems and may require alternative interpretation in other cases. Hence, we recommend that the reports are interpreted by professional consultants and include consideration of site-specific information.

Soil management recommendations were developed to address specific soil management constraints in agricultural systems (Gugino et al., 2007), but are still under development for non-agricultural uses. A training manual was developed which discusses the basic approaches to soil health assessment (including sampling methods, and field and laboratory assessment protocols), the reporting and interpretation of the results, and the suggested management approaches. It can be accessed and downloaded from the Cornell Soil Health web site at http://soilhealth.cals.cornell.edu.

3. Case Studies

Three case studies exemplify the use of the test for different land uses and management purposes. This illustrates the variety of conditions where soil quality analysis provides useful information to land managers, be it farmers, consultants or agencies.

3.1 Vegetable Farm

Fig. 3 shows the test report for a field from a farm near Geneva, NY (42^{o}52’N, 77^{o}05’W) on a glacial till-derived Honeoye-Lima silt loam (fine-loamy, mixed, active, mesic Glossic Hapludalf). The farm has been used for production of processing vegetables (cabbage, beets, etc.) using intensive tillage practices. It was left fallow during ownership transfer for a three-year period (2000 to 2003). During 2004 to 2006, it was again used for production of vegetables (beets, sweet corn, snap beans) using conventional (moldboard plow) tillage.

The test report shows favorable results for the chemical indicators, as indicated by the high rating scores (7.5 or above). The remaining indicators, however, have low scores and therefore show evidence of low physical and biological soil quality. Very unfavorable results for aggregate stability, available water capacity, and organic matter content (1, 2, and 1, respectively) are evidence of soil degradation from long-term intensive tillage, and limited use of soil-building crops. Low to intermediate scores for active carbon, PNM, and root health (3, 2, and 5, respectively) indicate that the soil was biologically degraded and unbalanced. The 3 to 4 scores for soil hardness indicate a mild soil compaction problem. The overall score of 49.5 signifies considerable opportunity foe improvement.

This report exemplifies the need for broader assessment of soil quality. Based on traditional soil testing methodology, i.e., the chemical indicators, the soil appeared to be in of good quality. This is commonly the case, as most farmers are diligent about submitting soil samples for nutrient analysis and subsequently correct the deficiencies. Chemical constraints are readily remedied by application of inorganic chemicals, which generally provides instant results at reasonable cost. In contrast, the lack of routine tests for soil physical and biological indicators has resulted in inadequate attention to these facets of the soil. Moreover, enhancing the physical and biological quality of soils generally requires a longer-term commitment in soil management through practices such as conservation tillage, improved rotations, use of cover crops, and organic amendments, as discussed in Gugino et al. (2007). The soil health test therefore identifies a broader set of constraints and provides farmers with information that allows for holistic soil management.

3.2 Rural Town Park

Fig. 4 shows the soil health test report for soil material collected from a recreational field in a park owned by the municipality of Lansing, NY (42^{o}32'N, 76^{o}32'W). The park is located on a small delta to a glacial lake and the soil is classified as a Genessee silt loam (fine-loamy, mixed, superactive, mesic Fluventic Eutrudepts). The area has been under grass for over 50 years and is extensively used for recreational purposes. The test report indicates that the soil scores high for all four biological indicators, aggregate stability, and available water capacity, which is presumably the result of a build-up of organic matter from long term untilled sod. The report indicates that soil hardness is high for both the surface and subsurface. This is presumably the result of foot and mower traffic, often at suboptimal conditions when the soil is readily compacted. It also contributes to an apparent problem with internal drainage at the site. The chemical test results indicate high pH values and suboptimal K levels. The elemental analysis for this site indicated that only Pb levels are elevated for this site (134 mg kg^{-1}), and above the 62 mg kg^{-1} standard in New York for unrestricted use sites (DEC, 2006; Table 3).

The soil health test report indicates that this soil is generally of good quality with an overall score of 69.2, but that addressing a compaction problem and suboptimal chemical conditions will alleviate some constraints and make the site a higher-quality environment for recreational purposes and ecosystem services.

3.4 Vacant Urban Lot

Fig. 5 shows the soil health test report for a vacant urban lot in Baltimore, MD (39^{o}17’N, 76^{o}36’W). The soil material is of mixed origin and of silty texture. The site is located in an urban area with early 1900’s housing that has fallen into decay. The soil is mostly anthropogenic, or at the least strongly influenced by human activities. The lot is currently vacant and mostly covered by a variety of weeds.

The test report indicates a very mixed picture on the quality of the soil material, an the overall score is 62.5. Although aggregate stability is high, available water capacity shows a low quality score, and soil hardness indicators are in the intermediate range. Both organic matter and active carbon content are low, which appears inconsistent with the high aggregate stability levels. This suggests the presence of chemical soil stabilizing materials on the site, most likely of anthropogenic origin. A high score for PMN is presumably the result of the presence of leguminous weeds of the lot, and high root health is most likely related to the lack of host plants for snap bean pathogens, which would likely be the case for urban lots, except when they are used as vegetable gardens. The chemical indicators show inadequate P levels.

The elemental analysis showed that several chemical contaminants were at elevated levels, and most were also higher that in the town park case (Table 3). The main concerns are with Cr , Pb, Ni, and Zn, which are all above the standard for unrestricted use in New York (DEC, 2006).

Based on the identified constraints for this site, soil quality can be improved through addition of organic matter (e.g., compost) or capping the surface with topsoil material. This will increase organic matter and active carbon levels, as well as available water capacity (water retention). This will also add P to the soil, although some additional fertilizer may be required, depending on the P content of the organic material or topsoil. In general, adding fresh topsoil to cap the soil material, possibly with additional surface mulch, is strongly preferred over mixing in organic material as it will provide a physical barrier from the tested soil material and reduce concerns about heavy metal levels, especially through dust or direct ingestion by infants. If future use of this site includes food production (e.g., vegetable gardens) the elevated metal levels should be considered, perhaps through re-testing after site remediation.

4. Conclusion

Soil health management requires an integrated approach that recognizes the physical, biological and chemical processes in soils. The development of an inexpensive integrated soil health test was seen as a priority to allow more widespread soil monitoring and better management decisions. From a total of 39 potential soil properties, a set of indicators was selected to represent an integrative assessment of soil health, which is now being offered on a for-fee basis. The test is a significant step forward from the conventional soil tests, which focus exclusively on chemical indicators. The use of a holistic test that provides information of all three aspects of soils, physical, biological, and chemical, provides a more meaningful approach to monitoring soil quality and provides farmers, consultants and agencies with a tool to identify soil constraints and target management practices or remediation strategies.

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Table 1. Thirty-nine soil health indicators evaluated for the Cornell Soil Health Test.

Physical Indicators	**Biological Indicators**	**Chemical Indicators**
Bulk density	Root health assessment	pH
Macro-porosity	Organic matter content	Phosphorus
Meso-porosity	Beneficial nematode population	Potassium
Micro-porosity	Parasitic nematode population	Magnesium
Available water capacity	Potential mineralizable nitrogen	Calcium
Residual porosity	Decomposition rate	Iron
Penetration resistance at 10 kPa	Particulate organic matter	Aluminum
Saturated hydraulic conductivity	Active carbon test	Manganese
Dry aggregate size (<0.25 mm)	Weed seed bank	Zinc
Dry aggregate size (0.25 - 2 mm)	Microbial respiration rate	Copper
Dry aggregate size (2 - 8 mm)	Glomalin content	
Wet aggregate stability (0.25 -2 mm)		
Wet aggregate stability (2 - 8 mm)		
Surface hardness (penetrometer)		
Subsurface hardness (penetrometer)		
Field infiltrability		

Table 2. Soil quality indicators included in the standard Cornell Soil Health Test, and associated processes.

Soil Indicator	Soil Process
Physical	
Soil Texture	all
Aggregate Stability	aeration, infiltration, shallow rooting, crusting
Available Water Capacity	water retention
Surface hardness	rooting at in plow layer
Subsurface hardness	rooting at depth, internal drainage
Biological	
Organic Matter Content	energy/C storage, water and nutrient retention
Active Carbon Content	organic material to support biological functions
Potentially Mineralizable Nitrogen	ability to supply N
Root Rot Rating	soil-borne pest pressure
Chemical-standard	
pH	toxicity, nutrient availability
Extractable P	P availability, environmental loss potential
Extractable K	K availability
Minor Element Contents	micronutrient availability, elemental imbalances, toxicity

Table 3. Concentrations of selected inorganic elements from the whole-soil digestion analysis of the town park and urban lot samples, and the New York DEC standards.

Element	**Town park**	**Urban lot**	**DEC Standard**
	- - - - - - - - - mg kg^{-1} - - - - - -		
As	3.32	<det	13
Ba	35.39	115.00	350
Be	0.24	0.72	7.2
Cd	<det	0.53	2.5
Co	5.22	15.72	
Cr	10.06	61.96	30
Cu	14.22	31.17	50
Hg	<det	<det	0.18
Li	17.68	10.22	
Mn	286.51	560.79	1600
Mo	<det	<det	
Ni	16.72	31.99	30
Pb	134.49	150.07	63
Sb	<det	1.15	
Se	1.77	5.48	3.9
Sr	35.34	16.65	
Ti	35.65	164.78	
V	17.40	79.86	
Zn	51.17	158.69	109

Figure captions

Figure 1. Models of scoring curves used for the interpretation of measured values of soil quality indicators.

Figure 2. Scoring curves used for interpretation of active carbon data for sand, silt, and clay soils.

Figure 3. Soil health test report for a field from the vegetable farm.

Figure 4. Soil health test report for a grass field in a rural town park.

Figure 5. Soil health test report for a vacant urban lot.

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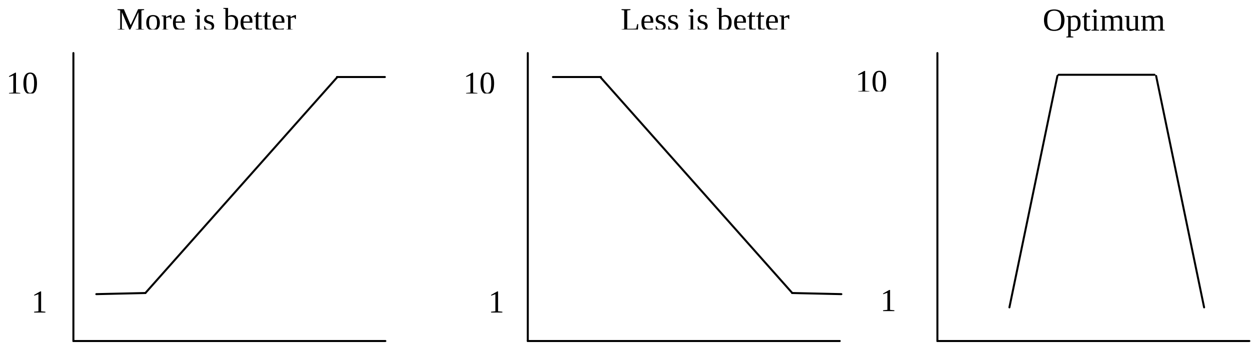


Figure 1.

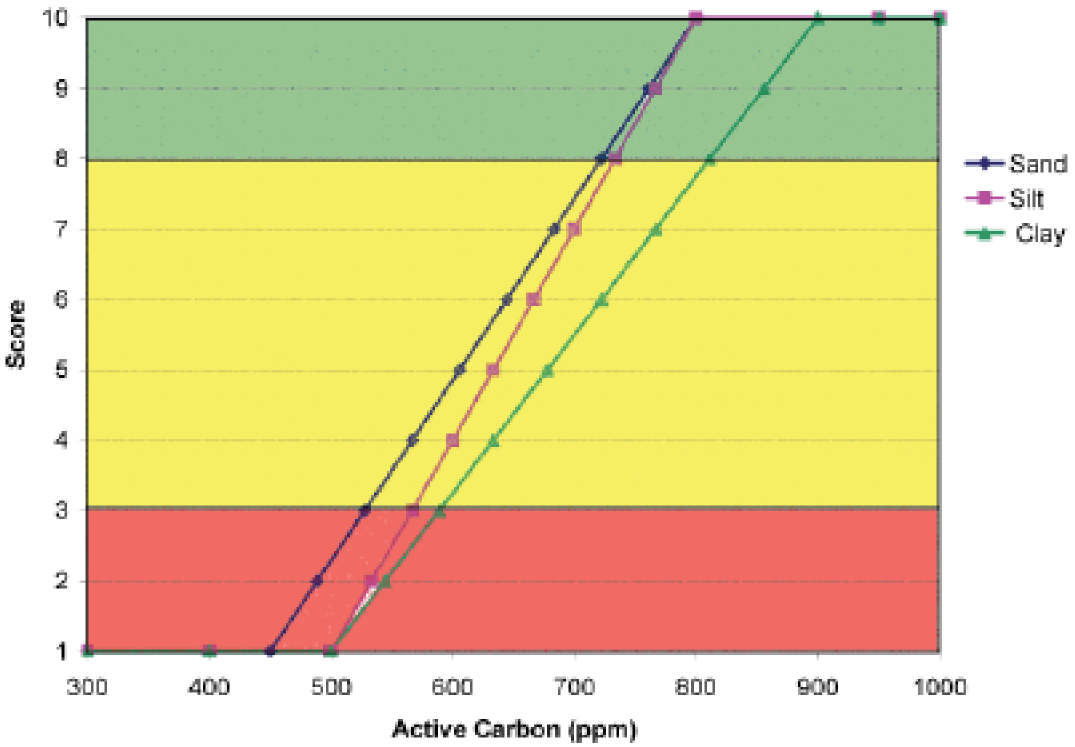
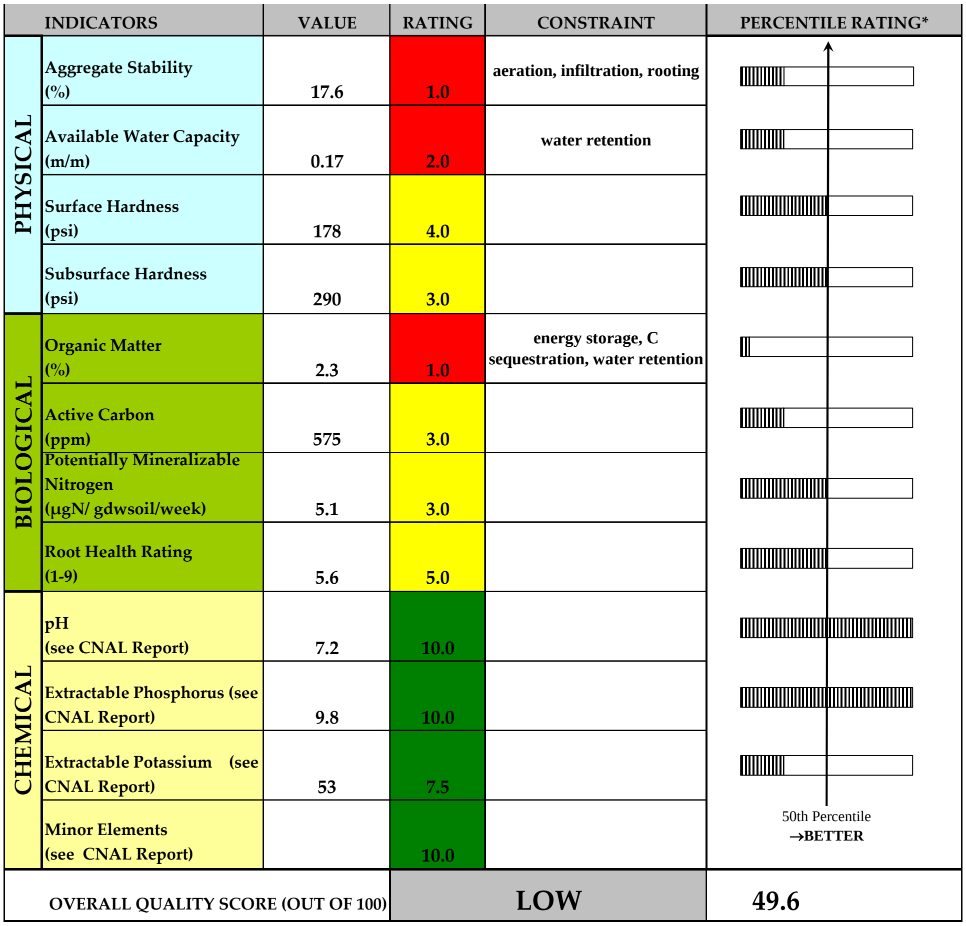
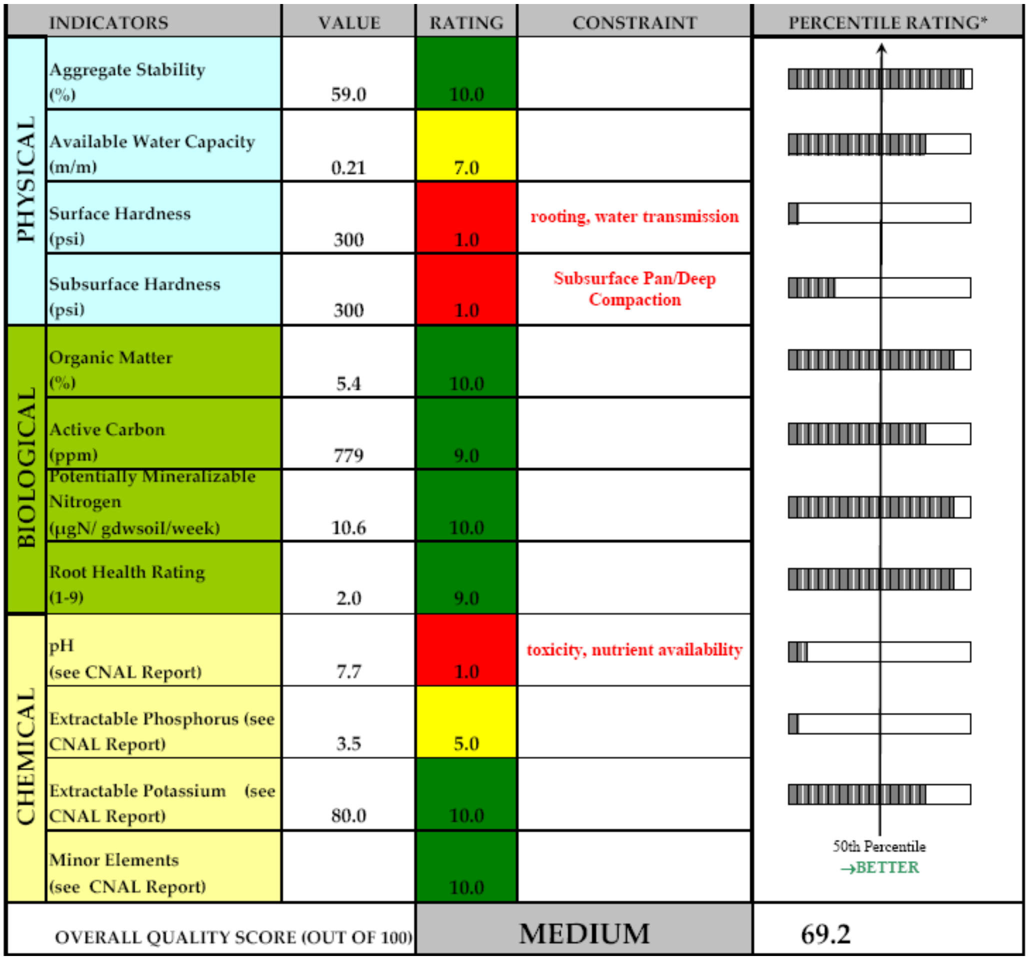

10
9
8
7
6
5
4
3
2
1
Score
300
400
500
600
700
800
900
1000
Active Carbon (ppm)
Sand
Silt
Clay

Figure 2.



	INDICATORS	VALUE	RATING	CONSTRAINT	PERCENTILE RATING*
PHYSICAL	Aggregate Stability (%)	17.6	1.0	aeration, infiltration, rooting	
	Available Water Capacity (m/m)	0.17	2.0	water retention	
	Surface Hardness (psi)	178	4.0		
	Subsurface Hardness (psi)	290	3.0		
BIOLOGICAL	Organic Matter (%)	2.3	1.0	energy storage, C sequestration, water retention	
	Active Carbon (ppm)	575	3.0		
	Potentially Mineralizable Nitrogen (µgN/ gdwsoil/week)	5.1	3.0		
	Root Health Rating (1-9)	5.6	5.0		
CHEMICAL	pH (see CNAL Report)	7.2	10.0		
	Extractable Phosphorus (see CNAL Report)	9.8	10.0		
	Extractable Potassium (see CNAL Report)	53	7.5		
	Minor Elements (see CNAL Report)		10.0		50th Percentile →BETTER
	OVERALL QUALITY SCORE (OUT OF 100)		LOW		49.6

Figure 3.



	INDICATORS	VALUE	RATING	CONSTRAINT	PERCENTILE RATING*
PHYSICAL	Aggregate Stability (%)	59.0	10.0		
	Available Water Capacity (m/m)	0.21	7.0		
	Surface Hardness (psi)	300	1.0	rooting, water transmission	
	Subsurface Hardness (psi)	300	1.0	Subsurface Pan/Deep Compaction	
BIOLOGICAL	Organic Matter (%)	5.4	10.0		
	Active Carbon (ppm)	779	9.0		
	Potentially Mineralizable Nitrogen (μgN/ gdwsoil/week)	10.6	10.0		
	Root Health Rating (1-9)	2.0	9.0		
CHEMICAL	pH (see CNAL Report)	7.7	1.0	toxicity, nutrient availability	
	Extractable Phosphorus (see CNAL Report)	3.5	5.0		
	Extractable Potassium (see CNAL Report)	80.0	10.0		
	Minor Elements (see CNAL Report)		10.0		50th Percentile →BETTER
	OVERALL QUALITY SCORE (OUT OF 100)		MEDIUM		69.2

Figure 4.

	INDICATORS	VALUE	RATING	CONSTRAINT	PERCENTILE RATING*
PHYSICAL	Aggregate Stability (%)	44.6	10.0		
	Available Water Capacity (m/m)	0.17	1.0	water retention	
	Surface Hardness (psi)	150	6.0		
	Subsurface Hardness (psi)	263	6.0		
BIOLOGICAL	Organic Matter (%)	2.5	2.0	energy storage, C sequestration, water retention	
	Active Carbon (ppm)	560	2.0	soil biological activity	
	Potentially Mineralizable Nitrogen (µgN/ gdwsoil/week)	11.0	10.0		
	Root Health Rating (1-9)	2.0	9.0		
CHEMICAL	pH (see CNAL Report)	7.5	7.0		
	Extractable Phosphorus (see CNAL Report)	81.4	2.0	plant P availability, env. loss potential	
	Extractable Potassium (see CNAL Report)	153.0	10.0		
	Minor Elements (see CNAL Report)		10.0		
OVERALL QUALITY SCORE (OUT OF 100)			MEDIUM		62.5

Figure 5.