**THE DEVELOPMENT OF A
SOIL QUALITY MONITORING KIT**

by

Rae-lyn Bennett-Blaney, B. A. Hons.

A thesis submitted to
The Faculty of Graduate Studies and Research
in partial fulfillment of
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Department of Geography and Environmental Studies

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Abstract

This project to develop a soil quality monitoring kit for Eastern Ontario consisted of two phases: development - carried out at the Central Experimental Farm in Ottawa; and kit application - which involved testing on farmer's fields, and farmer assessment of the kit's utility and ease-of-use. The soil tests adopted are: penetration resistance, slake resistance rating, earthworm numbers, organic matter, pH, and infiltration. Results from testing show that these tests are repeatable within acceptable ranges of variability, and that they are sufficiently sensitive to identify significant differences related to soil management systems. In the farmer's field, penetration resistance tests differentiated between wheel and non-wheel track areas. All 12 farmers who field-tested the kit agreed that it was easy to use, measured parameters that were important to them, and would assist their determination of whether their soil management practices were meeting their goals of maintaining or improving their soil quality.

Preface

During the completion of my undergraduate thesis, I had the fortune of working with 32 farmers to investigate the effects of their agricultural techniques on soil quality. Through this experience, I learned about many of the challenges farmers face associated with meeting increasing food demands, while maintaining a sustainable management system. While farmers are quite conscious of the importance of soil quality and sustainable land management; the economics of present day agriculture place ever increasing pressure on farmers to intensify land use, often exceeding the margins of what is truly sustainable (Beare, 1997). Where land use is intensive and non-restorative, the loss of soil quality increases the risk that soil conditions will limit crop productivity and cause environmental impacts. Consequently, tools are needed for farmers to monitor the sustainability of their management systems.

I have had the opportunity, through employment with Agriculture and Agri-food Canada, to evaluate two such tools (*United States Department of Agriculture* (USDA) and *New Zealand (NZ) Institute for Crop and Food Research Limited* Soil Quality Test kits (SQTk)) for their ease-of-use and applicability to conditions of eastern Ontario. It was concluded that the kits were either too technical (USDA) or where not suited for Ontario climate and soils (NZ). These aspects provide barriers for farmers adopting and regularly using the kits.

Thus increasing challenges faced by farmers in maintaining a sustainable management system, coupled with the lack of applicability of existing soil quality test kits motivated me to propose a practical, easy-to-use, inexpensive soil quality monitoring kit suitable for farmers of eastern Ontario (and possibly beyond). The ultimate goal of the SQMK is not to provide irrefutable answers with statistical confidence attached to them, but instead aims to provide simple methods - based on more complex approaches - for tracking change while providing the basis for adapting management decisions over time.

I would like to express my sincere gratitude to my advisors, Dr. Ken Torrance, Dr. Ed Gregorich and Dr. Elyn Humphries, for their invaluable support throughout this project. My appreciation is extended to all the farmers for their generous hospitality and assistance during the farm application phase of this project.

The laboratory and field analysis could not have been completed without the generous support of numerous people, whom I would like to thank. Dr. Ed Gregorich and David Kroetsch of Agriculture and Agri-Food Canada, Ottawa, Ontario for the use of laboratory facilities and field equipment; Jeff Brown, Dustin Rodgers, Greg Blaney, Gordon Blaney and Stacey Strilesky for their invaluable assistance with field and laboratory work.

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List of Acronyms

C-C	Clay compacted
CEF	Central Experimental Farm
CL-LTCT	Clay loam, long-term conventionally tilled
C-NC	Clay non-compacted
CT-CSW	Conventionally tilled, corn-soybean-wheat rotation
CT-SSS	Conventionally tilled, continuous soybean
NT-CCC	No-till, continuous corn
NT-CSW	No-till, corn-soybean-wheat rotation
NZ	New Zealand
OM	Organic matter
OMMC	Organic Matter Monitoring Card
PR	Penetration resistance
S-C	Sand compacted
S-NC	Sand non-compacted
SQMK	Soil Quality Monitoring Kit
SQTK	Soil Quality Test Kit
USDA	United States Department of Agriculture

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1. INTRODUCTION

1.1 BACKGROUND

Soil quality, which refers to the soil's capacity to support crop growth without resulting in soil degradation or harm to the environment is a critically important component of sustainable agriculture (Carter et al., 1997). The concern of humankind to understand and maintain soil quality, coupled with the desire to exploit the soil for the production of food and fiber has persisted for thousands of years. At some times, exploitation, with low regard for maintenance of soil quality, has dominated. Much has been written about loss of topsoil due to deforestation, cultivation of sloping land, and overgrazing. For at least a century, scientists have warned of widespread famine as the exponentially increasing population overwhelms the limited land resource. Some claim that ancient civilizations, such as those in the Tigris-Euphrates basin collapsed largely because of mismanagement of the land (McKeague, 1997).

During the last two decades, due to concerns with soil degradation and an increased global emphasis on sustainable land use, there has been renewed scientific interest in soil productivity. Coupled with this is the idea of "soil management" which has emphasized the value of soil and its properties for specific functions (Carter et al., 1997). Modern concerns with soil quality have been stimulated by increasingly broad awareness that soil is a vital component of the earth's biosphere, functioning not only in the production of food but also in the maintenance of local, regional, and global environmental quality (Doran and Parkin, 1994). This ecological approach to soils recognizes soil-human interactions, and the relationship of land managers to soil. Consequently, soil quality becomes inseparable from the idea of system sustainability,

and is considered a key indicator of ecosystem sustainability. The emphasis in soil quality considerations has moved away from being simply “suitability for use” to whether soil functions are operating at some optimum level within ecosystem boundaries (Carter et al., 1997).

Management-induced deterioration of soil quality has affected almost 40% of the World’s agricultural land (Olderman, 1994) and is one of the greatest agricultural problems that threaten the long-term sustainability of agroecosystems (FAO, 1990). In 1984, the report by the Canadian Senate’s Standing Committee on Agriculture, *Soil at Risk: Canada’s Eroding Future*, stated that soil degradation was hindering sustainable crop production. Other studies, such as the 1990 report of the Federal-Provincial Agriculture Committee on Environmental Sustainability, have raised concerns regarding the environmental impacts of agriculture, such as it causing declines in water quality and reduction of biodiversity (cited by McRae, 2002). While, intensive crop production to meet world food demands provides the primary long-term focus for soil quality studies, other issues include air quality, carbon sequestration, and climate change.

Agricultural researchers, agronomists and other extension specialists have access to tools that have been developed for assessing and monitoring soil quality; these include farmer-based scorecards, visual assessment procedures, fact sheets, and video presentations, all of which serve as educational materials to improve farmers’ ability to recognize, understand, and appreciate the complexity of soil resources. Soil Quality Test Kits have also been developed by the *United States Department of Agriculture (USDA)*, the *New Zealand (NZ) Institute for Crop and Food Research Limited*, and the *New York State Agricultural Experiment Station (Cornell University)* for use in their respective

countries; they provide tools and instructions necessary for taking relatively quick, simple, and inexpensive field measurements of soil quality indicators. They can be used both to monitor changes at one location over time, and to assess the nature of problems in areas of fields where crop stands are poorer than others. Two of these kits (USDA and NZ) have been tested recently on a range of agricultural soils in Eastern Ontario, and have been judged to have deficiencies for application on soils of Eastern Ontario (Appendix A1). It was concluded that an appropriate soil quality monitoring kit for Eastern Ontario soils should be developed. To this end, soils representative of the most common agricultural soils in Eastern Ontario located on land management research sites at the Central Experimental Farm in Ottawa, Canada were chosen as the test locations. The parameters of interest and the methods for measuring them were proposed and developed during 2005 and winter 2006. The goal is to provide farmers of Eastern Ontario (and possibly beyond), with the means to rapidly assess changes in the quality of their soil over time. Field testing was conducted during the spring and summer of 2006. The field objectives were to:

1. Test the kit on a variety of agriculturally important soils of Eastern Ontario, under different soil management systems;
2. Determine the ease-of-use of the kit in the field; and
3. Compare the field test results to standard laboratory analyses of the same soil.

The development of a soil quality monitoring kit for Eastern Ontario is novel because currently Canadian farmers do not have access to a soil quality monitoring kit specifically designed for their soils and climates.

1.2 SCOPE AND OBJECTIVES

The purpose of this study is to develop a practical, on-farm, soil quality monitoring kit designed specifically for soils of Eastern Ontario. Such a kit should;

1. Provide a means for farmers to trouble shoot problem areas in fields and to monitor changes over time after new management systems are begun.
2. Heighten farmers' awareness of the impact of different management systems on soil.
3. Assist farmers in monitoring changes in the physical, chemical and biological properties of their soils.

1.3 ORGANIZATION OF THESIS

This thesis is organized as follows. Chapter 2 provides a background review of soil quality concepts and soil quality indicators. Chapter 3 identifies site locations and describes the field and laboratory methods used in this analysis. Chapter 4 presents the results of testing on the Central Experimental Farm and on a farmer's field, followed by results from individual farmer evaluations. Chapter 5 summarizes the conclusions of this thesis, discusses limitations encountered during the research, and provides recommendations for further research.

2. CONCEPTS OF SOIL QUALITY

2.1 SOIL QUALITY

Definition and assessment of soil quality are complicated by the need to consider the multiple functions of soil and to integrate the physical, chemical, and biological soil attributes that define those functions. Many scientists argue that soil quality is an abstract characteristic of soils that cannot be defined, largely because it depends on external factors such as land use, soil management practices, ecosystem and environmental interactions, and socioeconomic and political priorities (Doran and Parkin, 1994). However, Doran and Parkin (1994) argue that to ensure the sustainability of our soil resource, soil quality must be defined, and the definition must encompass the many facets of soil functions.

In an agricultural context, soil quality can be defined in terms of soil productivity and the ability to sustain and nurture plant growth. Soils, however, serve other functions within and beyond agricultural ecosystems. Soils serve as a treatment filter for maintaining water quality, a key component in the regulation of the global biogeochemical cycles and an important medium for the disposal and degradation of wastes (Beare et al., 1997). The soil's ability to recycle organic materials into carbon dioxide and water and to degrade chemical pollutants is made possible by microbial decomposition, chemical hydrolysis, complexation, and sorption reactions. The ability of a soil to store and transmit water is a major factor regulating plant-available water and the transport of environmental pollutants to surface and ground water (Doran and Parkin, 1994). Hence, the quality of soils is important not only from a plant and agriculture perspective, but also to the overall quality of the environment.

While recognizing the other functions of soil in global ecosystems, the focus of this research is on soil quality from the perspective of agricultural production. In this context, soil quality is defined as the soil's intrinsic capacity to nurture and sustain plant growth. Ultimately, this capacity is related to the ability of the soil to: provide a suitable medium for seed germination and root growth/development; to accept, hold and release water; to be absent of adverse chemical conditions; and to provide a balanced supply of nutrients. Such processes are influenced by soil properties such as water holding capacity, acidity and bulk density. Changes in these properties directly affect crop productivity.

Numerous soil parameters, also known as soil quality indicators, have been proposed as criteria for measuring and monitoring soil quality. Soil quality indicators are measurable soil properties that define major processes functioning in soil and reflect conditions as they exist in the field (Doran and Parkin, 1994). As reported by Doran and Parkin (1994), soil quality indicators should meet the following criteria, they should: (1) encompass ecosystem processes; (2) integrate soil physical, chemical, and biological properties and functions; (3) be accessible to many users; (4) be applicable to field conditions; and (5) be sensitive to variations in land management and climate.

A proposed set of basic soil quality indicators that meets most of the above-mentioned criteria is given in Table 2.1. Other measurements will likely be needed as dictated by existing data banks and specific climatic, geographic, and socioeconomic conditions, or as indicated by assessment of basic indicators. Important soil quality indicators not included in Table 2.1 are soil cation exchange capacity and aggregate stability (Doran and Parkin, 1994). However, cation exchange capacity can be estimated

Table 2.1: Proposed soil physical, chemical, and biological attributes to be included as basic indicators of soil quality (Doran and Parkin, 1994) and their relation to soil function (Doran, 1996).

Soil Characteristics	Relation to Soil Condition and Function; Rationale as a Priority Measurement	Reference
Physical		
Soil texture	Retention and transport of water and chemicals; Modeling use, soil erosion and variability estimate.	Gee et al., 1986
Depth of soil and rooting	Estimate of productivity potential and erosion; Normalizes landscape and geographic variability.	Taylor et al., 1982
Soil bulk density and infiltration	Potential for leaching, productivity, and erosivity; Soil bulk density needed to adjust analyses to volumetric basis.	Blake et al., 1986
Water holding capacity	Related to water retention, transport, and erosivity; available water: calculate from soil bulk density and organic matter.	Cassel et al., 1986; Klute, 1986
Chemical		
Total organic C and N	Defines soil fertility, stability and erosion extent; use in process models and for site normalization.	Nelson et al., 1982; Schulte, 1988
pH	Defines biological and chemical activity thresholds; essential to nutrient availability.	Eckert, 1988
Mineral N, P and K	Plant available nutrients and potential for N loss; productivity and environmental quality indicators.	Geldermann et al., 1988
Biological		
Potentially mineralizable N	Soil productivity and N supplying potential; Process modeling; (surrogate indicator of biomass)	Keeney, 1982
Soil Respiration	Microbial activity measure (in some cases plants); Process modeling: estimate of biomass activity.	Anderson, 1982
Earthworm count	Bioturbation, aggregate stabilization, porosity, drainage, aeration.	Kleinhenz et al., 2001

from soil organic matter, pH and clay content. Inferences about soil aggregation can be made from organic matter content, soil infiltration rate after wetting, and soil bulk density (after wetting), which are included as basic indicators (Doran and Parkin, 1994).

2.2 THE IMPACTS OF AGRICULTURE ON SOIL QUALITY

Only 5 % of Canada's terrain is suitable for agriculture, and much of this area is threatened by soil degradation (Acton and Gregorich, 1995). The impacts of agriculture on soil quality result from a complex interaction between soil, climate, topography and management practices. In many situations, conventional farming practices, such as mechanical cultivation and the intensive growing of row crops, have resulted in decreases in soil organic matter content, the associated release of CO₂ to the atmosphere and soil loss through soil erosion. Decreased organic matter content and the use of heavy tillage machinery has resulted in deterioration of soil structure and tilth, decreased water holding capacity and water infiltration rates, and increased compaction (Doran and Parkin, 1994).

Numerous studies (Table 2.2) have investigated the impacts of agriculture on soil quality and many of these have shown the detrimental effects of intensive practices (farming practices that produce high output per unit area, usually by intensive use of agrochemicals and mechanization (Intensive Agriculture, 2007) on soil properties. For this reason, it is essential that farmers monitor soil quality to avoid soil degradation, and in doing so preserve the production capabilities of the soil and protect the wider environment (Beare et al., 1997).

2.3 WHAT CONSTITUTES A "GOOD" SOIL QUALITY?

The term "good" with respect to soil quality is somewhat subjective and relative. In the context of the present discussion, it is proposed that a "good" soil quality is one where soil quality factors permit maximum expression of productivity within the

Table 2.2: Some of the impacts of agricultural techniques on soil quality.

Agricultural Technique	Impact on Soil Properties	Possible Impacts on Soil Function	Reference
Tillage (Intensive (i.e., frequent mechanical cultivation))	-Increased bulk density (i.e., compaction)	- Increased risk of erosion (due to decreased infiltration and water holding capacity), inhibited root elongation and soil aeration, inhibited seedling emergence.	Livingston and West, 1990 Snyder et al., 2000 Peters et al., 1997 Pierce et al., 1997 Farkas et al., 2000 Moreno et al., 2000 Velykis, 2000 Dick et al., 1997
	-Poor aggregate stability	-Increased risk of erosion, soil surface crust formation (inhibits water infiltration, aeration, and seedling emergence) and to some extent, compaction (inhibits root elongation, aeration, and infiltration).	
	- Decreased biological activity	- Decreased organic matter formation (i.e., increased risk of soil erosion (due to decreased aggregate stability, water holding capacity and infiltration), increased risk of compaction (therefore reduced aeration, infiltration and root elongation), and depletion of important nutrient reserve).	Carpenter-Boggs et al., 2001 Larink et al., 2000 Vaclav, 1993 Petruszel, 1997
	-Decreased humus content	- Increased risk of soil erosion (due to decreased aggregate stability and water holding capacity), increased risk of compaction (i.e., reduced aeration, infiltration and root elongation), depletion of important nutrient reserve (due to associated decrease in biological activity and soil cation exchange capacity (CEC)).	Frye et al., 1997 Fenton et al., 1999 Hernanz et al., 2000 Alakukku, 2003 Wiermann et al., 2000 Weisskopf, 2000 Fleige et al., 2000 Black et al., 1997

(Table continued on next page)

(Table 2.2 continued)

Organic fertilizers (Practice usually associated with organic or low-impact farming)	-Increased nitrogen mineralization/availability	-Increased crop yield	Ezzanno et al., 1998 Vitosh et al., 1997
	-Lower bulk density -higher organic matter	-Decreased risk of erosion (due to increased aggregate stability, infiltration rate and porosity), decreased root penetration resistance. -Decreased risk of erosion (due to lower bulk density, higher aggregate stability and water holding capacity), increased storage and supply of plant nutrients (due to associated increase in biological activity and soil CEC).	Rose, 1990 Darmody et al., 1997 Lesoing et al., 1997
Crop rotations and residue management (usually associated with non-intensive farming)	-Increased aggregate stability	-Decreased risk of erosion and surface crust formation.	Reported in Paustian, 1997
	-Higher organic matter content	-Decreased risk of erosion (due to lower bulk density, higher aggregate stability and water holding capacity), increased storage and supply of plant nutrients (due to associated increase in biological activity and soil CEC).	Hargrove et al., 1987 Larson, 1978 Campbell et al., 1997 Reported in Fenton et al., 1999 Broizaed et al., 2000 Buyanovsky et al., 1997

constraints of extrinsic factors (factors apart from soil that influence crop yield). By this definition, a “good” quality soil would have: physical properties that do not restrict root growth or seed germination, and which embody the capacity to accept, hold, and release water; and chemical properties that supply a balance of essential nutrients and are absent of adverse chemical conditions. These desirable conditions are related to a wide array of chemical, physical, and biological soil properties (Table 2.3).

Thus far, a “good” soil quality has been defined from an agricultural perspective. From a broader ecological perspective, a “good” quality soil might be defined as one that is effective in maintaining environmental health. These considerations, however, are beyond the focus of this paper.

2.4 SOIL PRODUCTIVITY

Productivity is defined in terms of a soil’s capacity to produce a harvestable crop (Janzen et al., 1992). Productivity is influenced by extrinsic factors as well as by soil quality. Extrinsic factors include climate, topography and hydrology (Carter et al., 1997). In addition to the effects of soil quality and extrinsic factors, productivity is also influenced by management inputs, many of which are introduced into the system to compensate for deficiencies that have relationships to soil quality. For example, inadequacies in precipitation can be mitigated by irrigation, and poor soil structure can sometimes be alleviated by tillage (Janzen et al., 1992).

The effect of soil quality on production cannot be defined in isolation from extrinsic factors, for example, high clay content may be an important factor that positively affects productivity under a semi-arid moisture regime, where soil moisture retention is an advantage, but be undesirable under a humid moisture regime, where poor

Table 2.3: Summary of key soil processes and properties which constitute a “good” quality soil, in terms of crop production.

Process	Desirable soil characteristic	Controlling attribute or property	Comments	Indicator for Attribute	Importance of attribute to soil function
Suitable medium for seed germination and root growth and development	-Absence of soil surface crust	-Structural stability	-Related to texture and organic matter (OM).	-Aggregate stability or slaking.	-Determines susceptibility of soil to water and wind erosion (loss of topsoil and nutrients), soil surface crust formation (inhibits water infiltration, aeration, and seedling emergence) and to some extent, compaction (inhibits root elongation, aeration, and infiltration).
	- Soil not too dense	- Strength	-Related to bulk density, texture, OM and soil water content	-Penetrability	-Determines ability of soil to resist loss of structure through tillage and holds plants upright; soil must permit seedling emergence, root penetration, and burrowing soil fauna.
	-Tilth (i.e., ease of tillage)	-Structural form -Organic matter	- Related to soil aggregation -Related to residue additions, removals and texture	-Penetrability -Organic carbon	-Influences ability of water to infiltrate and ease of root penetration and aeration. -Encourages macropore formation (through aggregation) and stable soil structure.
	-Adequate air and water retention/drainage (important control of soil temperature and aeration)	- Water holding capacity -Infiltration -Earthworms	- Related to texture, OM and structure -Related to texture and structure.	-Organic matter and texture -Infiltration rate and texture -Earthworm count	- Provides buffer against drought conditions. -Determines transport of soil water to plant roots; drainage and therefore susceptibility to water logging or erosion. -Increased infiltration and aeration (through macropore formation), increased aggregate stability and organic matter formation.

(Table continued on next page)

(Table 2.3 continued)

Process	Desirable soil characteristic	Controlling attribute or property	Comments	Indicator for Attribute	Importance of attribute to soil function
Capacity to accept, hold, and release water.	Ability to store water	-Water holding capacity	-Related to water retention, transport, and erosivity.	-Organic carbon	-Provides buffer against drought conditions.
		-Texture	-Loam has greatest plant available water	-High clay content=high water holding capacity -High sand content=lower water holding capacity	-Determines inherent water holding capacity.
	-Ability of water to enter the soil	-Infiltration		-Infiltration rate	-Determines erosivity and ensures water supply to plant roots.
		-Earthworms		-Earthworm count	-Increase macroporosity and aggregate stability
		-Texture	-Related to retention and transport of water	-High clay content=slower infiltration rate -High sand content=higher infiltration rate	
	-Ability to withstand raindrop impact	-Structural stability	-Related to texture and OM	-Aggregate stability or slaking	-Determines potential for surface crust formation.

(Table continued on next page)

(Table 2.3 continued)

Process	Desirable soil characteristic	Controlling attribute or property	Comments	Indicator for Attribute	Importance of attribute to soil function
Absence of adverse chemical conditions	-Soil not too acidic or basic	-Reaction	-Influenced by parent material (PM) and management -Influenced by PM and management	-pH	-Affects soil CEC.
	-Absence of toxicities or deficiencies	-Reaction		-pH	-Indicator of potential toxicities (i.e., Al, Mn) or deficiencies (e.g., P, Mn, Zn, Cu, Fe, Mo).
Supply balance of nutrients	-Adequate nutrient reserve of essential nutrients.	-Texture	-CEC ranges from nil in sands to 1000 cmoles/kg, or higher, in clays and organic soils. -2:1-type minerals have higher CEC than 1:1-type minerals.	-Clay content and type	-Generally contributes substantially to CEC of soils.
		-Organic matter		-Organic carbon	-Contribute substantially to CEC of soils; promotes aggregate stability and stable soil structure (i.e., reduction of nutrient loss through soil erosion).
		-Reaction		-pH	-Important control of available nutrients to plants.

drainage can hinder crop growth. Because of such interactions, optimal soil quality criteria can only be defined for a given set of extrinsic factor conditions. In other words, there can be no universally accepted set of soil quality indicators or universal value ranges for the criteria (Carter et al., 1997).

The productivity of a soil in a farmer's field is an expression of extrinsic factors and soil quality across that area. Soil quality varies with factors such as slope position and parent material. Similarly, extrinsic factors can vary across space. For instance, moisture availability on a knoll will likely be less than that near the base of a slope. Thus, the overall productivity can be considered the mean of productivities at all points throughout the site, each of which is a reflection of individual extrinsic factors and soil quality combinations (Janzen et al., 1992).

2.5 DYNAMICS OF SOIL QUALITY PARAMETERS

Soil quality is not a fixed entity. Instead, it varies over time in response to soil management, parent material, climate, and topography. The various soil quality criteria exhibit change over varying time periods, for example, total organic matter may change over a period of years to decades. In contrast, microbial biomass, soil respiration and macroporosity can change over a period of hours or days (Janzen et al., 1992) (Table 2.4).

The detection of changes in soil quality requires that soil ecosystems are viewed at appropriate spatial and temporal scales. Some soil quality indicators, such as pH, can change rapidly, making them useful for determining short-term variations in soil quality during the course of a growing season but they may be less useful for monitoring long-term trends. Other soil quality indicators, such as texture or organic matter, change more

Table 2.4: Projected rates of change for soil quality indicator variables (Source: Halvorson et al., 1997).

Soil quality indicator	Projected rate of significant change (years)
pH	0.1-1.0
Soil organic matter	1-10
Infiltration	3-5
Water retention	3-5
Water holding capacity	3-5
Bulk density	1-3
Aggregation	1-5 (<1)
Depth to hardpan	1-3 (<1)

slowly, making them unsuitable for assessing changes in seasonal crop production, but appropriate for monitoring long-term trends in yield potential. Soil variables may also vary spatially in well-defined trends or patterns, fluctuate erratically or appear constant depending on the scale of measurements (Halvorson et al., 1997).

Improvements to (or degradation of) soil quality can perhaps best be visualized as trend changes that indicate a positive (or negative) general direction over the years. For instance, under a depletive management system, a linear decline in organic matter may become evident with changes in soil color. Recognition of trend changes is usually most important when assessing the sustainability of soil resources over a relatively long period of time, such as ten years. The identified changes need to be rapid enough so that

management can be altered (if necessary) to influence trends. However, there are drawbacks to defining soil quality by trend changes. A disadvantage is that it requires measurement of indicators at two points in time (at a minimum) and, therefore, does not provide immediate assessment of soil quality. In addition, a trend may essentially be flat; that is an assessment of a quality parameter such as soil respiration in year one may be equal to the assessment in year 10. Any interpretation must consider the possibility that the soil may be functioning at its highest level attainable and cannot improve, or at its lowest level and cannot go lower (Baldwin, 2000).

2.6 SOIL QUALITY TEST KITS

The USDA and NZ Soil Quality Test Kits (Table 2.5 and 2.6 respectively) have been tested for accuracy and ease of use at the Central Experimental Farm in Ottawa, Ontario and have been shown to be lacking in terms of practicality for in-field use and applicability to Ontario soils (Appendix A1). The following conclusions have been drawn from field evaluation of the test kits and provide the justification for this thesis:

USDA SQTk

1. The USDA test kit lacks tests to monitor soil organic matter. Organic matter is recognized as a primary indicator of soil quality (Fenton, 1994; Doran and Parkin, 1994).
2. A number of the tests are too technical and too time-consuming and some equipment has high maintenance costs. Both of these aspects are barriers to farmers adopting and regularly using the kit.

Table 2.5: United States Department of Agriculture (USDA) Soil Quality Test Kit- Methods and Tools.

Soil Quality Indicator	Methods and Tools
	USDA SQTK
Bulk Density	Test is performed using a 7.62-cm diameter ring, inserted 7.62 cm into the soil surface. Bulk density is determined by microwaving 1/8-cup sub-sample for 2 or more 4-minute cycles. Dry and wet weights of the samples are used to calculate bulk density.
Infiltration	Test is performed using a 15.24-cm diameter ring, inserted 7.62 cm into the soil surface. 2.54 cm of distilled water is poured into the ring and the time it takes for it to infiltrate is recorded. If soil is not at field capacity when test is performed a second infiltration test immediately follows.
Slaking	Test is performed using a stability kit, which consists of 16-box compartment and sieve baskets. 16 (1-cm) soil fragments are removed from the soil surface and placed in the stability kit and air dried. Upon air drying the soil fragments are removed from the stability kit and 2 cm of distilled water is added to each box compartment. Each fragment is lowered into the kit filled with water. Soil stability is rated according to the time required for the fragments to disintegrate within a 5-minute immersion and the proportion of soil fragment remaining on the mesh after 5 extraction-immersion cycles.
Aggregate Stability	A ¼ cup air-dried sub-sample is sieved using a 2-mm sieve. 10 grams of the sieved sample is weighed out into the 0.25-mm sieve and wetted for 5 minutes by placing a wet terry cloth underneath the sieve. The sieve containing the aggregates is immersed in distilled water and oscillated for 3 minutes. After wet sieving the sieve plus the aggregates is placed on top of a drying chamber and dried with a 1400 watt hair drier. After drying the dry weight of the sieve plus the aggregates is recorded. The dry aggregates are then dispersed by immersing the sample in Calgon solution for 5 minutes. The sample is returned to the drying apparatus to dry. Aggregate stability is calculated using the weight of the dry soil aggregates and sand particles.

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(Table 2.5 continued)

Soil Physical Observations and Estimates	A 30 X 30 cm pit is dug (to a depth of 30 cm) and a slice of soil is removed from the pit wall. The following soil properties are recorded; depth of topsoil; plant roots; penetration resistance (using a wire rod); soil structure (grade, type and size) and soil texture. Step-by-step instructions, pictures and background information assist the user with assessing soil physical properties.
Electrical Conductivity (EC)	Soil samples are removed from the 0-to 7.62- cm depth. A soil -water mixture is prepared using 1/8-cup sub-sample of soil and 1/8-cup of distilled water. EC is measured by inserting a Hanna Instruments EC pocket meter into the soil-distilled water mixture.
pH	The same soil-water mixture prepared for the EC test is used to conduct the pH test. Soil pH is measured by inserting a Hanna Instruments pH pocket meter into the soil-water mixture.
Soil nitrates	The same soil-water mixture prepared for the EC and pH tests is used for soil nitrates. The soil-water mixture is filtered and tested for soil nitrates using nitrate/nitrite test strips.
Earthworm Count	A 30 X 30 cm pit is dug (to a depth of 30 cm) and the soil sample is sorted against a pale colored background to help locate earthworms. Earthworms are separated and counted.
Soil Respiration	A 15.24 cm diameter ring is inserted 7.62 cm into the soil surface. The ring is covered and left for 30 minutes to allow CO ₂ to accumulate in the chamber. Evolved CO ₂ is measured using a Draeger tube apparatus. A second measurement follows 16-24 hours later if the soil was not at field capacity during the first measurements.

Table 2.6: New Zealand (NZ) Institute for Crop and Food Research Limited Soil Quality Test Kit-Methods and Tools.

Soil Quality Indicator	Methods and Tools
NZ SQTk	
Profile Density Assessment	Test is performed by examining properties such as root patterns, surface crusting, dense layers, shiny surfaces, pans and mottles in a 50 x 50 cm pit to a depth of at least 5-cm into the subsoil. Each property is given a score from the score card provided by the kit.
Bulk Density	Test is performed using a 73-mm diameter corer, inserted 75 mm into soil surface. 3 samples are bulked, weighted and air dried for approximately 3 days. The air-dried soil is dried further in a standard oven for a minimum of 4 hours at 105°C. Bulk density is calculated using the dry and wet weight of the soil samples.
Structural Condition Scorecard	Test is performed by removing a spade full (20 x 20 cm) of topsoil (top 10 cm) from a representative part of the plot. The soil is spread onto a tarp and sorted from the fine particles at one end to coarse particles at the other. The structural condition of the soil is scored by comparing the soil sample to photographs and written description on the scorecard.
Soil Structural Stability	Test is performed using a 73-mm diameter corer, inserted 75 mm into the soil surface. The sieved aggregates are air dried for 3 days. A 26 g sub-sample is wet sieved using the structural stability tester. The remaining aggregates are air dried for approximately 4 days. Soil structural stability is calculated using the final weight of the air-dried aggregates.
Water Holding Capacity	Test is performed by inserting a ring to a depth of 80 mm. The ring is filled with 1 liter of water and a core (73-mm diameter and depth of 75mm) is taken from the center of the ring approximately 24-36 hours after the addition of water. In the lab, the soil samples are air-dried for 3-days and then dried in a standard oven for approximately 4 hours at 105°C. Water holding capacity is calculated using the wet and dry weights of the soil samples.
Earthworms	A count is determined by removing 2 adjacent full spade samples (to a depth of approximately 20-cm) and placed on a tarp. The soil is sorted and earthworms are collected.

NZ SQTK

1. Pictures provided for tests such as the *Profile Density Assessment* scorecard and the *Soil Structural Stability* scorecard do not correlate well with common soil types of Eastern Ontario.
2. The test kit lacks tests to assess soil organic matter.
3. Some of the tests are too technical and time-consuming, which may dissuade farmers from adopting and regularly using the kit.
4. The test kit lacks a pH test. Soil samples must be sent to a laboratory for pH analysis.

In summary, results from the field investigation in Eastern Ontario indicate that the NZ and USDA SQTKs are either unsuitable for soils and climate of Eastern Ontario (and possibly the rest of Canada) (NZ SQTK), or are too technical (USDA SQTK).

Consequently, they are unacceptable for adoption by farmers. A kit suitable for local conditions needs to be developed.

2.7 EVALUATION OF SOIL QUALITY FOR PLANT GROWTH

In the context of this research, soil quality is defined in terms of the capacity of the soil to promote and sustain plant growth. Ultimately, this capacity is related to the following soil processes: soil must be a suitable medium for seed germination and root growth/development; it must have the capacity to accept, hold and release water; it must be devoid of adverse chemical conditions; and it must supply a balance of nutrients. Soil conditions that allow and/or promote these responses constitute “good” soil quality.

The following discussion presents some of the key physical, chemical and biological properties that most strongly influence the above-mentioned soil processes. It will discuss their importance to soil processes and propose soil quality indicators for each soil property. It is important to note that the divisions between physical, chemical, and biological properties are not as clear-cut as may be implied from the discussion in this paper. To truly understand soil processes, researchers must focus on the evaluation of the soil system as a whole, and therefore physical, chemical and biological components of soil and their interactions must be integrated (Per Schjonning et al., 2000).

2.7.1 PHYSICAL PROPERTIES

2.7.1.1. SOIL TEXTURE

Texture refers to the proportion of sand, silt and clay in soil. It is a key variable influencing many soil processes, particularly those involved in soil-water interactions (i.e., accepting, holding and transmitting air and water) and in supplying nutrients to plants. In general, coarse-textured soils tend to be low in organic matter content and native fertility, they have low water and nutrient holding capacity, low cation exchange and buffering capacities and high infiltration rates. Coarse-textured soils usually require careful attention to water management (i.e., generally including frequent irrigation and/or artificial drainage to suit the needs of specific crops) and proper fertilization (usually more frequent but lower quantities of nutrients per application) (Brady and Weil, 1999). In contrast, fine-textured soils generally are more fertile, have higher organic matter content, high cation and buffering capacities, have better water and nutrient holding capacities, and have lower infiltration rates. Greater microporosity of fine-textured soils results in reduced aeration and therefore lower rates of organic matter oxidation. Lastly,

the formation of clay-humus complexes protects organic matter from degradation (Brady and Weil, 1999).

Soil texture governs many of the farmer's practices. Often, soils with high clay content, are difficult to manage. Such soils are often sticky when wet and hard when dry, and thus are difficult to cultivate except within a narrow water content range. The ideal soil is often considered to be a loam, which contains relatively equal proportions of clay, sand, and silt. Fine-textured soils are more susceptible to compaction when the moisture content at the time of field operations (e.g., harvesting) is high. Thus a farmer with fine to medium textured soils must limit tillage to periods when the soil is not wet. In addition, sandy soils are more prone to drought than clay soils are, due to lower water holding capacity. Therefore, the farmer may need to irrigate the field, and/or use mulches to maintain adequate soil moisture content (USDA, 1996). Thus, texture is one of the most important characteristics of soil because it influences many soil processes that are of great significance to land management including: ease of tillage, porosity, aeration and fertility.

2.7.1.1.1 Proposed Indicators: Soil Texture

As an indicator of soil quality, soil texture is judged mostly in the context of its influence on productivity and the ease of soil management. Unlike other indicators of soil quality, soil texture is a fixed soil property that is not readily altered (except over long time periods or in extreme cases of erosion or sediment deposition), and therefore is not a property which needs to be monitored through time. Nevertheless, it is important to be knowledgeable about soil texture because it often sets limits on the maximum soil quality that management practices can achieve.

The “feel” or hand texture method can be used for determining soil texture.

Relative proportions of sand, silt and clay are estimated by manipulating a moistened sample between the thumb and forefinger. Accuracy depends mainly on experience; flow diagrams, which describe the method for determining texture by feel, aid interpretation.

2.7.1.2 SOIL STRENGTH

Soil strength can be defined as a transient property related to the soil’s solid phase cohesion and adhesion (Brady and Weil, 1999). It is a key physical attribute affecting seed germination and root growth/development through its influence on properties such as root penetration resistance and structural stability. From an agricultural perspective, soil strength relates to the ability of the soil to: resist the loss of structure through tillage-induced pulverization or remolding, traffic-induced compaction, and rainfall-or irrigation-induced slaking of aggregates; and resist penetration by crop roots and burrowing soil fauna. Soil strength should be strong enough to maintain soil structure and hold plants upright, but low enough to allow seedling emergence, root penetration, and burrowing soil fauna (Topp et al., 1997).

The main components of soil strength are shear, compressive and tensile strength (Topp et al., 1997). Shear strength refers to the soil’s ability to resist lateral movement under a tangential force, such as might occur at the sides of a tillage instrument. Shear strength arises primarily from the friction associated with the sliding of irregularly shaped soil particles past each other, and their cohesiveness. Compressive strength is the ability of the soil to resist compaction due to inward directed forces. Conversely, tensile strength refers to the soil’s ability to resist expansion due to outward directed forces (Topp et al.,

1997). All components of strength arise from cohesion between clay minerals, the presence of organic and mineral binding agents within and between soil particles, and adhesion between soil particles caused by the contractile force of pore water at subatmospheric pressures (Topp et al, 1997).

Mechanical impedance to root growth is correlated with soil penetration resistance measured by cone penetrometers. Although the functional relations between soil penetration resistance and physiological processes vary with the characteristic of the penetrometer, measurement technique and plant genotype, cone penetrometers provide a useful relative measure of the effect of different management systems on the resistance that may be encountered by roots (To and Kay, 2005). Penetration resistance arises from the resistance of the soil to displacement; this resistance causes the penetrometer to decelerate from its initial velocity, resulting from the hammer blow, to zero velocity (Herrick and Jones, 2002). The most common method for measuring penetration resistance is to determine cone index values using a dynamic cone penetrometer. These probes use one or more discrete applications of kinetic energy to advance the probe (Herrick and Jones, 2002). The force required to push or the number of blows to hammer a penetrometer relates to some combination of shear and tensile failure, compression, plastic soil flow, and both metal-to-soil and soil-to-soil friction (Topp et al., 1997). Kenney et al. (2002) reported that penetration resistance measurements appeared to be a more sensitive indicator of compaction (i.e., high soil strength) than either bulk density or field saturated hydraulic conductivity.

Cone index values depend on cone properties (i.e. diameter, height, and cone angle), drop height, as well as soil properties (Herrick and Jones, 2002). One of the most

important soil properties affecting penetration resistance is water content (Cassel, 1982; Hamblin, 1985; Bradford, 1986; Klepper, 1990; Cambell and Zenter, 1991). Vanags et al. (2006) found an exponential relationship whereby penetration resistance decreased with increasing soil moisture. This can be attributed to water molecules decreasing the cohesion between the particles and acting as a lubricant between clay particles, thus reducing frictional forces that need to be overcome to shear the soil. Texture, organic matter, particle surface roughness (Cassel, 1982; Campbell and Zenter, 1991) and structure (Bradford, 1986; Cambell and Zenter, 1991) may also produce a different penetration resistance in different soils or in different layers in the same soil (Lampurlanes and Cantero-Martinez, 2003). It is important to note that shaft friction causes penetration resistance to increase with depth (Stelluti et al., 1988; Campbell and Zenter, 1991).

Estimates of soil strength can also be made by measuring slake resistance. Slaking is a process of fragmentation that occurs when dry aggregates are suddenly immersed in water. Slaking occurs because the soil aggregates are not strong enough to withstand the internal stresses that arise from differential swelling and air entrapment during rapid water intake. These stresses may be released through creation of an increasingly extensive network of failure zones in the soil aggregates (USDA, 1999).

Lastly, estimates of soil strength can be made from soil bulk density. Bulk density is defined as the mass of dry soil per unit bulk volume (Acton, 1995) and in a non-cultivated field is governed by: (1) soil texture; (2) composition (organic matter, clay content and type); and (3) soil water content (USDA, 1996). Many studies have shown that increases in bulk density and soil strength occur from the pressure exerted by field

machinery and this is aggravated by frequent tillage (Livingston and West, 1990; Peters et al., 1997; Peirce and Fortin, 1997; Farkas et al., 2000; Moreno et al., 2000; Snyder et al., 2000).

Many important soil processes are inhibited if soil strength is too strong, thus the measurement of soil strength is very important when assessing and monitoring the ability of a soil to sustain and promote plant growth.

2.7.1.2.1 Proposed Indicators: Penetration Resistance, Slake Resistance Rating and Bulk Density

Soil penetration resistance can be used as an indicator of soil strength. When all variables are held constant, increased penetration resistance is correlated with higher soil strength (i.e., compaction) (Lampurlanes and Cantero-Martinez, 2003). Slake resistance rating can also be used as an indicator of soil strength (refer to previous section) because aggregates with higher soil strength are more likely to resist loss of structure. The main difference between tests of penetration resistance and slaking are the aspects of soil strength measured. The force required to push, or the number of blows to hammer, a penetrometer into the soil mainly relates to compressive strength, which determines root penetration resistance; whereas slake resistance rating measures tensile strength, an important influence on soil's resistance to water erosion. Lastly, bulk density can be used as an indicator of soil strength. Soils with high bulk density generally show lower water content and porosity, and consequently higher soil strength.

2.7.1.3 SOIL STRUCTURAL STABILITY

Agricultural soil structure refers to the spatial arrangement of both the soil particles and soil pores within and between particles (Topp et al., 1997). Some of the

effects of structure on plant growth include: (1) it ensures a suitable medium for seed germination and root growth/development through its influence on aeration and root penetration; and (2) it affects the soil's capacity to accept, hold and release water through its influence on water holding capacity, infiltration, drainage, and the soil's resistance to compaction and crusting (Govers et al., 2004).

Soil structural degradation can either take the form of weakened aggregates and/or compaction. Soils with weak and unstable aggregates are susceptible to accelerated structural damage. The breakdown of aggregates at the surface of fine-textured soils can result in surface crust formation which can prevent seedling emergence and impede soil infiltration (and therefore increase risk of erosion) and aeration (Topp et al., 1995). The contents of several of the water-stable-aggregate-increasing soil constituents can be increased through crop and soil management practices such as the application of organic residues, lime, or gypsum (Govers et al., 2004). In general, the greater the aggregation of the soil and the greater the aggregate stability, the less erodible the soil.

Soil compaction can be defined as the packing together of soil particles by forces exerted at the soil surface, resulting in increased soil density (USDA, 2004). Compaction has been reported as one of the largest challenges facing farmers of Eastern Canada (McBride et al., 2002). Compaction is mainly caused by repeated passes of heavy machinery on wet soils during tillage and harvesting. Fine textured soils in humid climates are the most susceptible to compaction (Topp et al., 1995). Compaction reduces crop yield through: (1) reduction of seedling emergence, thus decreasing crop stand; (2) reduction of macropore space which decreases oxygen supply to crop roots thereby

restricting their growth and increasing risk of root diseases, and also reduces rooting volume and water infiltration which limits plant available water (Topp et al., 1995).

2.7.1.3.1 Proposed Indicators: Slake Resistance Rating, Penetration Resistance and Bulk Density

As with soil strength, slake resistance rating, bulk density and penetration resistance can serve as an indicator of soil structural degradation (i.e., compaction) (Refer to section 2.7.1.2). Areas of compaction or crust formation can be expected to show greater soil penetration resistance, higher bulk density and lower soil stability rating than areas of the same soil with less or no structural deterioration.

2.7.1.4 INFILTRATION RATE

Infiltration refers to the downward entry of water into the soil surface (Brady and Weil, 1999). Infiltration is a key physical property affecting the suitability of soil for seed germination and root growth/development and for ensuring the soil's capacity to accept, hold, and release water. Infiltration affects these processes through its influence on soil properties such as plant-available water, soil-water storage, aeration and soil temperature.

Infiltration is important in providing an adequate volume and rate of supply of water for maximum crop production and for soil organisms; it is also an important determinant of soil erosion potential. Soil water provides the bulk of water necessary for the functioning of living cells in and on the soil and is the vehicle by which plants and soil organisms absorb nutrients and eliminate waste products (Topp et al., 1997).

Decreased infiltration rates have been shown to decrease the capacity of the soil to accept and therefore store water; thereby increasing surface runoff and consequently soil erosion. Studies on the effect of erosion on soil properties show that it negatively affects

many soil quality indicators including topsoil depth, organic matter content, nutrient status and aggregate stability (Govers et al., 2004).

Infiltration rate is also an important control on soil aeration and soil temperature. Low infiltration can result in low levels of soil oxygen. Soil aeration refers to the ability of the soil to store and transmit air. The volume of air “stored” in a soil (i.e., volumetric air content) is determined by soil porosity and volumetric water content, with volumetric air content decreasing with decreased soil porosity and high volumetric water content. Hence, a sufficient soil infiltration rate reduces the likelihood that waterlogged conditions will inhibit soil aeration (Topp et al., 1997).

The rate at which water enters the soil surface (i.e., infiltration rate) is dependent upon soil texture, structure and initial soil water content. Generally sandy soils have rapid infiltration rates, while clayey soils have lower rates of infiltration. However, infiltration rates may be high in expanding type clays when shrinkage cracks are present. As infiltration proceeds, macropores generally fill with water and shrinkage cracks close up (Brady and Weil, 1999). Soil structure (i.e., the arrangement and binding together of soil particles (by natural processes) into peds (soil units such as soil aggregates, prisms or blocks) is important for maintaining soil porosity and therefore infiltration (Brady and Weil, 1999). Channels between peds (interped pores) are important for infiltration. Well-structured soils generally have more interped pores than soils with poor or massive soil structures. Finer soils usually have a stronger, more defined structure than coarser soils due to shrink/swell processes dominating in clay-rich soils and more cohesive strength between particles (McCauley et al., 2005). If aggregates are stable, the structure remains intact throughout a rainstorm. The antecedent soil water content at time of measurement

affects the ability of the soil to accept water, such that the infiltration rate into dry soil will be higher than into wet soil (USDA, 1999).

The infiltration rate is sensitive to near-surface conditions and is subject to significant change with soil use, management, and time. It is affected by plant root development, earthworm burrows, soil aggregation, and increases in stable organic matter (USDA, 1999). Tillage has been shown to affect infiltration rates. Immediately following tillage infiltration may be high due to loosening of surface crusts and compact areas. However, over the long-term, tillage disrupts aggregates and soil structure, increasing the risk of compaction, crusting and loss of continuous surface-connected pores. Compacted soils have less pore space, resulting in reduced infiltration rates.

A “good” quality soil must therefore not only provide sufficient water for crop and soil organism requirements, but also quickly eliminate potentially harmful excess water. The extent to which a soil can achieve this is determined by its water storage and transmission relationships. Infiltration rate is a key indicator of a soil’s water storage and transmission capacity (Topp et al., 1997).

2.7.1.4.1 Proposed Indicators: Infiltration Rate

Infiltration rate can be used as an indicator of soil infiltration. It refers to the rate at which water enters the soil surface and is dependant upon soil texture, soil structure, or amount of aggregation, and the soil water content. Infiltration rate is not constant over time; generally it decreases during an irrigation or rainfall event (Brady and Weil, 1999).

2.7.1.5 ORGANIC MATTER

Soil organic matter is considered a key property affecting plant growth, through its effect on many essential physical, chemical, and biological soil processes. Soil organic matter can be defined as “that fraction of the soil composed of anything that once lived” (USDA, 1996). More specifically, the term organic matter is used to represent the organic constituents in the soil, including undecayed plant and animal tissues, their partial decomposition products, and the soil biomass. Thus this term includes: (1) Identifiable, high-molecular-weight organic molecules such as polysaccharide and proteins; (2) Simpler substances such as sugars, amino acids, and other small molecules; and (3) Humic substances.

Effects of soil organic matter on plant growth include: (1) It ensures a suitable medium for seed germination, root growth/development and increases the soil’s capacity to accept, hold and transmit water. It affects such processes through its influence on biological properties such as earthworm numbers and on soil physical properties such as soil aggregation, erosion, drainage, tilth, aeration, water-holding capacity, bulk density, evaporation, and permeability; and (2) It affects chemical properties such as the absence or presence of adverse chemical conditions and the supply of plant nutrients. It affects these through its influence on cation exchange capacity, metal complexing, buffering capacity, supply and availability of N, P, S, and micronutrients, and adsorption of pesticides and other added chemicals.

Numerous studies carried out under field and laboratory conditions have confirmed that organic materials are the main agents in the formation and stabilization of soil aggregates and soil structure (Lynch and Bragg, 1985; Rose, 1991 and; Swift, 1997).

Stevenson (1994) noted that soil organic matter is important because of its role in the cohesion of clay and/or clay-humic complexes into larger particles, by sharing intercrystalline ionic forces between clay particles or by bridging through the action of polyvalent cations and humus. He stated that soil organic matter provides the chemical and biological basis for soil components to form soil aggregates. Organic matter is involved in aggregate formation and stabilization in that it provides the energy source for the activities of fungi, bacteria and soil animals and, when soil organic matter decays, gels and other viscous microbial products encourage aggregate formation (Brady and Weil, 1999).

Stott et al. (1999) wrote that the organic matter associated with the surface of aggregates protects the aggregates from slaking by reducing the wetting rate. Degradation of organic matter leads to less stable aggregates and soil crust formation in many soils, particularly those high in silt content and with low organic matter content at or near the surface. Soil crusting results in reduced infiltration and air permeability and increased water runoff. These changes in organic matter and soil physical properties produce a chain of undesirable reactions, such as reduction in water storage, further erosion as runoff increases and increase in bulk density.

Organic matter contributes substantially to the availability and storage of plant nutrients. It accounts for 25-90% of the cation-adsorbing power of mineral soils (Stevenson, 1994). For instance, humus has a CEC of 300 cmol_e/kg, whereas mineral colloids such as fine-grained micas, kaolinite and hydrous oxides have CEC values of 25, 5, and 3 cmol_e/kg respectively (Brady and Weil, 1999). The charge on the organic matter fraction arises largely from ionization of COOH groups, although some contribution from

phenolic OH is suspected (Stevenson, 1994). The high CEC of organic matter greatly contributes to the soil's ability to retain positive ions in a form that is easily obtained by plants and at the same time is not easily lost through leaching.

In natural ecosystems, plant requirements for nutrients such as N, S, and P and trace elements are met entirely or in part by mineralization of organic matter (Sparling, 2003). A soil with 3 % organic matter contains approximately 3370 kg/ha of nitrogen/acre (Organic Matter Management, 2002). This N has been accumulated almost entirely by biological fixation and incorporated into the soil organic reserve by soil microorganisms. Biological processes also mineralize the organic reserves to plant-available forms. Over one year, approximately 1-5% of the organic N in a soil will typically mineralize, thus a soil with 1200 kg N/ha will provide approximately 50 kg of inorganic N/ha (Sparling, 2003).

Organic matter is considered a key soil property affecting plant growth, through its control of many essential physical, chemical and biological soil processes (Fenton, 1994; Doran and Parkin, 1994). A "good" quality soil must therefore have adequate soil organic matter. It is an essential component of soil that stores and supplies nutrients. A key biological function in that it greatly affects the activities of microflora and microfaunal organisms, and a key physical function in that it promotes good soil structure, thereby improving tilth, aeration, aggregate stability, and water-holding capacity (Stevenson, 1994).

2.7.1.5.1 Proposed Indicator: Soil Color

In the field, soil color changes can give a general indication of trends in soil organic matter levels under cropping (Shepherd, 2000). Generally, darker soil colors near

the soil surface are associated with higher organic matter levels. Schulze et al. (1993) found that within similar landscapes and soil texture classes, there was a good linear correlation between Munsell soil color and soil organic matter for Ap horizons (Cited by Krull et al., 2002, p. 55). It is important to note however, that factors other than organic matter also affect soil color, notably soil moisture content and mineralogical composition. Nevertheless, soil color assessment is quick and easy to conduct, making this one of the most widely accepted methods for monitoring trends in soil OM (Shepherd, 2000).

2.7.2 CHEMICAL PROPERTIES

2.7.2.1 SOIL REACTION

The degree of acidity or alkalinity (i.e., soil pH) is an important control on the availability of nutrients to plants and of potentially adverse chemical conditions. This is because the pH of a soil influences the rate of plant nutrient release by weathering, the solubility of all soil materials, the amounts of nutrient ions stored on the cation-exchange sites, and the likelihood that potential toxicities exist (e.g., Al and Mn). Major factors affecting soil pH include parent material, temperature and rainfall. Strong acidity is generally associated with leached soils of humid regions. Agricultural practices such as liming or addition of ammonium fertilizers can alter soil pH (USDA, 1999). Proxy measurements (i.e., soil quality indicators) are not required for soil pH measurement, as it is easily and directly assessed using standard field or laboratory methods.

Acidic soils are often associated with deficiencies of the basic nutrients (Ca, Mg, and K) and deficiencies of P. Some trace elements and soluble Al may be present at high enough concentrations to cause toxicity to plants in strongly acidic soils. Soil pH affects

CEC by altering the surface charge of colloids. A higher concentration of H^+ (lower pH) neutralizes the negative charge on colloids, thereby decreasing CEC. The opposite occurs when pH increases (McCaulry et al., 2005). Soil pH also affects the activity of beneficial microorganisms, which affects nutrient availability. Fungi generally function over a wide pH range, while bacteria and actinomycetes function better at intermediate and higher pH (USDA, 1996). Through its influence on the quantity and types of organisms responsible for organic matter formation, pH also affects aggregate stability and, in turn, the transfer of air and water in the soil (Brady and Weil, 1999).

2.7.2.2 Proposed Indicator: Soil pH

Soil pH is an important property of a soil because it influences many of the chemical and biological processes that occur in the soil. For instance, it influences the solubility of nutrients, the activity of micro-organisms responsible for organic matter breakdown, and the absence or presence of toxicities. For these reasons, it is important to regularly monitor soil pH as it provides vital information on the soil's capacity to promote and sustain plant growth.

2.7.3 HABITAT QUALITY

2.7.3.1 EARTHWORM ABUNDANCE

Earthworm numbers are favored by Paoletti (1999) as a key indicator of soil habitat quality (Quoted by Ivask et al., 2006). Their presence, in large numbers throughout the soil profile represents two inter-related phenomena. Not only are they excellent indicators of a soil's general habitat quality but also by their presence they improve soil conditions. Earthworms affect important soil processes including: the

suitability for seed germination and root growth/development; the capacity to accept, hold, and transmit water; and the capacity to supply plant nutrients. Earthworms affect such processes through their influence on aggregate stability, macroporosity, drainage, aeration and organic matter decomposition. They affect the soil environment through their burrowing, fecal excretion (casts), and feeding and digestion.

When earthworms burrow, they create tunnels in the soil, which increases infiltration capacity and improves soil aeration. Earthworm burrows also affect chemical transport during water flow. The burrows drain quickly, and soil aeration after wetting occurs rapidly, which keeps the soil well oxygenated (Linden et al., 1994). Earthworm burrows also provide channels for roots. In compacted soil, recent earthworm burrows may be the only channel for plant root growth. Earthworms enhance the rate of residue breakdown and nutrient release. For instance, some species of earthworms forage on the soil surface and pull residue into their burrows for later consumption. As residue passes through an earthworm's gut, soil minerals, water and microbes are mixed with residue matter. Within the gut and after excretion, this material has been shown to be metabolically active. Thus, earthworms play a significant part in the cycling of organic material in soils (Linden et al., 1994). Earthworms also mix soil; soil near the surface is often mixed into the subsoil. Similarly, subsoil can be deposited on, or close to, the surface. Burrow walls and casts (fecal material) are an enriched environment for microbial activity. Nitrogen fixation, denitrification, and mineralization often proceed at accelerated rates within burrow locations (Linden et al., 1994). In addition, earthworm casts contribute to the biotic aggregate-forming factors (Stott et al., 1999).

The use of earthworms as indicators has been criticized on the fact that environmental factors other than their disturbance can limit their distribution. Their numbers are subject to high spatial and temporal variability due to fluctuations in temperature, moisture, and substrate availability (Cameron et al., 1998). In addition, not all areas or soils support earthworms, either because they were never introduced to the area or environmental conditions are not favorable (e.g., high sand content). However, for those soils that constitute an appropriate habitat for earthworms, their abundance is generally an indicator of quality of habitat for organisms. Thus, for these soils their abundance would prove a useful indicator of change in soil quality. Conversely, soils that do not meet the requirements for earthworms will require other biological indicators. One such indicator is change in organic matter content; it is a key indicator of soil biological functioning and is easily monitored.

Thus, it may be difficult to make definite statements about earthworms as causes or indicators of high quality soils. However, stronger associations may be possible between changes in earthworm communities, and associated changes in soil quality. Despite such limitations, it is suggested that a minimum data set for assessing changes in soil quality should include earthworms because of their importance to the structural fabric of a soil, physical and chemical properties of a soil, and their potential contribution to soil quality functions (Linden et al, 1994). In addition, land managers generally relate to earthworms as a highly visible indicator of soil quality (Verhallen, personal communication, 2008).

2.7.3.1.1 Proposed Indicators: Earthworm Abundance

Earthworm numbers can be used as an indicator of earthworm abundance and activity. Because earthworm numbers vary spatially and seasonally, earthworm counts should be made several times during a season and averages should be used to gauge changes from year to year. Generally, they are most active during the spring and fall, which are the best times to observe their activity (USDA, 1999).

2.7.4 SYNTHESIS

Soil quality should be defined within the context of the functions ascribed to the soil. From an agricultural perspective, soil quality is defined in terms of the capacity of the soil to sustain plant growth. Ultimately, this capacity is related to the ability of the soil to: provide a suitable medium for seed germination and root growth/development; to accept, hold and release water; to be absent of adverse chemical conditions (e.g., Al or Mn toxicity); and to supply a balance of nutrients. Soil properties that allow and/or promote these responses constitute “good” soil quality, some of which include, medium soil strength, stable soil structure, moderate to high infiltration rate, high organic matter content, near-neutral soil pH and abundant earthworm populations.

Approaches to assessing soil processes must be holistic, involving integration of all parts of the soil system, and not reductionist in separating and measuring only the function of individual parts (Doran et al., 1999). For instance, interpretation of the relevance of soil biological properties apart from soil physical and chemical properties is of little value, and with respect to assessment of soil quality, can be misleading (Doran et

al, 1999). Therefore, physical, chemical and biological components of soil and their interactions must be integrated.

Once the key quality criteria have been identified and their relationship to plant growth characterized, changes in soil quality can be monitored and appropriate ameliorative measures can be proposed. Key soil attributes which constitute a “good” quality soil depend on the plant to be supported and the climate in which the soil functions. This is not to say that unifying factors do not exist; instead it is to clarify that a single “critical” level does not exist for all plant-soil-climate combinations.

3. MATERIALS AND METHODS

3.1 INTRODUCTION

The research program consisted of two phases: the Soil Quality Monitoring Kit (SQMK) development phase; and the farm application phase. The kit development phase involving design of procedures was conducted at Carleton University and the Eastern Cereal and Oilseed Research Center (ECORC), and the field testing of the kit during development was carried out on fields at the Central Experimental Farm in Ottawa. The farm application phase was conducted on fields owned by the individual farmers who cooperated in this essential step. Methods used in this study were not designed to prove that differences exist between management systems; rather they were designed for the development and selection of kit components.

3.2 SOIL QUALITY MONITORING KIT DEVELOPMENT PHASE, CEF, OTTAWA, ON.

3.2.1 EXPERIMENTAL FARM BACKGROUND-AGRICULTURE AND AGRI-FOOD CANADA, OTTAWA

In 1886, Experimental Farms Branch of the federal Department of Agriculture established the Central Experimental Farm, which aims to improve the sustainability of Canadian agriculture. Research activities are aligned to support Departmental priorities and the Agriculture Policy Framework (Agriculture and Agri-Food Canada, 2006). The locations of Central Experimental Farm sites included in this analysis are identified in Figure 3.2.

Figure 3.1: Location of the city of Ottawa within the province of Ontario (Hills et al., 1944).

Figure 3.2: Soils of the Central Experimental Farm, Ottawa, ON.- Red squares demarcate sample areas, Field One (CT-CSW, NT-CSW, CT-SSS, NT-CCC); Field 8 (S-C, S-NC, C-C, C-NC); and Field 9 (CL-LTCT 1, CL-LTCT 2 and CL-LTCT 3).

3.2.1.1 Regional Setting

The Central Experimental Farm is located within the city of Ottawa, Canada, which now has the boundaries of the former Carleton County (Figure 3.1). Ottawa is located on the southern shore of the Ottawa River in Eastern Ontario and lies within the physiographic region of Canada known as the Lowlands of the St. Lawrence. The bedrock consists of Precambrian metamorphic and igneous; and early Paleozoic carbonates, shales and sandstones. Precambrian rocks are located at the highlands to the N, S, and W, whereas Paleozoic rocks are located in the St. Lawrence Lowlands region and extends southward into the Lake Ontario basin and Eastward down the St. Lawrence River valley (Fulton, 1987).

3.2.1.2 Climate and Geography

3.2.1.2.1 Climate

Ottawa is located between 74°30' and 75°30' west longitude and 45°15' and 45°45' north latitude. The climate of Ottawa is dominantly humid, cool continental characterized by warm summers and severe winters, with considerable variability throughout the year (Ministry of Agriculture and Food, 1979). The yearly rainfall is 86 cm, with fairly even distribution throughout the year. The snowfall in Ottawa and the vicinity is the highest for the eastern parts of the province (Wicklund et al., 1962). Mean monthly temperatures of Ottawa range from -16°C during January to 27°C in July. The mean annual temperature is 5.8°C.

3.2.1.2.2 Quaternary Deposits and Glaciation

The soils of the Central Experimental Farm (Figure 3.2) are directly related to the nature of the underlying Quaternary deposits. The region consists of glacial deposits, both till and outwash sands that were deposited during the late Wisconsinan. The till is generally sandy and the texture of the finer-than-2 mm fraction in areas underlain by Paleozoic rocks has higher silt and clay content than in areas underlain by Precambrian rocks (Fulton, 1987). Glaciofluvial sediments are also abundant in this area. Outwash fans and pitted outwash plains are common at the northern limit of the Champlain Sea. In addition, subaqueous outwash such as eskers and fans are abundant within the basin of the Champlain Sea. Following the last glaciation (~11.5 to 10 ka), the region was inundated by the Champlain Sea, an extension of the Atlantic Ocean that occupied the lower Ottawa and upper St. Lawrence valleys (Fulton, 1987). During deglaciation, sediments deposited in the Champlain Sea basins included: stratified drift; subaqueous outwash; rhythmically-bedded silts and clays; and thick, extensive, marine sediments. The stratigraphically lowest marine deposits consist of massive to weakly stratified blue-gray clay and silty clay, that was deposited during deglaciation and while the Champlain Sea was a salinity-stratified body of water. The next lithoface consists of rhythmically-bedded gray, silty clay and red clay that was related to deltaic deposition. The stratigraphically highest marine deposit ranges from clay to sand texture, and was apparently the upper unit of prograding delta. Fine-textured sediments associated with deposits of the Champlain Sea reach thicknesses of ~100m adjacent to and north of the present location of the Ottawa River. In deeper sections of the basin, beach sands and gravels were deposited where suitable parent material existed at the limits of the

Champlain Sea. Also, during the retreat of the Champlain Sea, a thin layer of littoral and sublittoral sands was deposited over finer Champlain Sea deposits in many parts of the basin (Fulton, 1987).

3.2.2 DESCRIPTION OF SOIL SERIES SAMPLED IN EXPERIMENT

The kit was developed and tested on five agriculturally important soil series in Eastern Ontario: North Gower, Carp, Uplands, Grenville and Mountain soil series.

3.2.2.1 North Gower

The North Gower soil is an Orthic Humic Gleysol developed on moderately fine-textured, modified marine parent materials and occupies level and very gently sloping positions. It is poorly drained, slowly pervious and subject to water saturation for much of the growing season. The surface horizon is very dark gray to very dark grayish brown with granular to blocky structure. The subsoil is olive gray to dark gray with subangular to angular blocky structure (Marshall et al., 1979).

3.2.2.2 Carp

The Carp soil is a Gleyed Gray Brown Luvisol developed on moderately fine-textured, modified parent materials and occupies mid and upper slopes of gently sloping landforms. It is imperfectly drained and moderately to slowly pervious. The surface horizon is very dark gray with a granular surface layer, high in organic matter, 12 to 20 cm thick. The subsoil is grayish brown to brown with subangular to angular structure (Marshall et al., 1979).

3.2.2.3 Uplands

The Uplands soil is an Orthic Humo-Ferric Podsol developed in medium to fine-grained marine, estuarine and fluvial sands and occupies the crest of irregular undulating to hummocky dunes. It is excessive to well-drained. The surface horizon consists of a weak granular, dark gray to very dark brown Ah horizon, 8-12 cm thick. The subsoil is strong brown to reddish brown with a single grained structure (Marshall et al., 1979).

3.2.2.4 Grenville

The Grenville soil is an Eluviated Melanic Brunisol developed on moderately coarse to medium-textured, stony till and has good to rapid natural drainage and moderately pervious subsoils. The surface horizon is very dark grayish brown with a granular surface horizon (Ap), 12 to 18 cm thick, usually high in organic matter. The subsoil is grayish brown to light brownish gray with subangular blocky to granular structure. The parent material is a compact, massive, slightly impervious till, olive gray to light grayish brown in color (Marshall et al., 1979).

3.2.2.5 Mountain

The Mountain soil is a Gleyed Sombric Brunisol developed in strongly acid, coarse-textured marine, estuarine and fluvial veneer overlying neutral, moderately fine to fine-textured marine materials and occupies mid to lower slopes. It is imperfectly drained and therefore subject to water saturation for short periods during the growing season. The surface horizon is very dark grayish brown to dark brown, with a granular structure. The subsoil is grayish brown with a single grained structure (Marshall et al., 1979).

3.2.3 SOIL QUALITY “MONITORING” KIT VERSUS A SOIL QUALITY “TEST” KIT

Field investigation of soil quality test kits (SQTk) developed by the United States Department of Agriculture (USDA) and the New Zealand (NZ) Institute for Crop and Food Research indicate that the kits are either unsuitable for soils and climates of Eastern Ontario (and possibly the rest of Canada) (NZ SQTk), or are too technical (USDA SQTk). These aspects provide barriers for farmers adopting and regularly using the kits. While some of the tests used in the NZ and USDA test kits have been adopted for use in this project, the ultimate goal of the SQMK is to provide simple methods - based on more complex approaches - for tracking change, while providing the basis for adapting management decisions over time. Its purpose is not to provide irrefutable answers with statistical confidence attached to them, but if used correctly, the SQMK can accurately document changes in soil conditions and detect qualitative changes. Monitoring can help farmers know if changes in soil quality are really happening. Monitoring can also help farmers check the progress towards their goals and re-focus their efforts (Wrysinski, 2002).

3.2.4 DATA COLLECTION

The SQMK was tested at 11 sites (9 X 9 meters) at the Central Experimental Farm in Ottawa, Ontario during May to July, 2006 (Figure 3.2). Six of the 11 sites were used for comparative analysis among management systems (within soil types) and are therefore grouped as follows: compacted and non-compacted clay sites (C-C and C-NC respectively); compacted and non-compacted sand sites (S-C and S-NC respectively); and no-till and conventionally tilled corn-soybean-wheat rotation sites (NT-CSW and CT-

CSW respectively). The remaining 5 sites were used for analysis of test precision within individual sites (in conjunction with above-mentioned management sites) and consist of conventionally tilled continuous soybean (CT-SSS); no-till continuous corn (NT-CCC); and 3 clay loam long-term conventionally tilled sites (CL-LTCT 1, CL-LTCT 2, CL-LTCT 3). Four of the sample locations are in Field One-Center Field, which is a long-term tillage trial (under current management for 18 years). The tillage sites consist of CT-CSW and NT-CSW Grenville soil series (good to rapid natural drainage, fine sandy loam), and CT-SSS Grenville soil series and NT-CCC Uplands soil series (excessive to well-drained fine sandy loam), both of which are common agricultural soils of Eastern Ontario. Four of the sample locations are in Caldwell Field North (Field 8 and 9), which consists of long-term conventionally-tilled sites (i.e., 10 years). Field 8 consists of C-C and C-NC (North Gower, poorly-drained clay); S-C and S-NC sites (Mountain, imperfectly-drained very fine sandy loam over clay) (compacted in 2002 and 2003; under continuous corn for 10 years). The sites were compacted when the soil was wet using a heavy manure application truck. Field 9 (currently under soybean, previous 10 years under grass) consists of CL-LTCT 1 and CL-LTCT 2 (North Gower, poorly-drained clay loam); and CL-LTCT 3 (Carp, imperfectly-drained clay loam). Soil samples were collected from each field and analyzed for texture by standard laboratory methods. Site characteristics are summarized in Table 3.1.

Soil samples were collected from the headlands (i.e., the unplowed land at the end of a plowed field), in areas representative of the entire field. Samples were taken inter-row where applicable and obvious field implement tire tracks were avoided. All sample locations were geo-referenced using a Gorman hand-held GPS. For individual sites all

Table 3.1: Site characteristics of management systems at the Central Experimental Farm, Ottawa, Canada. CT-SSS= conventionally tilled continuous soybean; NT-CSW= no-till, corn-soybean-wheat rotation; CT-CSW= conventionally tilled, corn-soybean-wheat rotation; NT-CCC= no-till, continuous corn; C-C= clay compact; C-NC= clay non-compact; S-C= sand compact; S-NC= sand non-compact; CL-LTCT represents clay loam long-term conventionally tilled sites. Soil texture was determined by particle size analysis (University of Guelph, 2006). Management types with the same number of * were compared against one another for comparative analysis.

Site	Management	Soil Series	Texture	Slope	Drainage	Geologic Origin
Field 1- Center Field	CT-SSS	Grenville	Fine Sandy loam	1-5%	Good to rapid natural drainage	Glacial Till
	NT-CSW*	Grenville	Fine Sandy loam	1-5%	Good to rapid natural drainage	Glacial Till
	CT-CSW*	Grenville	Fine Sandy Loam	1-5%	Good to rapid natural drainage	Glacial Till
	NT-CCC	Uplands	Very Fine Sandy Loam	2-5%	Excessive to well drained	Marine and Fluvial

(Table continued on next page)

(Table 3.1 continued)

Field 8- Caldwell Field North	C-C**	North Gower	Clay	0-2%	Poorly Drained	Modified Marine
	C-NC**	North Gower	Clay	0-2%	Poorly Drained	Modified Marine
	S-C***	Mountain	Very Fine Sandy Loam over Clay Loam	1-3%	Imperfectly Drained	Marine and Fluvial veneer overlying marine materials
	S-NC***	Mountain	Very Fine Sandy Loam over Clay Loam	1-3%	Imperfectly Drained	Marine and Fluvial veneer overlying marine materials
Field 9- Caldwell Field North	CL-LTCT 1	North Gower	Clay Loam	0-2%	Poorly Drained	Modified Marine
	CL-LTCT 2	North Gower	Clay Loam	0-2%	Poorly Drained	Modified Marine
	CL-LTCT 3	Carp	Clay Loam	2-5%	Imperfectly Drained	Modified Marine

Management types with the same number of * were compared against one another for comparative analysis.

sampling was completed within the same day. No rainfall events occurred during any sampling, which minimized the risk of significant soil moisture differences.

3.2.5 THE SOIL QUALITY MONITORING KIT (SQMK): COMPONENTS AND METHODS

Preliminary assessment of the ease-of-use and utility of soil quality test kits created by the USDA (United States Department of Agriculture) and New Zealand Institute Crop and Food Limited facilitated the selection of components and procedures included in the SQMK (Appendix A1). The SQMK consists of a portable toolbox, which includes most of the equipment required to complete the tests. It is fully stocked, although pH indicator dye needs to be replenished periodically. The user must supply distilled water and a shovel. A guide, included in the kit, outlines each test, provides step-by-step instructions and offers an interpretation of typical results. Once data are collected, the results can be recorded in a data log where changes in their values can be monitored over time. The following discussion describes the proposed components and methods used in the SQMK.

3.2.5.1 PHYSICAL SOIL QUALITY ASSESSMENT

3.2.5.1.1 Penetration Resistance - Penetration resistance is a common measure of soil compaction (Fulton et al., 1996; Goodman and Ennos, 1998; Herrick and Jones, 2002; Kenney et al., 2002; Duiker, 2002; Vanags, 2006). It is measured by determining cone index values using a dynamic cone penetrometer (Figure 3.3). The penetrometer used in this study is based on the design of Herrick and Jones (2002). The penetrometer uses a 4.55 kg steel slide hammer falling 46 cm that strikes the anvil to cause penetration of a

Figure 3.3: The Dynamic Cone Penetrometer – at 30 cm penetration.

3.8-cm diameter cone (45° vertex angle). Rod diameter is slightly smaller than the cone base diameter, to minimize friction between the penetrometer and the soil material. For the measurement, the penetrometer is placed with the cone tip at the soil surface and the shaft oriented vertically. The cone is pressed into the soil until it just becomes buried (i.e., soil surface is level with the base of the cone). This reduces variability in starting

depth (Herrick and Jones, 2002). A small circular bubble level placed on the shaft of the penetrometer enables the operator to keep the penetrometer vertical. The slide hammer is raised to a height of 46 cm and then released. This operation defines one “blow” and this is repeated until a penetration depth of 30 cm is reached. Soil cores were taken (within 15 cm of PR readings) and dried at 105⁰C for 72 hours to determine gravimetric soil moisture content.

The dynamic cone penetrometer was chosen to evaluate soil compaction over other penetrometers (e.g., static-cone penetrometer) mainly due to its ease, speed-of-use and low instrument cost. The collar and extended shaft length help ensure repeatability since the weight is dropped from a specified height instead of relying on human energy to move the cone forward. This also makes the penetrometer adaptable to a wide range of field conditions due to its reliance on repeated blows rather than the strength of a particular operator. The range can be increased further by changing the drop height. This flexibility allows a single penetrometer to be used on a broad range of soils without a loss in sensitivity or an increase in measurement time by simply moving the adjustable collar. In addition, it allows the operator to increase the sensitivity in specific zones in which compaction is expected to occur. Lastly, there are no gauges to be recalibrated (Herrick and Jones, 2002).

3.2.5.1.2 Bulk Density - Bulk density is a measure of soil compaction. In the field, bulk density cores are taken using an 8-cm diameter ring (13 cm tall). Cores were taken at the mid-point between 0-15 and 15-30 cm depth (centered on 7.5 and 22.5 cm respectively). The cores are removed by digging around the ring and placing a trowel underneath it. Using a flat-bladed knife excess soil is trimmed from the bottom of the core to even it

with the edges of the ring. The soil core is placed in a bag and brought to the laboratory for further analysis. In the laboratory, bulk density is determined by drying the soil sample in a 105°C oven for 72 hours. Bulk density is then calculated by dividing the dry weight by the soil volume (i.e., volume of the corer).

3.2.5.1.3 Infiltration Rate - Infiltration rate provides a measurement of the rate at which water enters the soil surface. Infiltration tests are performed using a stainless steel, 15-cm diameter and 13 cm tall ring infiltrometer (Figure 3.4), which is inserted 8 cm into the soil surface. 444 ml (2.54 cm depth) of distilled water is poured into the ring and the time it takes for the water to infiltrate is recorded. If the soil is not at field capacity when the test is performed, a second infiltration test immediately follows. The first application of water wets the soil and the second application provides a more accurate measurement of the infiltration rate of the soil (USDA, 1999). Soil infiltration rate/hr is calculated by the equation: $(1/\text{second infiltration time (minutes)}) * 60$. Previously disturbed areas were avoided.

The single ring infiltrometer was chosen over other methods (e.g., double ring infiltrometer) to measure infiltration rate because it provides sufficiently accurate measurements without requiring excessive time and water to complete the test. Most importantly, the ring infiltrometer is inexpensive, portable, and easy to use.

3.2.5.1.4 Slake Resistance Rating - Soil slaking is an indicator of soil tensile strength; an important influence on soil's resistance to water erosion. Slaking can be assessed using a stability kit (Figure 3.5). The stability kit consists of a plastic tray with 12 box compartments and sieve baskets. Twelve (approximately 1 cm³) soil fragments are

Figure 3.4: Ring infiltrrometer.

Figure 3.5: Slake resistance tray

removed from the soil surface, placed in the sieve baskets of the stability kit and air-dried (alternatively, surface aggregates can be collected at field moisture content, on a day when the soil surface is dry (i.e., soil has not received rain or irrigation within 24-48 hours). After the fragments are air-dry, approximately 2 cm depth of distilled water is added to each box compartment, and sieve baskets containing the soil fragments are

lowered one by one into a water-filled box compartment. Soil stability is rated according to the time required for the fragments to disintegrate (if they do or to the extent that they do) during the 5-minute immersion and the proportion of soil fragment remaining on the sieve after subsequent 5 extraction-immersion cycles (Table 3.2). The stability rating is recorded for all 12-soil fragments and averaged for interpretation. The slake test yields a rating of 0 (unstable) to 6 (stable). Soil fragments or aggregates which fall into classes 0 to 3 are relatively unstable. Class 4 indicates some stability, but very little strength. Classes 5 and 6 represent relatively stable soil fragments or aggregates (USDA, 1999). The slake test was chosen over other methods (e.g., aggregate stability by wet sieving) to measure structural stability mainly because it can be performed in-field and provides quick results. Tests such as wet aggregate stability are detailed, time consuming and must be performed off-site in properly equipped laboratories.

3.2.5.1.5 Organic Matter Monitoring Card/Soil Color - This section emphasizes the use of soil organic matter as a physical soil quality indicator, as it affects many important physical properties such as soil aggregation and soil water availability. Important to note, however, is that soil organic matter can also be used as an indicator of a soil's chemical (e.g., nutrient storage and release, microbial enhancement of nutrient availability, cation exchange capacity, sorption of organic compounds, anion sorption, metal mobility and soil pH buffering and amelioration) and biological quality (e.g., activities of bacteria, fungi, actinomycetes, earthworms, roots, and other microorganisms) (Fenton, 1999).

Visual soil organic matter assessment provides a general indication of trends in soil organic matter levels under cropping. Soil organic matter content is estimated in the field by comparing field moist samples (collected at 5 cm depth using a spade) to the

Table 3.2: Stability Class Table (adopted from USDA, 1999).

Stability class	Criteria for assignment to stability class
0	Soil too unstable to sample (falls through sieve).
1	50% of original shape lost within 5 seconds of insertion in water.
2	50% of original shape lost 5-30 seconds after insertion.
3	50% of original shape lost 30-300 seconds after insertion or less than 10% of soil remains on the sieve after 5 dipping cycles.
4	10-25% of soil remaining on sieve after 5 dipping cycles.
5	25-75% of soil remaining on sieve after 5 dipping cycles.
6	75-100% of soil remaining on sieve after 5 dipping cycles.

Organic Matter Monitoring Card (OMMC) (Figure 3.6). This card consists of a 10YR Munsell soil color chart, which contains the range of soil colors most commonly found in Eastern Ontario. Generally a darkening of soil color over time indicates an increase in soil organic matter content; while a lightening of soil color can indicate degradation of soil organic matter content (assuming similar field moisture conditions). The OMMC was chosen over other methods (e.g., combustion method) to assess soil organic matter content because it can be performed on site and gives immediate results. All other methods of organic matter determination involve collection, and subsequent laboratory analysis.

Figure 3.6: Munsell color sheet (10 YR)/OMMC

3.2.5.2 CHEMICAL SOIL QUALITY ASSESSMENT

3.2.5.2.1 Soil pH - Soil pH provides a measure of the degree of acidity or alkalinity of a soil. It is measured using a colorimetric pH test kit (Figure 3.7). The kit consists of indicator dye, plastic test plates, a color chart and a glass rod. Soil pH is determined by filling the large depression in the spot plate approximately $\frac{1}{2}$ full of soil. Soil subsamples for pH were obtained from the wall of the earthworm count pit (5-10 cm depth). A small amount of *Chlorphenol Red* indicator dye is added. Chlorphenol Red covers the range from pH 5.0 to 6.8, which is adequate for Ottawa region soils. Using the glass rod, a thin layer of the dye is drawn into the groove on the test plate. Soil pH is determined by comparing the color of the dye with the color chart. A colorimetric pH test was chosen

Figure 3.7: Colorimetric soil pH test kit.

over other tests (e.g., pH meter) to measure soil pH because it is easy to use and inexpensive. Soil pH meters are more costly, require regular maintenance and calibration.

3.2.5.3 SOIL HABITAT QUALITY ASSESSMENT

3.2.5.3.1 Earthworm Count - Earthworm counts provide an estimate of earthworm abundance. A count is determined by removing soil from a 30 x 30 cm site (to a depth of approximately 15 cm) and placed on a tarpaulin. The soil is sorted, one handful at a time. Earthworms are collected in a bottle and returned to the soil when the count is complete (Figure 3.8). A manual earthworm count was chosen over other methods (e.g., mustard extraction) to assess earthworm populations because it is easy to perform and has no associated cost.

Figure 3.8: Earthworm count being conducted.

3.2.5.4 SQMK: SAMPLING GUIDELINES

3.2.5.4.1 Where to sample?

To monitor changes in soil quality parameters over time, the same local area (within 1-2 meters) within the field must be measured at each monitoring (testing) time. Measurements should also be taken in the same season and under similar moisture conditions each time to reduce variability (USDA, 1999).

3.2.5.4.2 How many samples?

The number of samples to take depends on the size and variability of the field. It is recommended that a minimum of 3 samples or measurements be taken on any one soil type and management combination (USDA, 1999). In general, the greater the variability of the field, the greater the sample number needed to get a representative value at the

field scale. When measuring penetration resistance and pH, eight or nine samples/measurements from across the field should be taken. Soil pH samples can be bulked and mixed, and two subsamples from the mixed samples can be analysed. When sampling across the field, it is important to stay away from areas that are not representative of the field, such as farm lanes and field borders, or eroded spots (unless one is specifically trying to use management practices to improve such locations) (USDA, 1999).

3.2.6 STANDARD FIELD AND LABORATORY METHODS

To explore how selected kit tests (soil pH, OMMC and slake resistance rating) relate to more standard measures, results from the kit were compared to results obtained using standard field and laboratory analysis. The following discussion describes the standard field and laboratory methods used in this study.

3.2.6.1 Physical Soil Quality Assessment

3.2.6.1.1 Soil Organic Matter - In the field, core samples are collected from 5-10 cm below the soil surface. In the laboratory, samples are oven dried at 105°C, ground and sieved using a 2-mm sieve. Organic carbon is determined by subtracting the inorganic carbon from the total carbon for each sample. Inorganic carbon is determined as follows. The sample is heated in a muffle furnace at 475°C for 4 hours (to eliminate organic carbon) and the inorganic carbon is measured, using a LECO C analyzer, by total combustion of the sample and infra-red determination of the resulting CO₂. The carbon is expressed in % compared with dry weight. The total carbon is also determined using the LECO C analyzer, but without prior removal of the organic carbon. Organic matter is

comprised of approximately 58% organic carbon; percent organic matter is therefore calculated by multiplying organic carbon by 1.724 ($1/0.58$) (Gregorich, personal communication, 2008).

3.2.6.1.2 Aggregate Stability - Aggregate stability provides an estimate of the soil's ability to resist water erosion. The more stable the aggregate, the less vulnerable it is to slaking or structural degradation from rapid wetting. Measurements are performed using a 73-mm diameter corer, which is inserted 75-mm into the soil surface. Soil samples are bulked and sieved using 5-mm and 2-mm sieves. The sieved aggregates are air-dried for 3 days. A 25-g sub-sample is wet sieved using a structural stability tester developed by USDA. The aggregates remaining on each sieve after wet sieving are air dried for approximately 4 days. Soil structural stability is calculated by comparing the final weight of the surviving air dried aggregates to the sub-sample initial weight (USDA, 1999).

3.2.6.2 Chemical Soil Quality Assessment

3.2.6.2.1 Soil pH - In the field, subsamples are collected from 5-10 cm below the soil surface. Soil pH measurements are made using a *Fisher Scientific Accumet pH AR20* meter, which consists of a conventional glass pH electrode. Solution temperatures are measured using an *Automatic Temperature Probe* (Fisher Scientific, p. 61).

3.2.7 FIELD SAMPLING DETAILS (SAMPLE NUMBER AND RELATIVE LOCATION): SQMK AND STANDARD TESTS

3.2.7.1 The Soil Quality Monitoring Kit

Using the components and methods of the SQMK described above, the SQMK was field tested at the Central Experimental Farm, Ottawa. Table 3.3 summarizes field sampling details (i.e., sample number and relative sample location).

Table 3.3: Summary of sample number and relative sample location-SQMK, CEF, Ottawa, ON.

Test	Experimental methods
Penetration resistance	<p>-20 measurements were taken 46 cm apart, along a linear transect in the center of each field.</p> <p>- PR is measured as the number of blows required to penetrate 0-15 cm and 15-30 cm depth ranges (note: PR can also be expressed as work done (Jcm^{-1}). Refer to Appendix A2).</p> <p>- To assess variability in soil moisture, soil cores were dried at 105°C for 72 hours to determine gravimetric water content. Core samples were immediately bagged, sealed and returned to laboratory for analysis.</p>
Infiltration*	<p>- 10 replications of infiltration were taken at each site. Samples were located 91 cm apart, along a linear transect near the center of each field.</p>
Soil Slaking/Soil Stability* Rating	<p>-10 replications of 12 aggregates were sampled at each site. The sample areas were located 91 cm apart, adjacent to bulk density pits. 12 surface zone (1-cm^3) aggregates were removed from a 30-cm squared area. Recently disturbed areas were avoided.</p>

(Table continued on next page)

(Table 3.3 continued)

Visual Soil Organic Matter Assessment/OMMC	10 measurements were taken, 91 cm apart, along the center of the field (adjacent to bulk density samples). Samples were taken randomly 5-10 cm below the soil surface using a spade. Samples were moistened with water prior to color assessment. Wet color is compared to a Munsell color chart (10YR).
Earthworm Abundance*	- 10 earthworm measurements were taken 91 cm apart, along a linear transect in the center of each field. Earthworm pits were 30 X 30 cm (to a depth of 15 cm). Endogeic (surface dwelling 0-15 cm) earthworms were counted only.
Soil pH	-10 replicates were performed at each site. Soil samples for pH were taken randomly from the wall of bulk density pits (5-10 cm below the soil surface). Soil pH was determined colorimetrically using a pH test kit.
Bulk density	<ul style="list-style-type: none"> - 10 measurements were taken adjacent to penetrometer readings (15-cm from penetrometer readings, 91cm apart), along the center of each field. -bulk density and PR measurements were taken simultaneously. - Bulk density cores were taken at the mid-point between 0-15 and 15-30 cm depth (centered on 7.5 and 22.5 cm respectively). -bulk density cores were oven dried at 105°C for 72 hours.

*method was adopted from the USDA Soil Quality Test Kit

3.2.7.2 Standard Measurements

Using the standard field and laboratory procedures discussed in section 3.2.3.4, measurements were taken to examine how results from the SQMK tests relate to more standard tests. Table 3.4 summarizes standard field sampling procedures used in this study.

3.3 FARM APPLICATION PHASE

3.3.1 FARM APPLICATION OF THE SOIL QUALITY MONITORING KIT, CARLETON PLACE, ONTARIO

3.3.1.1 Background

The main purpose of on-farm evaluation is to evaluate the kit and its ability to detect the maximum extent of current local differences within a farmer's field. Unlike fields at the CEF, a farmer's field commonly consists of a single soil series in which disturbed areas (i.e., cultivated field) are located within relatively close proximity to non-disturbed areas (i.e., long established fence lines). It is hypothesized that the selected kit tests will be sensitive to a range of differences in soil quality as they are present in a farmer's field. To test this hypothesis, areas expected to be of lower soil quality (conventionally managed farmer's field, perpendicular and parallel to tillage direction) and areas expected to be of higher soil quality (fence line and higher organic matter area) were sampled using selected tests from the SQMK; tests conducted include PR, OMMC and infiltration. Kit results were compared to results obtained using standard field and laboratory analysis of bulk density and organic matter content.

Table 3.4: Summary of sample number and relative sample location-Standard tests, CEF, Ottawa, ON.

Test	Experimental methods
Organic Matter	-Soil samples for organic matter determination were taken from the 0-15 cm bulk density samples. -10 random subsamples were obtained from each site.
Soil pH	-Soil subsamples for pH analysis were taken randomly from the wall of bulk density pits (5-10 cm below soil surface). -10 subsamples were obtained from each site.
Aggregate stability	-10 measurements were taken adjacent to bulk density pits (91 cm apart), along the center of the field.

3.3.1.2 Regional Setting and Geography

The experimental site chosen is located in Lanark County approximately 47 km west of the Central Experimental Farm on North Gower clay loam soil series. The topography is gently sloping, with slopes between 2-5%. The Ap horizon is about 15 cm thick, with medium to coarse, subangular and angular blocky structure. The structure of the underlying clays becomes more massive and bedded with depth. The soil is permeable, free of stones, and has a high moisture holding capacity (Ministry of Agriculture and Food, 1979).

3.3.1.3 Description of Experiment

Prior to this experiment, the site had been uniformly managed (for 15 years) in a vegetable rotation (tomatoes, cucumbers and cabbage), using conventional tillage management to control weeds. All tillage operations were performed using a moldboard plow. All sampling was completed within the same day and took place the first week of

October 2007. There were no rainfall events during or immediately before this sampling period. Areas of higher and lower soil quality were selected with the farmer's assistance. Location of samples with regards to row or inter-row areas was uncertain as moldboard plowing took place 1 week prior to sampling.

To assess the sensitivity of the penetrometer to soil quality variations within the farmer's field, soil penetrometer readings were taken along linear transects from small sections within the center of the cultivated field, along the fence line and in a slight depression assumed to have higher organic matter content. In the center of the field, 5 readings were taken, 15 cm apart, parallel to the tillage direction and 5 were taken perpendicular to tillage direction (Figure 3.9). Four penetrometer readings were also taken along a nearby fence line, 15 cm apart, and 4 were taken in a slight depression within the cultivated field (15 cm apart), which was darker in color but contained the same soil type and had similar moisture conditions. In cultivated soils, surface soil is most subject to both compression and displacement from machinery. A penetrometer measures the net of these opposing effects. Largely to avoid the variability of these effects in the surface soil, the first 2 measurements below the bottom of the Ap layer (which in this study lies at approximately 15 cm depth) are proposed for the assessment of changes in penetration resistance (PR). It is also postulated that measurements taken from this depth are most representative of soil PR as shaft friction is assumed to be 0 at approximately 15 cm depth and only minimal immediately following this depth; below this depth, the shaft friction is expected to increase. For the purposes of this study, PR is measured on a per blow basis, to a depth of 30 cm, and results are expressed as blows/cm. It is proposed that a depth resolution of 1 cm is necessary to detect the thin, dense layers

Figure 3.9: Field sample locations for bulk density and PR measurements (center of cultivated field), farmer's field, Carleton Place, ON. R=repetition number.

often found in soil compacted by wheels (Ball et al., 1997). By recording depth of penetration per blow, the depth resolution of the penetrometer, in terms of its ability to detect potentially problematic soil layers and their depth in the soil profile, could more closely be evaluated. Such an evaluation could not be achieved from the CEF data, as results were averaged over 15 cm depth increments. To examine the relationship between PR and bulk density, standard bulk density samples were taken within 15 cm of penetrometer readings, every 6 cm to a depth of 30 cm. Gravimetric soil water content was determined using samples collected for bulk density.

To assess the utility of the Organic Matter Monitoring Card (OMMC), areas (within the cultivated field) presumed to have different organic matter contents (with the

same soil type and similar moisture conditions) were sampled and Munsell values were recorded. Differences in organic matter content were verified by standard organic matter analysis. The area chosen was located in a slight depression, it appeared darker in color and it was therefore assumed to have higher organic matter content. Samples were also taken in a section of the field presumed to have lower organic matter content. This area was located adjacent to PR and bulk density transects (parallel to tillage direction), it appeared lighter in soil color and was not located in a depression. Ten measurements were taken for soil color assessment, and 10 samples were collected for standard organic matter analysis. Measurements were taken randomly 5-10 cm below the soil surface using a spade, within a 30 cm square area.

Lastly, the relationship between organic matter and infiltration was assessed. Three infiltration measurements (along a linear transect, approximately 35 cm apart) were made in the section of the field containing lighter soil color (adjacent to bulk density and PR samples, parallel to tillage direction) and 3 were made in the section of the field containing darker soil color (parallel to tillage direction).

3.3.2 FARMER ACCEPTANCE TESTING

3.3.2.1 Background

One of the most essential components of this research is farmer acceptance testing. The ease-of-use of the Soil Quality Monitoring Kit was assessed by 12 different farm owners at their farm sites. Of these farmers, 8 were organic and 4 were conventional (all were cash crop farms). Farm sizes ranged from less than 1 acre to approximately 100 acres. Farmers ranged in age from approximately 35 to 55 years old; and 11 of the 12

farmers were male. All farmers interviewed already practiced some sort of soil quality monitoring (e.g., fertility tests). Farmers completed a questionnaire (Appendix A3), which consisted of multiple choice questions relating to the ease-of-use of the kit. Space was also allotted for farmer comments on how to improve the kit.

3.3.2.2 Farmer Site Locations and Soil Characteristics

Farmer site locations were based on soil association and the farmer's willingness to cooperate. All farm sites were located within the Ottawa region. Locations include: Carleton Place; Plantagenet; Ottawa; and Almonte (Figure 3.10). To evaluate the ease-of-use of the Soil Quality Monitoring Kit on some of the major soil associations occurring in Eastern Ontario, 4 sites were located on Uplands associations, 4 on North Gower associations, and 4 on Grenville associations.

3.3.2.3 Field Methods Used

To assess the ease-of-use of the tools and manual included in the Soil Quality Monitoring Kit, all tests were conducted by the farmer, without researcher assistance. The farmers generally chose to test perceived problem areas within their fields, and using the manual, performed each test and recorded their results on the monitoring sheets provided with the Soil Quality Monitoring Kit.

3.4 STATISTICAL METHODOLOGY

Statistical analyses were performed on results from the soil analyses. Data were checked for normality using the Kolmogorov-Smirnov test in Microsoft Excel. For most data sets the null hypothesis was not accepted (i.e., the data were not normally distributed), thus the non-parametric versions of Student's t-test and Pearson's correlation

Figure 3.10: Relative location of farmer's sites who participated in kit assessment. Map represents dominant values of parent material mode of deposition (Soil Landscapes of Canada v.2.2).

coefficient were used, the Mann-Whitney U test and the Spearman Rank Correlation test respectively. To address precision of kit measurements the coefficient of variation of means was calculated.

3.4.1 Mann-Whitney U Test

The Mann-Whitney two-sample U test (using StatistiXL software) was used to determine if significant differences exist between 2 sample populations. It is sensitive to differences in central tendency and is therefore regarded as the most powerful alternative to the Student's t-test of a difference between two sample means, and is most appropriate when the assumptions of the Student's t-test are not met. The Mann-Whitney U test is applicable to small numbers of samples (i.e., $N=5$) as to large numbers, and unequal numbers of samples can be compared (Matthews, 1981). It requires that the data sets are taken independently of each other. If the calculated value of P is less than or equal to the critical value at a given level of significance (0.05), the null hypotheses can be rejected, meaning there is a significant statistical difference between the two sample populations (Matthews, 1981). In all cases a two-tailed test was used.

3.4.2 Spearman's Rank Correlation Coefficient

The Spearman's Rank Correlation Coefficient is a non-parametric measure of the relationship between two sets of data. It can be applied to data that are inherently ordinal, or to interval data converted to rank form and it does not require normal distributions or a linear relationship. It is therefore a useful alternative when the assumptions of the parametric correlation (Pearson's correlation coefficient) cannot be met. The calculated r_s statistic varies from -1.0 to +1.0. This number signifies two things: (1) the direction of the relationship (i.e., positive or negative); and (2) the strength of the relationship. If r_s is

close to 1, the two variables are considered to have a strong relationship. If the number is close to 0, the relationship between the two variables is considered to be weak. If the calculated value of P is equal to or greater than the critical value at a chosen significance level (0.05) the null hypothesis can be rejected, meaning there is a significant rank correlation between the two variables (Ebdon, 1985).

3.5 SQMK MANUAL

Detailed procedures for kit tests, as recommended to the user, are presented in a manual. The manual includes step-by-step instructions for individual tests, data monitoring sheets, and background and interpretative information (Appendix A5).

4. RESULTS AND DISCUSSION

The ultimate goal of this project is the development of a soil quality monitoring kit that will aid farmers in assessing the success or failure of their agricultural production practices in maintaining and improving the quality of the soil resource that is essential to their success. The questions that must be answered in the evaluation of such a proposed kit include:

Does the kit provide precise measurements of selected soil quality parameters?

Is the kit sensitive to differences in selected soil quality parameters?

Do farmers find the kit relatively quick and easy to use?

This section will address these questions for the proposed kit using three sources of information:

1. Field data, collected at the Central Experimental Farm, Ottawa, Canada, was used to assess the kit measurements of selected parameters against standard procedures of analysis for that parameter (where such procedures exist), or against a possible alternative procedure. The statistical characteristics of each measured parameter within a specific soil type and treatment type (where appropriate) was determined. The results of individual kit tests (where appropriate) were also compared with one another to determine if consistent correlations exist across soil types, or if these are soil type specific.
2. Field data, for a single soil type on a farmer's field near Carleton Place, Ontario, collected using selected kit tests and standard procedures of analysis, was analyzed in a similar manner to that from the Central Experimental Farm.

3. Field data on the efficiency and ease-of-use of the Soil Quality Monitoring Kit was assessed from responses of individual farmers who tested the kit on their farm. The farmers were interviewed as to: their judgment of the ease-of-use and applicability of the kit; whether, in their individual opinions, the kit measured parameters that they accept as being important aspects of soil quality; and whether they would see themselves taking advantage of the kit (if it became available) to monitor the responses of their soils to their management practices over extended time periods.

4.1 SOIL QUALITY MONITORING KIT DEVELOPMENT PHASE

4.1.1 PHYSICAL SOIL QUALITY ASSESSMENT

4.1.1.1 PENETRATION RESISTANCE (PR)

Penetration resistance is directly correlated with soil strength (Moreno et al., 2000; Boizard et al., 2000; Castrignano et al., 2000; Ferrero and Lipiec, 2004), and expresses the soil resistance to penetration by roots. Penetration resistance has been observed to decrease as moisture content increases, because the presence of more water decreases the cohesion between particles and acts as a lubricant, thus reducing frictional forces that need to be overcome to shear the soil (Vanags et al., 2006). Analyses of soil moisture between depths (0-15 cm and 15-30 cm) and management systems (clay compacted (C-C) vs. clay non-compacted (C-NC), and sand compacted (S-C) vs. sand non-compacted (S-NC) show no significant differences in soil moisture content by depth (with the exception of NT-CSW and CT-SSS) within individual management systems (Appendix A4, Table A) and between management systems (with the exception of NT-

CSW and CT-CSW sites) (Appendix A4, Table B) ($P < 0.05$). For the comparative analysis that follows, sites and depths showing significantly different moisture contents were not included.

Comparison of PR measurements for the compacted and non-compacted clay and sand soils demonstrate that the penetration resistance is greater over each depth range for the compacted sites than for the non-compacted sites (Table 4.1). At the C-C site PR averaged 14.9 ± 2.38 blows from 0-15 cm and 38.9 ± 8.30 blows from 15-30 cm, while the C-NC site averaged 6.5 ± 1.96 blows from 0-15 cm and 19.4 ± 5.48 blows from 15-30 cm. At the S-C site, PR averaged 5.9 ± 0.74 blows from 0-15 cm and 14.9 ± 2.69 blows from 15-30 cm, while the S-NC site averaged 4.2 ± 1.75 blows from 0-15 cm and 10.3 ± 1.34 blows from 15-30 cm. This is consistent with Moreno et al. (2000) who explained that compacted soils have higher PR than non-compacted soils because of higher soil strength. The Mann-Whitney U test confirms that, for all the above comparisons, the PR results come from different populations ($P < 0.05$).

These compacted and non-compacted clay and sand results can also show that over both depth increments for each treatment average PR for clay sites is higher than for sand sites. For 0-15 cm depth, PR results for clay were 14.9 ± 2.38 (compacted) and 6.5 ± 1.96 (non-compacted) while for sand they were 5.9 ± 0.74 (compacted) and 4.2 ± 1.75 (non-compacted); for 15-30 cm depth the results for clay were 38.9 ± 8.30 (compacted) and 19.4 ± 5.48 (non-compacted) while for sand they were 14.9 ± 2.69 (compacted) and 10.3 ± 1.34 (non-compacted). This is consistent with the results of Lamperlanes and Canter-Martinez (2003) who explain that clay enhances the formation of strong soil

Table 4.1: Statistical summary of PR results for all sites (0-15 cm and 15-30 cm), CEF, Ottawa, ON. C-C=clay compacted, C-NC=clay non-compacted, S-C=sand compacted, S-NC=sand non-compacted, NT-CSW=no-till corn-soybean-wheat rotation, CT-CSW=conventionally tilled corn-soybean-wheat rotation, NT-CCC=no-till continuous corn, CT-SSS=conventionally tilled continuous soybean, CL-LTCT=clay loam long-term conventionally tilled sites, SD=standard deviation and CV=coefficient of variation (N=10).

Site	Depth	Mean (No. of blows)	SD	Max	Min	CV (%)
C-C	0-15	14.9	2.34	18	12	16
	15-30	38.9	8.30	55	29	21
C-NC	0-15	6.5	1.96	11	4	30
	15-30	19.4	5.48	31	21	28
S-C	0-15	5.9	0.74	7	5	13
	15-30	14.9	2.68	19	11	18
S-NC	0-15	4.2	1.75	7	2	42
	15-30	10.3	1.34	12	8	13
CT-CSW	0-15	5.4	1.17	7	4	14
	15-30	10.8	1.99	14	8	26
NT-CSW	0-15	5.7	1.34	8	4	24
	15-30	11	1.05	13	9	10
NT-CCC	0-15	5.3	0.95	7	4	17
	15-30	13.0	2.21	16	9	17
CT-SSS	0-15	8.2	1.13	10	6	14
	15-30	13.5	1.08	15	12	8
CL-LTCT 1	0-15	4.7	0.48	5	4	10
	15-30	8.6	1.90	12	7	22
CL-LTCT 2	0-15	9.9	3.75	17	5	38
	15-30	33.1	8.24	44	19	25
CL-LTCT 3	0-15	7.0	1.25	17	5	18
	15-30	8.7	1.16	11	7	13

aggregates which increases PR readings. The Mann-Whitney U test demonstrated that the clay and sand results were from different populations ($P < 0.05$).

Comparison of PR data (Table 4.1) by depth (0-15 cm and 15-30 cm) across all management treatments (except NT-CSW and CT-CSW) show that average PR is higher for the 15-30 cm depth range than for the 0-15 cm depth range over all 9 sites tested. Soil strength increases with soil depth mostly as a result of lower organic matter content, less aggregation and root penetration as well as pressure exerted by overlying layers (Ditsch et al., 1996; Tsimba et al., 1999; Landsberg et al., 2003). Important to note, however, is that some of the increase in PR with depth may also be associated with increased shaft friction due to the increased contact area with the penetrometer shaft (Herrick and Jones, 2002). When PR data over the two depth ranges are tested for significance using the Mann-Whitney U test, they are confirmed to come from different populations ($P < 0.05$).

Repeated measures of PR within individual sites (Table 4.1) show CV values ranging from 8% to 42% across soil types, depths and management types. Compared to other studies, these results show comparable, and in many instances, better precision than similar penetrometers. For example, Meshalkine et al. (1995) used a static cone penetrometer to sample 55 locations within cultivated field and forest plots, results showed CV values of 75% and 35% respectively. Similarly, Utset and Cid (2001) reported CV values ranging from 7% to 80% for PR tests using a cone penetrometer within a cultivated field. Zimbone et al. (1996) tested PR within a cultivated field using 4 different soil strength devices (two torvanes, one hand held vane tester and one pocket penetrometer). CV results from each device ranged from 10% to 77%. Ferrero and Liepic (2005) reported CV values of 51% and 57% using a recording cone penetrometer. Roison

(2006) measured PR using an automated cone penetrometer and reported CV values ranging from 15% to 50%. The results from this study are well in line with these values and we can conclude that the dynamic cone penetrometer included in the kit offers precision comparable to other penetrometers.

4.1.1.1.1 Penetrometer - Suitability as a Monitoring Tool

The dynamic cone penetrometer provides a promising tool for assessing and monitoring compaction within a field. Results show that it is sensitive to differences in soil strength. In addition, under constant soil texture and moisture conditions, the penetrometer provides precision comparable to other penetrometers. The only problem of consequence occurred with stony soil into which the penetrometer could not be inserted satisfactorily. The penetrometer can be used to locate areas with compaction problems and has sufficient precision to monitor significant changes in soil condition in response to management. The principal advantages of using this method, compared to measuring bulk densities, are: its ease and speed of use; potential relationship with root elongation; immediate availability of results on-site, ability to rapidly locate areas of compaction within a field and zones of compaction within a profile (depth resolution is approximately 0.5 cm); and minimal disturbance of the surrounding area.

4.1.1.2 BULK DENSITY

Bulk density is a physical property that expresses the relationship between its mass and the volume it occupies; it indirectly reflects the structural condition and compactness of a soil (Hernanz and Sanchez-Giron, 2000). Unlike PR measurements which detected significant differences between all management sites tested (C-C vs. C-

NC and S-C vs. S-NC) at both depth increments (0-15 cm and 15-30 cm) (Table 4.1), bulk density only detected significant differences between 1 (C-C vs. C-NC) of the 3 (C-C vs. C-NC, S-C vs. S-NC and CT-CSW vs. NT-CSW) management sites tested at both depth increments (Table 4.2) ($P < 0.05$, Mann-Whitney U test). Furthermore, unlike PR measurements which detected significant differences between 0-15 cm and 15-30 cm depths for all sites tested (Table 4.1), bulk density measurements only showed significant differences between 0-15 cm and 15-30 cm depth increments for 4 of the 11 sites tested (Table 4.2) ($P < 0.05$, Mann-Whitney U test). Bulk density and PR generally increase with increasing soil depth mostly as a result of low organic matter, less aggregation and root penetration as well as pressure exerted by overlying layers (Ditsch et al., 1996; Tsimba et al., 1999; Landsberg, 2003). These results are consistent with similar studies that show the penetrometer is more sensitive to changes in soil strength than are bulk density cores (Ball et al., 1997; Sojka et al., 2001; Kenney et al., 2002; Motavalli et al., 2003; Czyc, 2004; Ferrero and Lipiec, 2005). The greater sensitivity of the penetrometer may be related to the different nature of the soil physical characteristics which PR is measuring (shear, compressive and tensile strength), that may not be related directly to bulk density (Motavalli et al., 2003). In addition, in this study, more samples were taken per site for the penetrometer data ($N=20$) compared to soil bulk density ($N=10$) and, therefore, soil PR may have been more representative of the treated area. Lastly, bulk density tests offer less depth resolution and consequently appear to be less sensitive than the penetrometer in detecting change in soil density.

When repeated measures of bulk density are analyzed (Table 4.2) results show CV values ranging from 2% to 11%. Warrick and Nielson (1980) summarized previous

Table 4.2: Statistical summary of bulk density results (0-15 cm and 15-30 cm), CEF, Ottawa, ON. C-C=clay compacted, C-NC=clay non-compacted, S-C=sand compacted, S-NC=sand non-compacted, NT-CSW=no-till corn-soybean-wheat rotation, CT-CSW=conventionally tilled corn-soybean-wheat rotation, NT-CCC=no-till continuous corn, CT-SSS=conventionally tilled continuous soybean, CL-LTCT=clay loam long-term conventionally tilled sites, SD=standard deviation and CV=coefficient of variation. Depths within the same site with different letters are significantly different from one another ($P < 0.05$; Mann-Whitney U test).

Site	Depth	Mean (g/cm ³)	SD	Max	Min	CV (%)
CC	0-15a	1.29	0.07	1.39	1.16	5
	15-30b	1.15	0.08	1.30	1.05	5
C-NC	0-15a	1.18	0.09	1.34	1.01	8
	15-30b	1.06	0.12	1.35	0.90	2
S-C	0-15a	1.45	0.08	1.55	1.35	5
	15-30a	1.53	0.11	1.66	1.32	7
S-NC	0-15a	1.39	0.11	1.50	1.17	6
	15-30a	1.45	0.10	1.56	1.30	7
CT-SSS	0-15a	1.44	0.04	1.49	1.36	3
	15-30b	1.48	0.06	1.60	1.37	4
NT-CSW	0-15a	1.39	0.04	1.45	1.33	3
	15-30a	1.47	0.04	1.52	1.37	3
CT-CSW	0-15a	1.38	0.11	1.54	1.21	8
	15-30b	1.51	0.10	1.68	1.40	7
NT-CCC	0-15a	1.30	0.07	1.46	1.16	6
	15-30a	1.32	0.05	1.40	1.24	4
CL-LTCT 1	0-15a	1.39	0.11	1.50	1.17	8
	15-30a	1.39	0.16	1.67	1.08	11
CL-LTCT 2	0-15a	1.21	0.09	1.36	1.07	7
	15-30a	1.22	0.10	1.46	1.12	9
CL-LTCT 3	0-15a	1.50	0.10	1.65	1.26	7
	15-30a	1.49	0.08	1.64	1.37	5

works showing that this property is not very variable within sites. They reported a spatial average CV of 7% which supports the results from this study.

4.1.1.2.1 Bulk Density Core Method - Suitability as a Monitoring Tool

The bulk density measurement was judged to be unsuitable for on-farm use. The amount of time required for sample removal and analysis (oven drying and weighing) may discourage farmers from using this test. Thus, unlike PR measurements, bulk density measurements are more technical, time consuming and do not provide instant feedback. In addition, bulk density tests offer less depth resolution and consequently appear to be less sensitive than the penetrometer in detecting change in soil strength. For these reasons, bulk density was not chosen for inclusion in the kit.

4.1.1.3 INFILTRATION RATE

Infiltration rate is one of the physical properties controlling leaching, runoff and crop water availability. Comparison of infiltration measurements (Table 4.3) for the compacted and non-compacted sand and clay sites demonstrate that average infiltration rate was slower for the compacted sand (13.06 ± 4.75 cm/hr) and clay (10.01 ± 3.66 cm/hr) sites than for the non-compacted sand (28.72 ± 17.82 cm/hr) and clay (17.98 ± 6.71 cm/hr) sites respectively. This is expected since soil compaction decreases porosity, and shifts pore shapes and size distributions towards smaller pore sizes (Topp et al., 1995; Zhang et al., 2006). Similarly, results show that infiltration rate was slower for CT-CSW (9.61 ± 3.19 cm/hr) than for NT-CSW (25.65 ± 16.04 cm/hr). Many studies have shown that tillage can cause deterioration of soil structure (i.e., compaction) and biochannels; consequently, lowering infiltration rates (Doran and Parkin, 1994; Franzluebbers, 2002). The Mann-Whitney U test confirms that, for all the above

Table 4.3: Statistical summary of infiltration results for individual sites, CEF, Ottawa, ON. C-C=clay compacted, C-NC=clay non-compacted, S-C=sand compacted, S-NC=sand non-compacted, NT-CSW=no-till corn-soybean-wheat rotation, CT-CSW=conventionally tilled corn-soybean-wheat rotation, NT-CCC=no-till continuous corn, CT-SSS=conventionally tilled continuous soybean, CL-LTCT=clay loam long-term conventionally tilled sites, SD=standard deviation and CV=coefficient of variation (N=10).

Site	Mean (cm/hr)	SD	Max	Min	CV (%)
C-C	10.01	3.66	16.93	4.35	37
C-NC	17.98	6.71	30.48	8.96	37
S-C	13.06	4.75	19.05	5.64	36
S-NC	28.71	17.82	76.2	13.85	62
CT-CSW	9.61	3.19	13.85	4.92	33
NT-CSW	25.65	16.04	66.04	12.70	63
CT-SSS	13.71	5.49	25.40	5.26	40
NT-CCC	21.45	15.49	50.80	2.93	72
CL-LTCT 1	28.59	20.67	76.20	4.12	72
CL-LTCT 2	19.35	7.41	30.48	6.10	38
CL-LTCT 3	3.54	1.40	5.82	1.64	40

comparisons, the infiltration results come from different populations ($P < 0.05$).

The compacted and non-compacted clay and sand results show that for each treatment average infiltration rate for sand sites is faster than for clay sites. Infiltration results for sand were 13.06 ± 4.75 cm/hr (compacted) and 28.71 ± 17.82 cm/hr (non-compacted) while for clay they were 10.01 ± 3.66 cm/hr (compacted) and 17.98 ± 6.71 cm/hr (non-compacted). This is expected since sandy soils generally exhibit greater macroporosity than clay soils. However, the Mann-Whitney U test demonstrated that the clay and sand results were not from different populations ($P < 0.05$).

Infiltration rates from this study fall within normal steady infiltration rates for sandy soils but not for clayey soils (Table 4.4). For sandy sites (NT-CSW, CT-CSW, NT-CCC, CT-SSS, S-C and S-NC) infiltration rates ranged from 9.61 to 28.71 cm/hr, this compares to typical infiltration rates of >2 cm/hr for sandy soils. For clayey sites (C-C, C-NC, CL-LTCT 1, CL-LTCT 2, and CL-LTCT 3), infiltration rates ranged from 3.54 to 28.59 cm/hr, which is much faster than typical values reported for clayey soils (0.1 to 0.5 cm/hr). It is postulated that infiltration rates are much faster for the clay sites due to surface cracks that were observed during sampling (Figure 4.1). As noted by Hillel (1998), clayey soils often shrink on drying and form cracks that begin at the soil surface and extend to some depth in the profile. During the initial period of infiltration, water intake by cracked soil can be extremely fast; much faster than the saturated hydraulic conductivity of the soil matrix. Thus, this demonstrates the infiltration test should not be conducted when soil conditions are too dry, particularly in clay soils.

Repeated measures of infiltration rate within individual sites tested (Table 4.3), show CV values ranging from 33% to 72% across soil and management types. This range of CV values is similar to values previously reported for agricultural soils. Machiwal et al. (2006) explained that soil infiltration rates vary considerably even in the same soil mapping unit, which may have coefficients of variation in excess of 100%; Diiwe et al. (1998) reported a CV value of 68% using undisturbed soil samples; Gupta et al. (1993) measured 50% using a double ring infiltrometer; Gregory et al. (2005) reported CV values of 39%, 24% and 37% when comparing three types of double ring infiltrometers; Vieira et al. (1981), Zapata and Playan (2000), and Nuutinen et al. (1997) measured CV values of 40%, 57% and 105% respectively using a single ring

Table 4.4: Steady infiltration rate values for different soil types (Hillel, 1998).

Soil Type	Steady Infiltration rate (cm/hr)
Sands	> 2
Sandy and silty soils	1-2
Loams	0.5-1
Clayey soils	0.1-0.5

Figure 4.1: surface cracks observed at clay sites during sampling, CEF, Ottawa, ON.

infiltrometer; and Tsegaye and Hill (1998) reported an extreme CV value of 172% using undisturbed samples. Thus previous works support the results from this study showing the single ring infiltrometer used offers comparable precision to infiltration tests done elsewhere.

4.1.1.3.1 Single Ring Infiltration Test - Suitability as a Monitoring Tool

Overall, the single ring infiltration test is a promising on-field method for measuring the rate of water entry into the soil. Results indicate that the single infiltration ring used offers comparable precision to reported infiltration tests. It is very easy to conduct, non-technical and mobile. Several tests can be conducted concurrently allowing the test to be performed in a relatively short time span. The only problem of consequence occurred with stony soil in which the infiltration ring could not be inserted satisfactorily. For monitoring infiltration rate, it is important to perform the test at the same location (within 1-2 meters) and at the same time of year. In addition, it should be performed under similar weather conditions, and when the soil is not too wet or too dry (optimally 24 to 48 hours after a rainfall).

4.1.1.4 SLAKE RESISTANCE RATING

Soil slaking is an indicator of soil tensile strength; an important influence on a soil's resistance to soil erosion. The utility of the slake resistance rating is evaluated by comparing the results to more standard procedures (i.e., wet aggregate stability). Trends detected by the slake resistance tests were consistent with results obtained from aggregate stability tests (Table 4.5); at all sites tested, slake resistance ratings were higher at sites with higher aggregate stability measurements (within soil types). Results from the clay,

Table 4.5: Descriptive statistics of slake resistance rating and aggregate stability results from individual sites, CEF, Ottawa, ON. C-C=clay compacted, C-NC=clay non-compacted, S-C=sand compacted, S-NC=sand non-compacted, NT-CSW=no-till corn-soybean-wheat rotation, CT-CSW=conventionally tilled corn-soybean-wheat rotation, NT-CCC=no-till continuous corn, CT-SSS=conventionally tilled continuous soybean, CL-LTCT=clay loam long-term conventionally tilled sites, X= mean, and SD=standard deviation (N=10).

Site	Mean Slake Resistance Rating	Aggregate Stability (%)
C-C	X=4.18 SD=0.24 Max=5.17 Min=4.3	X=2.64 SD=0.14 Max=2.88 Min=2.48
C-NC	X=4.76 SD=0.15 Max=4.33 Min=3.89	X=10.92 SD=0.12 Max=11.08 Min=10.76
S-C	X=3.00 SD=0.11 Max=3.17 Min=2.83	X=4.56 SD=0.14 Max=4.82 Min=4.4
S-NC	X=4.50 SD=0.22 Max=4.83 Min=4.11	X=10.04 SD=0.79 Max=11.60 Min=8.52
NT-CSW	X=5.82 SD=0.09 Max=5.94 Min=5.72	X=8.29 SD=1.05 Max=9.84 Min=5.64
CT-SSS	X=2.84 SD=0.13 Max=3 Min=2.61	X=6.78 SD=0.70 Max=7.72 Min=5.84
CT-CSW	X=3.75 SD=0.23 Max=4.05 Min=3.33	X=4.03 SD=0.57 Max=4.76 Min=2.76
NT-CCC	X=5.66 SD=0.11 Max=5.83 Min=5.5	X=11.60 SD=0.99 Max=13.64 Min=10.44
CL-LTCT 1	X=5.35 SD=0.09 Max=5.5 Min=5.22	X=12.76 SD=0.10 Max=12.92 Min=12.60
C-LTCT 2	X=4.74 SD=0.14 Max=4.94 Min=4.55	X=7.24 SD=1.06 Max=8.08 Min=4.84
C-LTCT 3	X=3.43 SD=0.12 Max=3.65 Min=3.23	X=5.48 SD=0.39 Max=5.92 Min=4.52

North Gower sites show that aggregate stability is higher for C-NC (10.92%) than for C-C (2.64%). Slake resistance rating results are consistent with these results showing higher slake resistance rating for C-NC (slake resistance rating of 4.76) than for C-C (slake resistance rating of 4.18). Similarly, for the fine sandy loam, Mountain sites, aggregate stability was higher for S-NC (10.04%) than for S-C (4.56%). Slake resistance rating was also higher for S-NC (slake resistance rating of 4.50) than for S-C (slake resistance rating of 3.00). For the fine sandy loam, Grenville sites, NT-CSW (8.29%) showed higher aggregate stability than for CT-CSW (6.78%) and CT-SSS (4.03%) sites. Consistent with these results, slake resistance rating was higher for NT-CSW (slake resistance rating of 5.82) than for CT-CSW (slake resistance rating of 3.75) and CT-SSS (slake resistance rating of 2.84) sites. For the clay loam, North Gower sites, aggregate stability was higher for CL-LTCT 1 (12.76%) than for CL-LTCT 2 (7.26%). Slake resistance ratings were consistent with these results, showing higher slake resistance rating for CL-LTCT 1 (slake resistance rating of 5.35) than for CL-LTCT 2 (slake resistance rating of 4.74). Thus, slake resistance ratings are consistent with standard tests, showing higher slake resistance rating at sites with higher aggregate stability (within soil types). The Mann-Whitney U tests confirms, that for all the above comparisons, slake resistance rating and aggregate stability results come from different populations ($P < 0.05$).

Repeated measures of slake resistance rating (Table 4.5) show good consistency within individual sites. Results from individual sites show low standard deviations ranging from 0.09 to 0.24 and the largest range between maximum and minimum values was 0.87, thus demonstrating the precision of the slake resistance test.

4.1.1.4.1 Slake Resistance Rating - Suitability as a Monitoring Tool

The slake resistance test provides a promising tool for monitoring change in soil's risk of erosion due to management. Results show that repeated measurements of soil stability made using the slake resistance test are reproducible (within individual sites). In addition, it is consistent with aggregate stability tests, showing higher slake resistance rating for sites with higher aggregate stability (within soil types). Most importantly, it is quick, easy to use and inexpensive.

4.1.1.5 ORGANIC MATTER MONITORING CARD/ SOIL COLOR

Organic matter assessment provides an estimate of many important soil properties such as cation exchange capacity, structural stability and water holding capacity. The utility of the Organic Matter Monitoring Card (OMMC) is evaluated by comparing the results to those produced by standard analytical procedures (dry combustion). When Munsell color results from air dry samples are compared to percent organic matter (%OM) content, values ranged from 5 to 6 (across management types) (Table 4.6), and showed no trends with %OM content. Thus it was concluded that air dry samples were not appropriate for soil color determination. However, when Munsell color is determined using moistened soil samples, trends in soil color between management systems are evident; Munsell color distinguished differences in soil color for sites showing significantly different %OM contents (within soil types) ($P < 0.05$, Mann-Whitney U test).

The CL-LTCT 1 site showed significantly different %OM content (3.25%) than the CL-LTCT 2 site (1.87%); Munsell color reflected these differences showing a Munsell value of 2 for CL-LTCT 1 and 3 for CL-LTCT 2. For the fine sandy loam,

Table 4.6: Summary of percent organic matter (%OM) and Munsell value (10YR), by soil type, CEF, Ottawa, ON. Sites within the same soil series with the same letter are not significantly different from one another at $P < 0.05$. Test for significance was determined using Mann-Whiney U test ($N=10$).

Soil Type	Site	OM (%)	Wet Munsell Color (value)	Dry Munsell Color (value)
Clay, North Gower series	Clay compacted	3.56a	2	5
	Clay non-compacted	4.67a	2	5
Very Fine Sandy Loam, Mountain series	Sand compacted	2.38b	3	6
	Sand non-compacted	2.44b	3	6
Fine Sandy Loam, Grenville series	NT-CSW	3.17a	3	5
	CT-CSW	2.68b	4	5
	CT-SSS	3.02c	3	5
Clay loam, North Gower soil series	CL-LTCT 1	3.25a	2	6
	CL-LTCT 2	1.87b	3	6

Grenville sites, NT-CSW showed significantly different %OM content (3.17%) than the CT-CSW site (OM=2.68%); Munsell values were consistent with these results showing a Munsell value of 3 for NT-CSW and 4 for CT-CSW. In both of the above comparisons, Munsell value is lower for sites showing higher %OM content (as expected).

Results from the clay, North Gower sites show no significant ($P < 0.05$) difference between %OM content for C-C (3.56%) and C-NC (4.67%) sites. Munsell color results are consistent with these results showing no difference in Munsell value between both sites (value=2). Similarly, for the fine sandy loam, Mountain sites, %OM was not significantly ($P < 0.05$) different between S-C (2.38%) and S-NC (2.44%) sites; Munsell color results also show no difference in value (value=3). However, although NT-CSW

showed significantly ($P < 0.05$) different %OM content (OM=3.17%, value=3) than CT-SSS (OM=3.02%, value=3) Munsell color did not reflect these differences.

The compacted and non-compacted clay and sand results show that %OM is significantly different between clay and sand sites ($P < 0.05$, Mann-Whitney U test); this difference was detected using Munsell color. Percent OM results for clay sites were 3.56% (compacted) and 4.67% (non-compacted) while for sand they were 2.38% (compacted) and 2.44 % (non-compacted). Consistent with these results, Munsell value was 2 for the clay sites (C-C and C-NC) and 3 for the sand sites (S-C and S-NC). This observation is consistent with Needleman et al. (1999) who stated that sandy soils generally have lower OM content than clay soils due to higher OM decomposition rates.

Important to note, is that while some changes in organic matter content may not be sufficient to create a change in soil color, this does not necessarily indicate that such a change is not important in terms of its effect on soil quality. Results show that the spread in Munsell color values is relatively small (values range from 2 to 4) in comparison to the spread of %OM data (1.87% to 3.56%). Theoretically, however, a small change in OM should have a substantial impact on soil quality (Gregorich, personal communication). For some of the sites tested, a difference of approximately 0.5% in OM appears to be distinguishable using Munsell color values.

Spearman rank correlation showed that 49% of the variation in soil color was associated with variation in OM content; however this correlation was not significant ($P = 0.13$). This is not surprising since 4 different soil series were included in this analysis, thus differences in soil color when compared across soil series may also be attributed to differences in soil mineralogy and texture. Konen et al. (2003) noted that unique

relationships exist for different soil landscapes as local mineralogical, texture, and organic C composition likely cause differences in soil color parameters. When grouped by soil type (sand and clay), soil color does not show a significant relationship ($P=0.06$, $r = -0.83$) with %OM for sand soils ($N=5$); however, this relationship would be significant at the 10% significance level. Significant correlations were also not found between %OM and soil color for clay sites ($P=0.564$). The absence of significant correlations between %OM and soil color may be attributed to a small sample number. Nevertheless, many researchers have documented high correlations between organic matter and soil color (Schulze et al, 1993; Konen et al., 2003). For instance, Burras et al. (1993) reported a correlation coefficient as high as 93%.

Results from this study suggest that Munsell color is sufficiently sensitive to identify differences in soil organic matter, as Munsell color was able to distinguish differences in %OM content between sites (where significant differences existed). Where significant differences were found, Munsell values were generally lower for sites with higher OM content (within soil types).

4.1.1.5.1 OMMC/Soil Color - Suitability as a Monitoring Tool

In the field, soil color changes can give a general indication of trends in soil organic matter levels under cropping (Shepherd, 2000). It is important to note, however, that factors other than organic matter affect soil color, such as soil moisture content and mineralogical composition. Nevertheless, soil color assessment is quick and easy to conduct, making this one of the most widely accepted methods for monitoring trends in soil OM (Shepherd, 2000).

4.1.2 CHEMICAL SOIL QUALITY ASSESSMENT

4.1.2.1 SOIL pH

Soil pH provides a measure of the degree of acidity or alkalinity of a soil. The degree of acidity or alkalinity is an important control on the availability of nutrients to plants and of potentially adverse chemical conditions (USDA, 1999). The utility of the kit's soil pH test was evaluated by comparing the results to those produced by standard analytical procedures (pH meter) (Table 4.7). At all sites tested, colorimetrically determined pH results were not significantly ($P < 0.05$, Mann-Whitney U test) different than results from the standard pH test (across soil and management types). There were no treatment effects on soil pH detected by either the laboratory or field kit measurements.

Precision estimates for repeated measures of soil pH assessment are given in Table 4.7. Precision is assessed by comparing coefficient of variation values for kit and standard test measurements. Across soil and management types, coefficients of variation between standard and kit pH tests are different by less than 1%. Results indicate a comparable degree of precision between the kit test and standard evaluations.

4.1.2.1.1 Colorimetric pH Test - Suitability as a Monitoring Tool

Results show that the kit's pH test is sufficiently accurate compared to the standard electrometric test and is a precise test for monitoring changes in soil pH over time. Most importantly, it is relatively inexpensive, easy to use and provides quick measurements.

Table 4.7: Mean soil pH and coefficient of variation values, kit and standard tests, CEF, Ottawa, ON. C-C=clay compacted, C-NC=clay non-compacted, S-C=sand compacted, S-NC=sand non-compacted, NT-CSW=no-till corn-soybean-wheat rotation, CT-CSW=conventionally tilled corn-soybean-wheat rotation, NT-CCC=no-till continuous corn, CT-SSS=conventionally tilled continuous soybean, CL-LTCT=clay loam long-term conventionally tilled sites, CV=coefficient of variation, and SD=standard deviation (N=10).

Test Kit- Colorimetric soil pH test					
Site	Mean	SD	Max	Min	CV (%)
C-C	5.79	0.07	5.9	5.6	1.27
C-NC	5.99	0.03	6.0	5.9	0.53
S-C	5.35	0.13	5.6	5.2	2.37
S-NC	5.45	0.05	5.5	5.4	0.97
NT-CSW	5.38	0.17	5.6	5.2	3.13
CT-CSW	6.62	0.08	6.7	6.5	1.19
NT-CCC	5.97	0.16	6.2	5.8	2.62
CT-SSS	6.67	0.05	6.7	6.6	0.72
CL-LTCT 1	5.81	0.11	6.0	5.6	1.89
CL-LTCT 2	5.61	0.13	5.8	5.4	2.29
CL-LTCT 3	5.84	0.07	6.0	5.8	1.20
Laboratory soil pH test					
Site	Mean	SD	Max	Min	CV (%)
C-C	5.82	0.05	5.9	5.7	1.17
C-NC	6.07	1.02	6.2	8.0	1.69
S-C	5.43	0.14	5.8	5.2	2.53
S-NC	5.48	0.03	5.5	5.4	0.66
NT-CSW	5.43	0.19	5.7	5.2	3.44
CT-CSW	6.72	0.08	6.8	6.6	1.20
NT-CCC	6.10	0.18	6.3	5.9	2.93
CT-SSS	6.70	0.06	6.8	6.6	0.95
CL-LTCT 1	5.90	0.10	6.1	5.7	1.73
CL-LTCT 2	5.62	0.20	5.8	5.2	3.61
CL-LTCT 3	5.87	0.08	6.0	5.8	1.31

4.1.3 HABITAT QUALITY ASSESSMENT

4.1.3.1 EARTHWORM COUNT

Earthworm count results were transformed (as the square root of the sum of the count plus 0.5; Wuest, 2001) prior to statistical analysis because many samples within sites gave counts of zero (Sites C-C, S-C, CL-LTCT 1, CL-LTCT 2, CL-LTCT 3, CT-SSS, and CT-CSW). Earthworm sampling took place during early to mid-summer, which may account for the low earthworm numbers within sites; ideally earthworm counts should be conducted late fall to early spring (USDA, 1999). Transformed variables were back-transformed for presentation (Table 4.8). Results show that both the non-compacted clay and sand sites (sum of 42 and 39 earthworms respectively) exhibit higher earthworm numbers than the compacted clay and sand sites (sum of 4 and 0 respectively). These results are consistent with many studies showing that compaction induces factors such as lower organic matter content, high bulk density, lower soil temperature and decreased porosity which contribute to low earthworm numbers (Nuutinen et al., 1997; Larink and St. Schrader, 2000). Similarly, the NT-CSW site showed higher earthworm numbers (sum of 46 earthworms) than the CT-CSW site (sum of 10 earthworms). Many studies have shown that tillage is associated with higher earthworm mortality (Needleman, 1999; Ivask et al., 2006); tillage effects include: increase in surface temperature, decreased soil moisture regimes, reduced litter input, and more rapid oxidation of crop residues. (USDA, 1999). The Mann-Whitney U test confirms that, for all the above comparisons, the earthworm results come from different populations ($P < 0.05$).

Table 4.8: Statistical summary of back-transformed earthworm data (i.e., original units) from individual sites, CEF, Ottawa, ON. C-C=clay compacted, C-NC=clay non-compacted, S-C=sand compacted, S-NC=sand non-compacted, NT-CSW=no-till corn-soybean-wheat rotation, CT-CSW=conventionally tilled corn-soybean-wheat rotation, NT-CCC=no-till continuous corn, CT-SSS=conventionally tilled continuous soybean, CL-LTCT=clay loam long-term conventionally tilled sites, SD=standard deviation and CV=coefficient of variation (N=10).

Site	Sum	Mean	SD	Max	Min	CV* (%)
CC	4	0.4	0.84	2	0	76
C-NC	42	4.2	2.25	8	1	23
SC	0	NA	NA	NA	NA	NA
S-NC	39	3.9	2.02	6	0	11
CT-CSW	10	1.0	0.82	2	0	57
NT-CSW	46	4.6	1.71	7	2	16
CT-SSS	34	3.4	2.17	7	0	60
NT-CCC	4	0.4	0.84	2	0	15
CL-LTCT 1	36	3.6	0.97	5	2	30
CL-LTCT 2	5	0.5	0.71	2	0	62
CL-LTCT 3	8	0.8	0.79	2	0	51

* Data presented are transformed.

The compacted and non-compacted clay and sand results show that for each treatment mean earthworm numbers are higher for clay sites than for sand sites. Mean earthworm results for clay were 0.4 (compacted) and 4.2 (non-compacted) while for sand they were 0 (compacted) and 3.9 (non-compacted). Sandy soils are generally less favorable for earthworms due to abrasive sand grains and higher drought potential (Edwards, 2004). Nordstrom and Rundgre (1974) reported a positive relationship between clay content and earthworm abundance (cited by Edwards, 2004). However, the

Mann-Whitney U test demonstrated that the clay and sand results were not from different populations ($P < 0.05$).

Repeated measures of earthworm counts (transformed data) within individual sites tested (Table 4.8), show CV values ranging from 0 to 76% across soil and management types. This observation is consistent with Rossi et al. (1999) and Wuest (2001) who explained that earthworm populations have high intrinsic in-field variability. The range of CV values from this study is similar to values previously reported for agricultural soils. For instance, Nuutinen et al. (1997) performed earthworm sampling using combined formalin-extraction soil sampling. Reported CV values ranged from 58% to 374%. Thus previous work supports the results from this study showing that the manual in-field earthworm count offers comparable precision to earthworm count tests done elsewhere.

4.1.3.1.1 Earthworm Count - Suitability as a Monitoring Tool

For those soils which constitute an appropriate habitat for earthworms, their abundance should prove to be a useful indicator of change in soil quality (given that earthworm counts are performed at the same time every year and under similar weather conditions). Earthworm counts are quick and easy to conduct, making this test one of the best methods available (USDA, 1999). Results show that measurements made using the manual earthworm counts are reproducible. In addition, this measurement is sensitive to differences in soil management.

4.1.4 OVERALL TEST KIT CRITIQUE

Results from this investigation show that the kit is sufficiently sensitive to identify differences in soil quality related to soil management. Significant differences were found among the management systems for PR, earthworm numbers, slake resistance rating, and infiltration rate. Results from the pH test, OMMC, and slake resistance rating compared well with standard tests. In addition, repeated measures of each kit test fell within acceptable ranges of variability. Lastly, results indicate that the kit is applicable to major soil types of Eastern Ontario as kit tests detected differences in selected soil quality parameters between management systems regardless of soil type. The only problem of consequence occurred with stony soil in which the penetrometer and the infiltration ring could not be inserted satisfactorily.

With the exception of bulk density measurements, all tests are easily and rapidly conducted which makes it a suitable farm-based tool. The bulk density test was judged to be unsuitable for on-farm use. The amount of time required for sample removal and analysis (oven drying and weighing) may discourage farmers from using this test. In addition, bulk density tests offer less depth resolution and consequently appear to be less sensitive than the penetrometer in detecting change in soil density. A summary of methods deemed the best fit to the goals of precision, ease-of-use and sensitivity are summarized in Table 4.9.

4.1.5 CORRELATIONS BETWEEN SELECTED SQMK TESTS

Correlation analysis can do one of two things: indicate a relationship between parameters (either causative or chance) or indicate a lack of relationship (i.e.

Table 4.9: Evaluation of the suitability of on-farm methods for inclusion in SQMK.

Y= yes, N= no

Soil Quality Indicator	On-Farm Method	Suitability	Accept
Water Infiltration Rate	Single ring infiltrometer	Moderate Precision, Moderate Sensitivity	Y
Soil Compaction	Dynamic cone penetrometer	Good Precision, Good sensitivity	Y
	Bulk Density	High Precision, Moderate to low sensitivity, Not practical for on-farm use	N
Soil Structural Stability	Slake Resistance Rating	Good Precision, Good sensitivity	Y
Earthworms	Hand sorting	Moderate Precision, Good sensitivity	Y
pH	Colorimetric test	High Precision	Y
OM levels	Soil color (OMMC)	Acceptable sensitivity	Y

independence from one another). Some correlations are expected since soil quality variables are highly interrelated. For instance, one would expect earthworms to positively correlate with infiltration rate since earthworms increase macroporosity. However, a very high relationship (i.e., correlation) (e.g., $r_s = 0.8$ or 0.9) between tests may indicate that the measurements are duplicative and, if this holds across all soils, would be a justification for choosing the easier to conduct or the least expensive test (Torrance, personnel communication). Results from correlation analysis, using Spearman Rank correlation are presented in Table 4.10.

Table 4.10: Summary of Spearman rank correlation coefficients between kit tests.

Spearman Rank Correlation Test			
Test	Sand and Clay (N=110)	Sand (N=60)	Clay (N=50)
PR (0-30 cm) vs. earthworms	P= 0.01 $r_s = -0.26$	P= 0.01 $r_s = -0.36$	P= 0.09 $r_s = -0.24$
PR (0-15 cm) vs. infiltration rate	P= 0.00 $r_s = -0.31$	P= 0.06 $r_s = -0.24$	P= 0.06 $r_s = -0.27$
PR (0-15 cm) vs. slake resistance rating	P= 0.35 $r_s = -0.09$	P= 0.10 $r_s = -0.21$	P= 0.08 $r_s = -0.72$
Earthworms vs. infiltration rate	P= 0.00 $r_s = 0.34$	P= 0.01 $r_s = 0.35$	P= 0.00 $r_s = 0.31$
Infiltration rate vs. slake resistance rating	P= 0.01 $r_s = 0.25$	P= 0.11 $r_s = 0.21$	P= 0.02 $r_s = 0.32$
Earthworms vs. slake resistance rating	P= 0.00 $r_s = 0.37$	P= 0.00 $r_s = 0.54$	P= 0.23 $r_s = 0.17$

4.1.5.1 Penetration Resistance and Earthworms

Many studies have shown that earthworms reduce PR though the creation of macropores and through their contribution of biotic aggregate-forming factors (Stott et al., 1999). It is therefore expected that PR will correlate with earthworm numbers (in soils which support earthworm populations). Results from Spearman Rank correlation show that across soil and management types, earthworm numbers show a significant negative rank correlation with PR ($P=0.01$, $r_s = -0.26$). When sites are analysed by soil type, PR shows a significant rank correlation with earthworms for sand sites ($P=0.01$, $r_s = -0.36$), but not for clay sites ($P=0.09$, $r_s = -0.24$). These results suggest that for sand sites 36% of the variation in PR is explained by earthworm numbers; as PR increases, earthworm numbers decrease. Conversely, factors other than earthworm numbers

presumably explain the variation in PR for clay sites, such as mineralogy and soil moisture.

4.1.5.2 Penetration Resistance and Slake Resistance Rating

PR is a measure of the compactedness of a soil, it is therefore expected that soils with high PR will also exhibit lower structural stability and hence lower slake resistance rating than areas within the same field with lower PR (assuming water content and texture are held constant). Results from Spearman Rank correlation show that across soil and management types there is no significant rank correlation ($P=0.34$, $r_s=-0.09$) between slake resistance rating and PR. Similarly, when sites are divided by soil type, significant rank correlations do not exist within clay ($P=0.08$, $r_s=-0.72$) or sand ($P=0.10$, $r_s=0.21$) sites. Thus, for sand and clay sites, factors other than slake resistance rating explain the variability in PR such as mineralogy, soil moisture, and bulk density.

4.1.5.3 Penetration Resistance and Infiltration Rate

PR is a measure of the compactedness/density of a soil and it is therefore expected that soils with high PR will also exhibit low infiltration rates. Results from Spearman Rank correlation show that across soil and management types there is a significant negative rank correlation between PR and infiltration ($P=0.00$, $r_s=-0.31$); as PR increases, infiltration rate decreases. When sites are divided by soil type, there is no correlation between PR and infiltration for sand ($P=0.06$, $r_s=-0.24$) and clay ($P=0.06$, $r_s=-0.27$) sites; however, there would be a significant correlation at the 10% significance level. These results suggest that for both sand and clay soils, sites with high PR are more likely to show lower infiltration rates than soils with low PR. This is not surprising, since macropores are likely to be more abundant in soils with low PR (due to lower bulk

density, and increased seedling emergence, root penetration, and burrowing soil fauna) than in soils with high PR (Topp et al., 1997).

4.1.5.4 Infiltration Rate and Slake Resistance Rating

The ability of soil to withstand rapid wetting indirectly affects infiltration rate. When aggregates slake they break apart into smaller pieces that can clog pore spaces. When the surface dries, a crust will form which impedes soil water infiltration (Hollier, 2006). It is therefore expected that infiltration rate will correlate with slake resistance rating. Results from Spearman Rank correlation show that across soil and management types, infiltration rate shows a significant rank correlation with slake resistance rating ($P=0.01$, $r_s=0.25$). When sites are divided by soil type, infiltration rate shows a significant rank correlation with slake resistance rating for clay sites ($P=0.02$, $r_s=0.32$), but not for sand sites ($P=0.11$, $r_s=0.21$). These results are consistent with those of Lado et al. (2004) who showed that soil slaking increases as clay content increases. An increase in clay content creates an increase in soil slaking mechanisms (e.g., differential swelling and explosion of entrapped air) that compensate for the increase in aggregate stability. Thus the higher correlation between slake resistance rating and infiltration in clay soils can be explained by the interaction between clay content, and aggregate slaking.

4.1.5.5. Slake Resistance Rating and Earthworm Numbers

Many studies have shown that earthworms contribute to aggregate stability through their contribution of biotic aggregate-forming factors (Stott et al., 1999). It is therefore expected that earthworm numbers will correlate with slake resistance rating; as earthworm populations increase, slake resistance rating should increase. Results from Spearman Rank correlation show that across soil and management types, earthworm

numbers show a significant rank correlation with slake resistance rating ($P=0.00$, $r_s=0.37$). When sites are grouped by soil type, earthworm numbers shows a significant rank correlation with slake resistance rating for sandy sites ($P=0.00$, $r_s=0.54$), but not for clay sites ($P=0.23$, $r_s=0.17$). These results suggest that for sandy sites 54% of the variation in slake resistance rating is explained by earthworm numbers. Conversely, factors other than earthworm numbers explain the variation in slake resistance rating for clay sites, such as percent clay content.

4.1.5.6 Earthworm Numbers and Infiltration Rate

Many studies have related increases in infiltration rate to an increase in earthworm holes (Ehlers, 1975; Willoughby et al., 1997; Nuutinen et al, 1997; Wuest, 2001; Katsvario et al, 2002). When earthworms burrow they increase soil macroporosity and increase the distribution of pore size. It is therefore expected that infiltration rates should correlate with earthworm numbers; as earthworm numbers increase, infiltration rate should increase. Results from Spearman Rank correlation show that across soil and management types, earthworm numbers show a significant rank correlation with infiltration rate ($P=0.00$, $r_s=0.34$). When sites are grouped by soil type, earthworm numbers show a significant rank correlation with infiltration rate for both sand ($P=0.01$, $r_s=0.35$) and clay ($P=0.00$, $r_s=0.31$) soil types. These results suggest that earthworms generally improve infiltration rate in both sandy and clayey soil types.

4.1.5.7 Conclusions

Soil quality parameters are highly interrelated. For example, characteristics of soil structure such as aggregate stability and PR influence and are influenced by the activity of earthworms. Water infiltration, which is influenced by soil structure, affects plant

growth. Organic residue and root biomass from crops feed soil organisms and contribute to soil organic matter, which in turn enhances soil structure. These relationships demonstrate the interrelatedness of soil quality parameters; thus, it is not surprising that results show significant correlations between most kit tests. However, correlation coefficients between kit tests were low to moderate, ranging from 0.25 to 0.54. Thus, although the tests appear to be interrelated, they presumably measure different aspects of soil functioning. The absence of high correlations between soil quality tests further justifies the inclusion of all of the test procedures chosen in the kit, because they appear to be non-duplicative.

4.2 FARM APPLICATION PHASE

4.2.1 FARM APPLICATION OF THE SOIL QUALITY MONITORING KIT, CARLETON PLACE, ONTARIO.

The main purpose of on-farm evaluation was to evaluate the kit and its ability to detect the maximum extent of current local differences within a farmer's field. Areas expected to be of lower soil quality (conventionally managed farmer's field, perpendicular and parallel to tillage direction) and areas expected to be of higher soil quality (fence line and higher OM area) were sampled using selected tests from the SQMK; the tests conducted include PR, OMMC and infiltration.

4.2.1.1 Penetration Resistance

PR is expressed by the number of blows required to penetrate each centimeter (blows/cm) of the soil profile down to 30 cm. PR is expected to be higher when measured within the cultivated field, particularly in areas crossed by the tractor as they are expected

to be more compact, unlike the fence line area, which has better soil structure due to lack of soil disturbance and higher organic matter content. Results show that average PR measured parallel to tillage direction (0.48 ± 0.09 blows/cm) is higher than measurements taken along the fence line (0.35 ± 0.06 blows/cm) (PR data are taken from the first 2 measurements starting at the bottom of the Ap layer (which in this study lies at approximately 15 cm depth) (Table 4.11), however, the Mann-Whitney U test demonstrates that these results come from the same population ($P < 0.05$). This is surprising since one would expect PR of the cultivated field to be significantly different than that of the fence line. It is postulated, however, that the cultivated field does not differ significantly from the fence line area because the area sampled is located in a row as opposed to an inter-row. Average PR measured perpendicular to tillage direction (0.54 ± 0.17 blows/cm) is higher than PR measured along the fence line (0.35 ± 0.06 blows/cm) (Table 4.11). This is not surprising since PR is expected to be higher when measured perpendicular to tillage direction as areas crossed by the tractor are expected to be more compact. The Mann-Whitney U test confirms that these results are from different populations ($P < 0.05$). When average PR is compared between measurements taken perpendicular (0.54 blows/cm) and parallel (0.48 blows/cm) to tillage direction, results show that they are not significantly different from one another ($P < 0.05$, Mann-Whitney U test). This is not surprising since PR data measured perpendicular to tillage direction represents the sum of two distinct sample distributions (areas crossed by the tractor and areas that were not crossed by the tractor). Differences between soil moisture were not significant ($P < 0.05$, Mann-Whitney U test) (Table 4.11). It can thus be concluded that moisture differences at the time of sampling were not the cause of variations in PR.

Table 4.11: Summary of mean PR, bulk density and moisture content for cultivated field and fence line area, farmer's field, Carleton Place, ON. N=sample number, X=mean, and SD=standard deviation.

Site		Penetration Resistance (blows/cm)*	Bulk Density (g/cm ³)*	Mean Gravimetric Soil Water Content (g) 0-30 cm*
Cultivated Field	Perpendicular to tillage direction (crosses tire tracks)	N=5 X=0.54 SD=0.17 Max=0.81 Min=0.4	N=5 x=1.05 SD=0.02 Max=1.08 Min=1.03	34
	Parallel to tillage direction (presumed to be in a row position)	N=5 X=0.48 SD=0.09 Max=0.61 Min=0.4	N=5 x=1.05 SD=0.07 Max=1.16 Min=0.98	33
Fence Line		N=4 X=0.35 SD=0.06 Max=0.4 Min=0.3	N=5 x=1.06 SD=0.01 Max=1.07 Min=1.04	32

*Data are from the first 2 measurements below the bottom of the Ap layer (which in this study lies at approximately 15 cm depth).

Unlike PR results, which showed significant differences between the cultivated field (perpendicular to tillage direction (0.54 ± 0.17 blows/cm) and fence line area (0.35 ± 0.06 blows/cm), bulk density results did not show significant differences between the cultivated field (perpendicular to tillage direction= 1.05 ± 0.02 g/cm³; parallel to tillage direction= 1.05 ± 0.07 g/cm³) and fence line area (1.06 ± 0.01 g/cm³) ($P < 0.05$, Mann-Whitney U test) (Table 4.11). This suggests that the penetrometer picked up differences between wheel and non-wheel track areas, but bulk density did not, suggesting that the penetrometer is a more sensitive indicator of soil compaction than bulk density is. These

results compare with those from the CEF (Section 4.1.1.2), which showed the penetrometer was more sensitive to differences in soil strength (due to management and soil depth) than bulk density measurements. Sojka et al. (2001) and many other researchers have reported similar findings (Ball et al., 1997; Kenney et al., 2002; Motavalli et al., 2003; Czyc, 2004; Ferrero et al., 2004).

Figure 4.2 shows the number of blows required to penetrate each cm of the soil profile down to 30 cm. The number of blows required increases as the soil's resistance to penetration increases. Tractor passes caused an increase in PR. Of particular interest is the large increase in PR approximately 15 cm depth (below the plow layer) in the transect conducted perpendicular to the tillage direction (Figure 4.2, b and e). Figure 4.2 b, shows less than 1 blow per cm resistance to penetration to approximately 14.5 cm, with a dramatic increase to 2 blows per cm for the next centimeter. Below this depth, resistance suddenly decreases to 0.5 to 1 blow/cm from approximately 15.5 cm to 30 cm. Similarly, Figure 4.2 e shows that less than 1 blow per cm is required to approximately 14 cm, 2 blows per cm between 14 cm to 15 cm and 0.22 to 1 blow/cm from approximately 15 cm to 30 cm depth. This thin zone of high PR is interpreted to indicate the presence of compaction. The other samples taken perpendicular to tillage direction show penetration resistance profiles that are comparable to those conducted parallel to the direction of plowing (Figure 4.2 f to j). The higher average PR sites correspond with the location of the inter-row track followed by the tractor during planting and cultivation operations. It is presumed that the location of inter-rows with respect to rows can be seen in data measured perpendicular to tillage direction (Figure 4.3a). If maximum PR values (2 blows/cm) represent inter-rows (Rep 2 and 5) and minimum PR values (1 blow/cm)

Figure 4.2: Blows per cm of soil penetration, farmer's field, Carleton Place, ON. a to e are perpendicular to tillage direction. f to j are parallel to tillage direction.

Figure 4.3: Maximum PR values for individual sample sites, perpendicular and parallel to tillage direction, farmer's field, Carleton Place, ON.

represent rows (Reps 1, 3, and 4), inter-rows are located approximately 45 cm apart from one another (as samples were taken every 15 cm).

Such large increases in PR were not apparent parallel to the tillage direction (Figure 4.2, f to j, and Figure 4.3 b). Results show that the largest PR occurring down the profile is 1 blow/cm, which varies from 14 to 30 cm depth. This further supports the conclusion that the area measured parallel to tillage direction is located in a row position. Unlike the area measured perpendicular to tillage direction, PR measured parallel to tillage direction remained relatively stable. Data perpendicular to tillage direction ranged from 0.08 to 2 blows/cm (0-30 cm) with a standard deviation of 0.40 (mean=0.63 blows/cm), while data parallel to tillage direction ranged from 0.13 to 1 blow/cm (0-30 cm) with a standard deviation of 0.20 (mean=0.55 blows/cm). These differences in variation are also apparent when data are analysed by depth of penetration per 2 blows (Figure 4.4). Samples taken parallel to tillage direction show results that are much

Figure 4.4: Depth of penetration every 2 blows, perpendicular and parallel to tillage direction, farmer's field, Carleton Place, ON.

more uniform down the profile for every two blows than the area sampled perpendicular to tillage direction. The higher variability of data measured perpendicular to tillage direction is expected since areas crossed by the tractor are expected to offer more resistance to penetration than those that were not.

Contrary to PR results, bulk density results did not appear to detect the presence of compaction (Figure 4.5). Bulk density results remained relatively stable down the profile, data perpendicular to tillage direction ranged from 0.90 to 1.17 g/cm³ (0-30 cm) with a standard deviation of 0.07 (mean=1.04 g/cm³) (Figure 4.5, a to e), while data

Figure 4.5: Mean bulk density measurements, perpendicular and parallel to tillage direction, farmer's field, Carleton Place, ON. a to e are perpendicular to tillage direction. f to j are parallel to tillage direction.

parallel to tillage direction ranged from 0.86 to 1.24 g/cm³ (0-30 cm) with a standard deviation of 0.86 (mean=1.04 g/cm³) (Figure 4.5, f to j). These results are comparable to those of Ball et al. (1997) who reported that the depth resolution of bulk density cores may not be sufficient to detect the thin, dense layers often found in soils compacted by wheels.

When PR is compared between the lower and higher organic matter areas (both areas are within the cultivated field, parallel to tillage direction) (0-15 cm), PR is expected to be lowest for the area with higher organic matter content. This relationship is compatible with improved aggregation, decreased bulk density, reduced strength and increased ease of formation of microcracks that are associated with increasing organic matter content (To et al., 2005). Results show that PR is lower (0.33 ± 0.07 blows/cm) for the higher organic matter area than for the lower organic matter area (0.48 ± 0.08 blows/cm) ($P < 0.05$) (Table 4.12). The Mann-Whitney U test confirms that these results come from different populations ($P < 0.05$). However, care must be taken in interpretation of this data, as it was uncertain if sample sites were located within row or inter-row positions.

The relationship between bulk density and PR is shown in Figure 4.6. To allow correlation analysis between PR and bulk density data, PR data were interpolated using equivalent depth intervals as bulk density measurements, thus data were interpolated every 6 cm to a depth of 27 cm, starting at 3 centimeters depth. Results show no correlation between bulk density and PR ($r^2 = 0.04$). This is not surprising since Vanags et al. (2006) and other investigators have documented poor correlations between cone index and bulk density. Herricks and Jones (2002) concluded that the dynamic cone

Table 4.12: Summary of average percent organic matter, moisture content, bulk density, PR, infiltration rate and Munsell value for lower and higher organic matter area, 0-15 cm depth, farmer's field, Carleton Place, ON. Results in the same row with different letters are significantly different from one another at $P < 0.05$. Test of significance was determined using the Mann-Whitney U test. N=sample number

Variables	Site	
	High Organic Matter Area	Lower OM area
Mean %Organic Matter Content 0-15 cm	5.53a N=10	4.29b N=10
Mean Gravimetric Soil Water Content (g) 0-15 cm	33a N=4	33a N=5
Mean Bulk Density (g/cm^3) 0-15 cm	1.00a N=4	1.06a N=5
Mean Penetration Resistance (blows/cm) 0-15 cm	0.33a N=4	0.48b N=5
Average Infiltration Rate (cm/hr)	127a N=3	10.35b N=3
Munsell Value	2 N=10	3 N=10

Figure 4.6: Correlation between bulk density and PR, farmer's field, Carleton Place, ON.

penetrometer, like other penetrometer designs, is sensitive to differences in soil texture and moisture, and cannot be used as a direct measurement of bulk density. Similarly, Sojka et al. (2001) reported that cone index correlated strongly with soil moisture content but not with bulk density.

4.2.1.2 Infiltration Rate

Infiltration rate was compared between high organic matter and lower organic matter areas (with uniform soil texture in cultivated field, parallel to tillage direction). Means of infiltration and organic matter are given in Table 4.12. As expected, results show that infiltration rate was faster for the higher organic matter area (127 cm/hr) than for the lower organic matter area (10.35 cm/hr). The Mann-Whitney U test confirms that these results come from different populations ($P < 0.05$).

4.2.1.3 Organic Matter Monitoring Card

Differences in soil color within the field were scored using the OMMC and sampled for standard organic matter determination. Results obtained from the OMMC corresponded well with percent organic matter results obtained using standard laboratory analysis (Table 4.12). The darker field area (2 Munsell value) showed a higher organic carbon content (5.53%) than the lighter field area (3 Munsell value), which showed an average organic carbon content of 4.29%. The Mann-Whitney U test confirms that these results come from different populations ($P < 0.05$).

4.2.1.4 Conclusions

Results from this investigation suggest that selected kit tests (PR, OMMC and infiltration rate) are sufficiently sensitive to detect the maximum extent of current local

differences within a farmer's field. PR was able to distinguish significant differences between the cultivated field and the fence line area. PR also differentiated between row and inter-row areas showing higher average PR in areas crossed by tractor tires (perpendicular to tillage direction). In addition, the penetrometer detected dense layers down the soil profile that bulk density did not, suggesting the penetrometer is a more sensitive indicator of compaction than bulk density is. The OMMC was also successful in differentiating between areas of higher and lower organic matter content, showing lower Munsell values for areas with higher organic matter content. Similarly, the infiltration test differentiated between areas of higher and lower soil quality, showing a faster infiltration rate for the higher organic matter area than for the lower organic matter area.

4.2.2 FARMER ASSESSMENT OF THE SOIL QUALITY MONITORING KIT

Field data on the efficiency and ease-of-use of the Soil Quality Monitoring Kit was assessed from responses of 12 farmers who tested the kit on their farm. A general overview of results from farmer assessment of the SQMK is presented in Table 4.13. Interview questions and individual farmer responses are located in Appendix A3. Farmer responses were transcribed by the researcher during and after the kit assessment.

When farmers were asked to test the SQMK on their farm, most responded with interest and enthusiasm. The two main reasons farmers expressed for wanting to test the kit include: (1) to assess perceived problem areas within their field and; (2) to assess if their new soil management methods are indeed improving their soil quality. All but three farmers conducted each test only once. There appeared to be no differences between the views of conventional and organic farmers regarding the kit's utility. Overall, farmers of

Table 4.13: Summary of farmer responses on the “ease-of-use” and utility of the SQMK.

	Organic Farmers (total 8)	Conventional Farmers (total 4)
Number of farmers who rated the overall kit as very easy to use.	8/8	4/4
Number of farmers who believe the kit measured important aspects of soil quality	8/8	4/4
Number of farmers who believe the kit heightened their awareness of their soil quality	8/8	4/4
Number of farmers agreeing that they would use the SQMK in the future if it became commercially available.	8/8	4/4
Tools favored most	-Penetrometer (6/8) -OMMC (4/8) -Earthworm count(6/8)	-Penetrometer (3/4) - OMMC (2/4) -Earthworm count (2/4)
Tools favored the least	-Soil pH test (3/8) -Slake resistance rating (3/8)	-Soil pH test (2/4) -Slake resistance rating (1/4)
Suggested revisions	-Larger slaking tray (3/8) -Larger pH test kit (5/8)	- Larger slaking tray (1/4) -Larger pH test kit (1/4) -Brighter depth markings on penetrometer (1/4)

both farming philosophies (8 conventional and 4 organic) and soil associations (Uplands, Grenville and North Gower) reported that the kit provides a valuable and easy to use tool for assessing and monitoring the soil quality of their fields. The only exception occurred for a farmer located on a stony soil. Stones prevented full PR readings and insertion of the infiltration ring. Thus the kit may be unsuitable for stony soils.

When farmers were asked which tool(s) they favored most, the largest number cited the penetrometer, followed by the earthworm test, and the OMMC. The overall

consensus on the penetrometer appeared to be that it was very easy to use, and provided instant feedback. One organic farmer reported, “You can actually “feel” trouble spots and how deep they are within the soil”. One farmer also commented that, “using the penetrometer has made me realize that the area I suspected to be compact has a dense layer at about 15 cm, whereas the area that is not plowed does not”. Thus the penetrometer helped verify the farmer’s assumptions about compacted areas within his field. The only recommendation for improvement of the penetrometer was to make the depth increments brighter. This was accomplished by marking the increments with bright red paint.

The earthworm count was another test favored by most farmers. The overall consensus on the earthworm count appeared to be that it was easy to perform and provided valuable feedback. Most farmers were aware of the importance of earthworms and many were taking actions to increase numbers (e.g., reduced tillage and greater residue and/or compost additions). For instance, one organic farmer commented that she was adding compost to her vegetable crop to increase the earthworm population. After conducting an earthworm count, she was pleased to report a large number. Thus the earthworm count helped to verify that her methods were working. A conventional farmer who initially believed his soil was devoid of earthworms (he stated that he has never noticed earthworms in his field), discovered his soil actually had an abundance of earthworms. Thus, in this instance, the earthworm count heightened the farmer’s awareness of his soil quality.

Many farmers also favored the OMMC. The general consensus appeared to be that it was easy to use and provided information that was important to them. One

conventional farmer commented, “I especially like the fact that the OMMC gives you a way to record your soil color so that it can be referred to down the road.” Another conventional farmer commented that the OMMC is a good test because, “it is related to organic matter which we are always trying to improve”. Thus farmers were aware of the importance of soil organic matter to soil quality and viewed the OMMC as a viable tool for long term monitoring of trends in soil organic matter.

When farmers were asked which tools they favored the least, the overall consensus appeared to be the slake resistance and pH tests. Five out of twelve farmers interviewed reported the components of the pH test were too small, and four of the twelve farmers reported the slaking tray was too small. Both tests were improved by replacing them with larger components. For instance, a larger slaking tray was constructed and a larger version of the colorimetric pH test was included. The original pH test consisted of a small test tube and pill sized capsule containing powder. Soil pH is determined by mixing the soil sample with the powder and water inside of the test tube. The color is then compared to a color pH chart. The new pH test proposed for the kit uses the same principles but larger components (Section 3.2.5.2.1).

All farmers reported that they would use the kit if it became commercially available. The overall consensus appeared to be that they would use it because: (1) it is easy to use; (2) it could help them make better management decisions, and; (3) because it provides a tool for monitoring the impact of their management techniques on soil quality. Examples of farmer’s answers when they were asked if they would use the kit in the future include:

“Yes (I would use the kit), because it yields fast results, it is easy to use, I can do the test on my own time schedule, there is not consultation or appointments

necessary. In other words it is time wise and it can be used at your own convenience”

“Yes (I would use the kit), I always wonder if what I am doing is changing the soil. We need to know what types of change we are causing (negative or positive), how to interpret these changes and what to do to improve our soil quality”.

“Yes (I would use the kit), because a better soil, gives you better crops, higher yield and therefore more money.”

“Yes (I would use the kit) because it is easy to use and it helps you know how to improve your soil and manage it better.”

“Yes (I would use the kit), because it makes you more aware of how your methods affect different aspects of your soil, which allows you to make different management decisions.”

“Yes (I would use the kit), because it enables you to notice if your methods are changing your soil in a good or bad way.”

“Yes (I would use the kit), because it would help you increase yield because of better soil. For example, monitoring could help prevent soil erosion.”

“Yes (I would use the kit), because it gives you everything you need to assess some of the most important factors of your soil. The more you know about these factors the better decisions you can make about your practices and the better yield you get.”

“Yes (I would use the kit), because the kit enables you to easily and quickly record the condition of the soil in one point in time and then to look at it down the road, which will help you tell if the farming practices you are using are good for your soil or not.”

All farmers interviewed also commented that the kit measured parameters that they accept as being important aspects of soil quality. One farmer commented that all the tests, especially the PR test is important because compaction is an issue for many farmers. It was also noted that the earthworm count was very valuable because earthworms are very beneficial to soils. Another farmer commented that all of the kits measurements are valuable because they are all important for crop yield and therefore

affect income. Lastly, it was noted that all of the kits measurements are important because they all relate to things that farmers regularly worry about.

4.2.2.1 Conclusions

Farmer's responses suggest that the SQMK may have value as a quick, practical, on-farm soil quality monitoring kit. Farmers of both conventional and organic farming philosophies spoke of its ease-of-use and quick feedback. In addition, the kit was reported to measure aspects of soil quality important to the farmer. Most importantly, all farmers commented that it was a tool they would use if it became commercially available. As stated by one farmer, he would use the kit because it is "easy and practical for farmers to use, otherwise farmers will be dissuaded from using it".

The results of this research also had practical implications for improvement of the Soil Quality Monitoring Kit and appropriate measures were taken to address these issues. However, the new pH kit has not been tested by farmers. Further evaluation of farmer's perceptions on the new pH test should be undertaken.

5. CONCLUSIONS AND RECOMMENDATIONS

The SQMK has the capability to provide sufficient information about the soil quality of a site, and measurements are sufficiently precise, so that their change through time provides the basis for assessing the direction of soil quality change under soil management being applied by the farmer.

Kit Development Phase, CEF, Ottawa, ON.

Results from the investigations conducted on the CEF fields demonstrated that the kit procedures could be carried out on all the soils tested, and that the kit has sufficient range and precision to identify significant differences in penetration resistance (PR), earthworm numbers, slake resistance rating, and infiltration rate among the management systems. Results from the pH test, Organic Matter Monitoring Card (OMMC), and slake resistance rating compared well with standard tests. The ability of the kit to distinguish differences among management systems makes it an appropriate method to show soil parameter trends through time as a result of management. Furthermore, results indicate that the kit is applicable to most of the major soil types of Eastern Ontario as kit tests detected differences in selected soil quality parameters between management systems regardless of soil type. The only problem of consequence occurred with stony soil in which the penetrometer and the infiltration ring could not be inserted satisfactorily. Repeated measurements with individual kit tests demonstrate that each test fell within acceptable ranges of variability. Most importantly, all tests could be conducted easily and rapidly.

Farm Application Phase

Kit Trial on Farmer's Field, Carleton Place, Ontario

This test allowed for a preliminary test of the kit procedures on a private farm situation where a private farmer rather than agricultural scientists had made the land management decisions. Results showed that the kit was able to detect differences between parts of the field where the farmer perceived the soil quality was poorer and where he perceived that it was better. Also, in comparing regularly cropped areas with fence line areas, the penetration resistance (as expected) was higher for the cropped field than for the fence line area. Penetration resistance also differentiated between row and inter-row areas within the field, showing higher average PR for inter-row areas. The penetrometer, when penetration distance was measured for each individual blow, proved to be much better than when the blow count to penetrate 15 cm and from 15-30 cm was recorded or when the average bulk density was measured for these zones. The measurement of penetration for each individual blow also allowed the thickness of the hard-to-penetrate zone to be ascertained. The OMMC was also successful in differentiating between areas of higher and lower organic matter content, with areas containing higher OM content having lower Munsell color values. The OM differences were confirmed by standard organic matter analysis.

Farmer Assessment of the Soil Quality Monitoring Kit (SQMK)

Farmers' responses indicate that the SQMK accomplished the main objective of this study, that is to develop a quick, easy to use, on-farm soil quality monitoring kit. Overall, it performed well on most soil associations tested; the only exception was for

stony soils. Farmers were particularly pleased with its ease-of-use and quick feedback. As stated by one farmer, he would use the kit because it is “easy and practical for farmers to use, otherwise farmers will be dissuaded from using it”. The farmers also agreed that the properties measured by the kit are ones that they personally consider to be important aspects of soil quality. Most importantly, all farmers commented that it was a tool they would use if it became commercially available.

Summary

In summary, the SQMK consists of a suite of tools deemed to meet the goals of precision, ease-of-use and sensitivity. It allows the user to measure a suite of physical, chemical and biological soil properties that are essential indicators of soil quality because they are factors that definitely affect the functioning of the soil. The kit can be used to identify the effects of management practices on general trends in soil quality over time and space. Baseline data from the first use can be used to establish management goals and monitoring over time can follow the success (or not) of the management regime.

The kit tools can be produced for relatively low cost. The plastic slake resistance tray and its sieves are neither difficult nor expensive to construct. Individual plastic dishes or cups could potentially be used. Similarly, the infiltration test ring can be produced from a thin walled metal pipe; a large metal coffee tin (~15 cm diameter) with the bottom cut out would suffice. Soil pH tests are readily available at low cost. The Munsell color sheet costs approximately \$35. The largest associated cost is the penetrometer; our construction cost was approximately \$150.

5.1 Limitations

The main limitation encountered during this project was that the experimental sites at the Central Experimental Farm were obviously not designed to allow testing of the effects of management on soil quality within a single year. Regardless, the CEF testing confirmed the ability of the kit to monitor soil quality differences, and trends in the kit measurements over time would allow the determination of whether the soil quality is changing over time and in which direction. It is not clear that a solution to the problems of penetrometer and infiltration measurements in stony soils can be overcome, but the remaining kit should still be applicable to these soils.

5.2 Steps toward Adoption

The results from this project are very promising, and it would be useful to determine whether the Soil Quality Monitoring Kit can be applied over a broader region of Canada than just the Eastern Ontario region. At present, the actual values of the individual parameters that would constitute “good soil quality” for soils cannot be stated, and no universal values for individual parameters is to be expected. Soil types (for example sandy loams and clay loams) are sufficiently different that such “calibration” would have to be done at the individual soil series level.

Over time, if the kit is widely used, it should be possible to develop a protocol for the frequency at which the testing should be done under various management systems. Presumably, the more intensively a field is used, the more frequently the soil quality should be monitored. Also, some important questions that use over time may allow to be answered include: can organic matter substitute as the habitat assessment test in soils

lacking earthworms? Does the inability of the penetrometer and infiltration test in stony soils mean that the remaining kit tests would be inadequate for monitoring soil quality in these difficult cases? Are the parameters that are measured by the test kit sufficient, or have some important aspect been missed?

With the utility of the SQMK established, its existence should be made known to agricultural service organizations (e.g. Canadian Organic Growers Association, Ontario Ministry of Agriculture, Food and Rural Affairs, and local agricultural suppliers). Such organizations have the ability to promote the kit's utility (e.g., through newsletters, on-line news or other publications) and they could be the agents to make it available to farmers either for a fee or as a complimentary service. The latter would make the kit easily accessible to farmers, make efficient use of the investment and assure that the kits are maintained in good condition. The SQMK could also be used by farm consultants as one of their tools for informal soil quality assessment or as an educational resource for teaching about soil quality. The USDA and NZ soil quality test kits have found a market in their constituencies, there is no obvious reason why a soil quality monitoring kit adapted to Eastern Canadian conditions could not also find a market.

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Appendix A1

**United States Department of Agriculture and
New Zealand Institute for Crop and Food Research Limited
Soil Quality Test Kits-
Current and Proposed Methods**

USDA represents the United States Department of Agriculture Soil Quality Test kit, and NZ represents the New Zealand Institute for Crop and Food Research Limited Soil Quality Test kit.

Soil Quality Indicator	Current Methods	Limitations	Proposed Method	Justification	Final method included in Soil Quality Monitoring kit
Physical Indicators					
Bulk Density	Soil coring method + off field analysis (USDA and NZ)	Corers bend easily; sampling is destructive, detailed off field analysis.	Penetrometer	Non-destructive, quantitative, quick, accurate, easy-to-use, test conducted in field.	Dynamic Cone Penetrometer. Provides an indirect assessment of areas of compaction (i.e. high bulk density).
Infiltration	Infiltration ring; time for 1" of water to infiltrate is recorded (USDA and NZ)	Unsuitable for high clay content soils due to low permeability.	Infiltration ring, with modified measurement procedures, to enable more timely analysis in high clay content soils	Quicker testing	Infiltration ring, with time limit applied to clay soils.
Slaking	Stability kit (USDA)	Stability kit comes with only 1 slaking tray for 3 replicates.	Stability kit with 1 slaking tray per replicate	Quicker testing	Slaking kit requiring fewer samples. 12 as opposed to 16. Inclusion of 3 slaking kits as opposed to one.
Soil Structural Stability	Soil core collection + off field analysis (NZ)	Analysis cannot be completed within the field and is time consuming.	None	Test is redundant. Inferences can be made from organic matter assessment and slaking.	None

(Table continued on next page)

(Table continued)

Soil Quality Indicator	Current Methods	Limitations	Proposed Method	Justification	Final method included in Soil Quality Monitoring kit
Water Holding Capacity	Soil core collection + off field analysis (NZ)	Analysis cannot be completed within the field and is time consuming.	None	Test is redundant. Inferences can be made from organic matter assessment	None
Structural Condition Scorecard	Field evaluation of structure using a visual scorecard (NZ)	Photographs were not representative of important agricultural soils of eastern Ontario	A scorecard using photographs of agriculturally important soils of eastern Ontario and possibly beyond.	Scorecard would be more representative of soils of eastern Ontario.	Not included in Soil Quality Monitoring kit due to time constraints. However, one designed specifically for soils of eastern Ontario is recommended.
Aggregate Stability	Soil sample is air-dried, then wet and dry sieved. Remaining soil is dispersed, dried and weighed.	Detailed and time consuming off-field analysis.	None	Test is redundant. Inferences can be made from organic matter assessment and slaking.	None
Profile Density Assessment	Field evaluation of soil compaction using a visual scorecard.	Time consuming field analysis.	Dynamic Cone Penetrometer	Quick, accurate and ease to use.	Dynamic Cone Penetrometer.

(Table continued on next page)

(Table continued)

Soil Quality Indicator	Current Methods	Limitations	Proposed Method	Justification	Final method included in Soil Quality Monitoring kit
Biological Indicators					
Earthworm Count	Manual count (NZ and USDA)	Weather and season dependent	Manual earthworm count with specific reference to seasonal and climatic variation.	Higher accuracy	Manual earthworm count recommended in spring season.
Soil Respiration	Insertion of CO ₂ chamber and measurement of evolved CO ₂ using a Draeger tube apparatus (USDA)	Detailed and time consuming field analysis. Draeger tubes are costly to replace.	None	Test is redundant. Inferences can be made from organic matter assessment, pH, and infiltration.	None
Chemical Indicators					
Organic Matter	Not available (USDA and NZ)		Visual assessment scorecard	Easy-to-use, quick, inexpensive, and accurate.	Organic Matter Monitoring Card.
pH	Hanna Instruments Pocket Meter (USDA)	Expensive, requires calibration and maintenance.	Colorimetric soil pH test kit	Inexpensive, quick, easy-to-use	Soil pH test kit, designed specifically for common soil pH ranges of eastern Ontario.
Electrical Conductivity	Hanna Instruments EC Pocket Meter (USDA)	Expensive, requires calibration and maintenance.	None	Generally, soil salinity does not pose as a soil quality limitation for soils of eastern Ontario.	None

Appendix A2

Conversion of Penetrometer Results to Work Done

Resistance can be calculated as the work done by the soil to stop the movement of the penetrometer. The work done by the soil is calculated according to the Energy-Work theorem as the change in the kinetic energy of the penetrometer. When the penetrometer is driven into the soil by the hammer, the kinetic energy of the hammer is transferred to the penetrometer cone. When the penetrometer is halted by the soil, its kinetic energy is zero. Thus, the work done by the soil equals the kinetic energy transferred to the cone from the penetrometer when its hammer contacts the strike plate. Resistance can be calculated by the work done by the soil to stop the movement of the penetrometer divided by the distance the penetrometer travels:

$$R_s = W_s / P_d \quad (1)$$

Where R_s is the soil resistance (newton (N)), W_s is the work done by the soil (joules (J)), and P_d is the distance the penetrometer travels through the soil (m). The soil's resistance for each blow of the hammer can be calculated by substituting the kinetic energy (KE) for a hammer into equation 1. The kinetic energy for a hammer of mass 4.5 kg falling 49 cm is 20.32 J.

$$KE = W_s = 1/2mv^2 = 20.32 \text{ J}$$

The resistance calculated by equation 1 represents the average value of soil resistance across the penetration distance of the penetrometer. The penetrometer measurements can either be expressed as the number of blows per meter of penetration, or as the average soil resistance for each depth of soil traveled with each blow of the hammer. This approach does not assume soil uniformity because it generates an average resistance across the depth the cone travels (Herric et al., 2002).

Appendix A3

Summary of Farmer's Assessment of Soil Quality Monitoring Kit and Interview Questions

CT=conventional farmer, OR=organic farmer, NG=farmer's field is located on North Gower soil association, UP=farmer's field is located on Uplands soil association, MT=farmer's field is located on Matilda soil association.

Question: How would you classify the ease-of-use of the penetrometer, very easy to use, somewhat easy to use, somewhat difficult to use, or very difficult to use?

Responses:

CT-NG1: Very easy to use
 CT-NG2: Very easy to use
 OR-NG4: Very easy to use
 OR-NG4: Very easy to use
 CT-UP1: Very easy to use
 OR-UP2: Very easy to use
 OR-UP3: Very easy to use
 OR-UP4: Very easy to use
 CT-MT1: Very easy to use
 OR-MT2: Very easy to use
 OR-MT3: Very easy to use
 OR-MT4: Very easy to use

Question: How would you classify the ease-of-use of the infiltration test, very easy to use, somewhat easy to use, somewhat difficult to use, or very difficult to use?

Responses:

CT-NG1: Very easy to use
 CT-NG2: Very easy to use
 OR-NG3: Very easy to use
 OR-NG4: Very easy to use
 CT-UP1: Very easy to use
 OR-UP2: Very easy to use
 OR-UP3: Very easy to use
 OR-UP4: Very easy to use
 CT-MT1: Very easy to use
 OR-MT2: Very easy to use
 OR-MT3: Very easy to use
 OR-MT4: Very easy to use

Question: How would you classify the ease-of-use of the slaking test, very easy to use, somewhat easy to use, somewhat difficult to use, or very difficult to use?

Responses:

CT-NG1: Very easy to use
 CT-NG2: Very easy to use
 OR-NG3: Very easy to use
 OR-NG4: Very easy to use
 CT-UP1: Very easy to use
 OR-UP2: Very easy to use
 OR-UP3: Very easy to use

OR-UP4: Very easy to use
CT-MT1: Very easy to use
OR-MT2: Very easy to use
OR-MT3: Very easy to use
OR-MT4: Very easy to use

Question: How would you classify the ease of the earthworm count, very easy to use, somewhat easy to use, somewhat difficult to use, or very difficult to use?

Responses:

CT-NG1: Very easy to use
CT-NG2: Very easy to use
OR-NG3: Very easy to use
OR-NG4: Very easy to use
CT-UP1: Very easy to use
OR-UP2: Very easy to use
OR-UP3: Very easy to use
OR-UP4: Very easy to use
CT-MT1: Very easy to use
OR-MT2: Very easy to use
OR-MT3: Very easy to use
OR-MT4: Very easy to use

Question: How would you classify the ease-of-use of the pH test, very easy to use, somewhat easy to use, somewhat difficult to use, or very difficult to use?

Responses:

CT-NG1: Somewhat difficult to use
CT-NG2: Somewhat difficult to use
OR-NG3: Somewhat difficult to use
OR-NG4: Very easy to use
CT-UP1: Very easy to use
OR-UP2: Somewhat easy to use
OR-UP3: Somewhat difficult to use
OR-UP4: Very easy to use
CT-MT1: Very easy to use
OR-MT2: Very easy to use
OR-MT3: Somewhat easy to use
OR-MT4: Very easy to use

Question: How would you classify the ease-of-use of the Organic Matter Monitoring card, very easy to use, somewhat easy to use, somewhat difficult to use, or very difficult to use?

Responses:

CT-NG1: Very easy to use

CT-NG2: Very easy to use
OR-NG3: Very easy to use
OR-NG4: Very easy to use
CT-UP1: Very easy to use
OR-UP2: Very easy to use
OR-UP3: Very easy to use
OR-UP4: Very easy to use
CT-MT1: Very easy to use
OR-MT2: Very easy to use
OR-MT3: Very easy to use
OR-MT4: Very easy to use

Question: How would you classify the instruction manual, very easy to understand, somewhat easy to understand, somewhat difficult to understand, or very difficult to understand?

Responses:

CT-NG1: Very easy to understand
CT-NG2: Very easy to understand
OR-NG3: Very easy to understand
OR-NG4: Very easy to understand
CT-UP1: Very easy to understand
OR-UP2: Very easy to understand
OR-UP3: Very easy to understand
OR-UP4: Very easy to understand
CT-MT1: Very easy to understand
OR-MT2: Very easy to understand
OR-MT3: Very easy to understand
OR-MT4: Very easy to understand

Question: How would you classify the ease-of-use of the Soil Quality Monitoring sheets, very easy to use, somewhat easy to use, somewhat difficult to use, or very difficult to use?

Responses:

CT-NG1: Very easy to use
CT-NG2: Very easy to use
OR-NG3: Very easy to use
OR-NG4: Very easy to use
CT-UP1: Very easy to use
OR-UP2: Very easy to use
OR-UP3: Very easy to use
OR-UP4: Very easy to use
CT-MT1: Very easy to use
OR-MT2: Very easy to use
OR-MT3: Very easy to use
OR-MT4: Very easy to use

Question: How would you classify the overall “ease-of-use” of the Soil Quality Monitoring Kit, very easy to use, somewhat easy to use, somewhat difficult to use, or very difficult to use?

Responses:

CT-NG1: Very easy to use
 CT-NG2: Very easy to use
 OR-NG3: Very easy to use
 OR-NG4: Very easy to use
 CT-UP1: Very easy to use
 OR-UP2: Very easy to use
 OR-UP3: Very easy to use
 OR-UP4: Very easy to use
 CT-MT1: Somewhat easy to use
 OR-MT2: Very easy to use
 OR-MT3: Very easy to use
 OR-MT4: Very easy to use

Question: What recommendation (s), if any, could you make that would improve the ease-of-use of the Soil Quality Monitoring Kit?

Responses:

CT-NG1: Make depth marks on the penetrometer brighter
 CT-NG2: Make the pH test and slaking test apparatus larger.
 OR-NG3: Make the pH test and slaking test apparatus larger.
 OR-NG4: Make slaking test apparatus larger.
 CT-UP1: None
 OR-UP2: Make the pH test and slaking test apparatus larger
 OR-UP3: Make the pH test larger.
 OR-UP4: None
 CT-MT1: Make the terms in the manual more masculine. Mention in the manual that if you have a rocky soil try different spots until you find one that has no rocks.
 OR-MT2: None
 OR-MT3: Make the pH test larger.
 OR-MT4: None

Question: Do you believe the monitoring kit could assist you in trouble shooting problem areas in your fields and to monitor changes over time after new management systems are begun? Please explain.

Responses:

CT-NG1: Yes, I believe the kit could assist me in both trouble shooting and monitoring, especially monitoring. The tools such as the OM score card, penetrometer, earthworms and infiltration are useful in providing us with information that farmers always wonder about.
 CT-NG2: Yes, because it may help you verify something you think may be wrong with you're your soil, which is important.
 OR-NG3: Yes, because it helps me know what my soil needs.

OR-NG4: Yes, the kit makes you more aware of the things such as biology, compaction, and pH.

CT-UP1: Yes, because it is straightforward.

OR-UP2: Yes, the kit makes you more aware of the condition of your soil and makes it easy for you to note changes over time.

OR-UP3: Yes, the kit allows you to make quick measurements, which would encourage farmers to use it on a regular basis.

OR-UP4: Yes, because it gives you all of the tools and you can do it yourself.

CT-MT1: Yes, all of the tools are useful but I think the penetrometer and infiltration ring may not work so well because of all of the rocks in my soil, I keep hitting rocks.

OR-MT2: Yes, the kit would help with these things because it is easy to use, which is why I think the kit would be successful. If it is hard to use people will not use it.

OR-MT3: Yes, because it covers all of the most important aspects that we worry about as farmers and gives you easy to use tools to help you investigate these aspects.

OR-MT4: Definitely, sometimes it is hard to notice changes in your soil quality unless you take the time to look at the conditions. The kit allows you to easily do this.

Question: Do you believe the monitoring kit heightened your awareness of the impact of different management systems on your soil quality? Please explain.

Responses:

CT-NG1: Yes, if we compare different spots.

CT-NG2: Yes, because it helps me know what my soil needs.

OR-NG3: Yes, I learned that my soil has a good infiltration rate and lots of worms, which is good.

OR-NG4: Yes, it made me realize that my earthworm numbers are higher in the area I have been applying more compost, which is what I intended.

CT-UP1: Yes, it made me more aware of factors I may not have thought about before.

OR-UP2: Yes, it made me realize that my soil has a lot of earthworms and the area that I cultivate most doesn't have any compact layers. I kind of figured my soil was in good condition but the kit helped me to verify this.

OR-UP3: Yes, especially the penetrometer because it made me aware of dense areas in my field. Using the penetrometer has made me realize that the area I suspected to be compact has a dense layer at about 15 cm, whereas the area that is not ploughed does not. You can actually "feel" trouble spots and how deep they are within the soil

OR-UP4: Yes, it made me realize that I have lots of worms, when I thought that I had none. I never notice them while I am in the field.

CT-MT1: Somewhat but I couldn't do two of the tests

OR-MT2: Yes, it did because I realized my soil isn't in as bad of a shape as I initially thought.

OR-MT3: Yes, it helped me verify what I already thought about different areas within my field.

OR-MT4: Yes, because it makes you take a closer look at your soil.

Question: What aspect(s) of the monitoring kit did you dislike? Why?

Responses:

CT-NG1: The pH test is hard to conduct because the apparatus is so small.

CT-NG2: The pH and slaking test apparatus is too small.

OR-NG3: The pH and slaking test apparatus is too small.

OR-NG4: None

CT-UP1: None

OR-UP2: The pH and slaking test apparatus is too small.

OR-UP3: The pH and slaking test apparatus is too small.

OR-UP4: None

CT-MT1: The worm count, I don't like counting worms.

OR-MT2: None

OR-MT3: None

OR-MT4: None

Question: What aspect(s) of the monitoring kit did you like best? Why?

Responses:

CT-NG1: The penetrometer and earthworm count, because it is interesting, easy-to-use and provided useful information.

CT-NG2: The earthworm count, penetrometer and infiltration test because they are interesting and easy to do.

OR-NG3: The earthworm count, because it is interesting.

OR-NG4: The penetrometer, because we try to avoid compaction the most. We aim to have soils that are not compact, this is what we work on the most.

CT-UP1: I liked the OM scorecard and the penetrometer, because they are practical. I especially like the fact that the OMMC gives you a way to record your soil color so that it can be referred to down the road. The penetrometer does this too.

OR-UP2: The earthworm count and penetrometer, because it is interesting and gives you instant feedback about the condition of your soil.

OR-UP3: The penetrometer, because you can take test anywhere in you field and it gives quick results.

OR-UP4: I liked all aspects

CT-MT1: The color chart is easy to use. And it is related to organic matter which we are always trying to improve.

OR-MT2: I liked all aspects.

OR-MT3: The earthworm count, OM card, and the infiltration test.

OR-MT4: All aspects, especially the organic matter score card.

Question: Could you see yourself using the Soil Quality Monitoring Kit to monitor the soil quality of our farm in the future? Explain.

Responses:

CT-NG1: Yes, I always wonder if what I am doing is changing the soil. We need to know what types of change we are causing (negative or positive), how to interpret these changes and what to do to improve our soil quality.

CT-NG2: Yes, because it yields fast results, it is easy to use, I can do the test on my own time schedule, there is not consultation or appointments necessary. In other words it is time wise and it can be used at your own convenience

OR-NG3: Yes, because a better soil, gives you better crops, higher yield and therefore more money.

OR-NG4: Yes, because it is easy to use and it helps you know how to improve you your soil and manage it better

CT-UP1: Yes, because it enables you to notice if your methods are changing your soil in a good or bad way.

OR-UP2: Yes, because it makes you more aware of how your methods affect different aspects of your soil, which allows you to make different management decisions.

OR-UP3: Yes, because it is quick and easy to use.

OR-UP4: Yes, because it is quick and easy to use.

CT-MT1: Yes, because it would help you increase yield because of better soil. For example, monitoring could help prevent soil erosion.

OR-MT2: Yes, because it is quick and easy to use.

OR-MT3: Yes, because it gives you everything you need to assess some of the most important factors of your soil. The more you know about these factors the better decisions you can make about your practices and the better yield you get.

OR-MT4: Yes, because the kit enables you to easily and quickly record the condition of the soil in one point in time and then to look at it down the road, which will help you tell if the farming practices you are using are good for your soil or not.

Question: Do you believe the parameters measured by the kit are important to soil quality?

Responses:

CT-NG1: Yes especially earthworms, PR, infiltration and organic matter.

CT-NG2: Yes they all are

OR-NG3: Yes they all are.

OR-NG4: Yes, especially the earthworm test. Because earthworms are very beneficial to soil health.

CT-UP1: Yes, they all are.

OR-UP2: Yes, all of them are.

OR-UP3: Yes, especially PR because compaction is an issue may of us have to deal with.

OR-UP4: yes they all are because they all test things which farmers often worry about.

CT-MT1: Yes, they all are.

OR-MT2: Yes, they all are

OR-MT3: yes, they all are.

OR-MT4: Yes they all are.

Appendix A4

Soil Gravimetric Water Contents CEF, Ottawa, On.

A: Statistical comparison of mean gravimetric water contents by depth (0-15 and 15-30 cm) for all sites. Results are significantly different if $P < 0.05$.

Site		Depth (cm)		Mann-Whitney U-test (95% significance)
		0-15	15-30	
Gravimetric water content (g) 0-15 cm vs. 15-30 cm depth	Clay compact (C-C)	22.19	23.44	P= 0.579
	Clay non-compact (C-NC)	21.82	21.91	P= 0.912
	Sand compact (S-C)	15.44	14.39	P= 0.123
	Sand non-compact (S-NC)	15.93	14.2	P= 0.089
	Conventionally tilled continuous soybean (CT-SSS)	19.38	16.47	P= 0.000
	No-till corn-soybean-wheat rotation (NT-CSW)	19.53	16.83	P= 0.000
	Conventionally tilled corn-soybean-wheat rotation (CT-CSW)	15.52	16.29	P= 0.481
	No till continuous corn (NT-CCC)	23.44	21.8	P= 0.075
	Clay loam long-term conventionally tilled site 1 (CL-LTCT 1)	16.17	16.7	P= 0.247
	Clay loam long-term conventionally tilled site 2 (CL-LTCT 2)	23.71	23.81	P= 0.315
	Clay loam long-term conventionally tilled site 3 (CL-LTCT 3)	17.94	17.66	P= 0.353

B: Statistical comparison of gravimetric water contents between management systems (sand and clay compact vs. non-compact; and no-till vs. conventional tillage). Results are significantly different if $P < 0.05$.

Site	Clay compact (N=10) (g)	Clay non-compact (N=10) (g)	Mann-Whitney U-test (95% significance)
Clay compact vs. clay non-compact (0-15 cm)	22.19	21.82	P=0.436
Clay compact vs. clay non-compact (15-30 cm)	23.44	21.91	P=0.28
Sand compact vs. Sand non-compact (0-15 cm)	Sand compact (N=10) (g) 15.44	Sand non-compact (N=10) (g) 15.94	P=0.684
Sand compact vs. Sand non-compact (15-30 cm)	14.39	14.2	P=0.529
Conventional tillage vs. No-till (corn-soybean-wheat rotation) (0-15 cm)	CT-CSW (N=10) (g) 15.52	NT-CSW (N=10) (g) 19.53	P=0.00
Conventional tillage vs. No-till (corn-soybean-wheat rotation) (15-30 cm)	16.29	16.83	P=0.853

Appendix A5

Soil Quality Monitoring Kit Manual

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PREFACE

Soil quality, from an agricultural perspective, is defined in terms of the capacity of the soil to sustain plant growth. Ultimately, this capacity is related to the ability of the soil to: provide a suitable medium for seed germination and root growth/development; to accept, hold and release water; to be absent of adverse chemical conditions; and to supply a balance of nutrients. Soil properties that allow and/or promote these responses constitute “good” soil quality and include: medium soil strength, stable soil structure, moderate to high infiltration rate, high organic matter content, near-neutral soil pH and abundant earthworm populations. This manual describes the Soil Quality Monitoring Kit tests that are used to monitor the selected physical, chemical and biological properties that influence the above-mentioned soil processes. The divisions between physical, chemical, and biological properties are not as clear-cut as may be implied from their presentation in this manual. To truly understand soil quality, land managers must focus on the evaluation of the soil system as a whole (Per Schjonning et al., 2000). For instance, interpretation of the relevance of soil biological properties apart from soil physical and chemical properties is of little value, and with respect to assessment of soil quality, can be misleading (Doran et al, 1999); their interactions must be integrated. The goal of the Soil Quality Monitoring Kit is to provide a practical, on-farm, soil quality kit suited specifically for soils of eastern Ontario. The kit can;

1. Provide a means for land managers to trouble shoot problem areas in fields and to monitor changes over time after new management systems are begun.
2. Heighten land managers’ awareness of the impact of different management systems on soil.
3. Assist land managers in monitoring changes in the physical, chemical and biological properties of their soils.

Section 1 provides a description of the tools and procedures used to measure the selected soil quality parameters. Section 2 provides background and interpretative information on the tests. The tests are designed to measure the effects of management practices on trends in soil quality rather than to provide an absolute measure. Trends in these indicators over a period of several years can be taken as evidence for improvement (or deterioration) of soil quality, and the success (or lack thereof) of the management practices.

The kit was developed at Carleton University and the Eastern Cereal and Oilseed Research Center (ECORC), and the field testing of the kit was carried out on fields at the Central Experimental Farm in Ottawa. Feedback from farmers, who tested the kit within their fields, aided in the development of this kit.

The guidebooks for some other soil quality testing efforts have been a valuable resource in deciding what to do and what not to do for this particular project. All such sources are listed at the conclusion of this manual.

1. Sampling Guidelines

WHERE TO SAMPLE?

The determination of where to sample depends on the purpose of the sampling program. At all the individual sampling sites, the various measurements should be made within a relatively small area—about 3m by 3m—with care being taken to minimize the area disturbed while conducting each test.

- You may wish to obtain a comparative overview of the properties of the soil within a field to determine the uniformity of the soil properties or to locate areas where the properties are less favorable so that a management program for remediation can be applied to the whole field, or to areas of lesser quality. This is the most probable purpose for a first time user of the kit.

When sampling to obtain the base-line soil quality data:

- Select sites that are representative of the field or site. When performing soil quality assessments, avoid areas such as headlands, which may have had heavier traffic than the rest of the area.
 - For fields that are non-uniform in terms of topography, soil texture, or other factors, the sampling pattern should take these factors into account by following a pattern that allows each sub area that is similar to be adequately assessed.
- You may wish to target specific areas where you believe (or know) that you have a soil quality problem, in order to identify the nature of the problem or to obtain base-line information before starting a management program for remediation.

When sampling to obtain the base-line soil quality data:

- Sample areas that are representative of the trouble spots.
- When monitoring changes in soil quality over time, ensure that the same sites within the field are measured at each sampling time. Mark the locations well. You must be able to go back to the same spot (within 1-2 meters) seasonally or yearly. Wire flag markers and field edges can be useful. Field edge landmarks such as telephone poles or trees can be used to triangulate from. Then you can pace the distance to the monitoring site. Draw a sketch, noting the number of paces.
- If you wish to test the soil conditions in an area that has not be cultivated for a long period, in order to compare them with the cultivated field, the various tests can be conducted in long established fence lines along the field edges.

WHEN TO SAMPLE?

- Timing of sampling is important, because soil properties vary with season and with management operations such as tillage (USDA, 1999).
- For the detection of long-term changes in soil quality, it is recommended that sampling take place once a year, at approximately the same time each year.

NOTE: It is important to take the measurements under approximately the same soil moisture conditions at each sampling time because some measurements are substantially affected by the soil moisture content. The soil should be neither very wet nor very dry; the optimal water content at the time of sampling is approximately what would be considered desirable for good plant growth.

HOW MANY SAMPLES?

Sample number will depend on the variability of the field. It is recommended that a minimum of 3 samples or measurements be taken on any one soil type and management combination (USDA, 1999). In general, the greater the variability of the field, the greater the sample number needed to get a representative value at the field scale. When measuring penetration resistance and pH, eight or nine samples/measurements from across the field should be taken. Soil pH samples can be bulked and mixed, and two subsamples from the mixed samples can be analysed. When sampling across the field, it is important to stay away from areas that are not representative of the field, such as farm lanes and field borders, or eroded spots (unless one is specifically trying to use management practices to improve such locations) (USDA, 1999).

TESTING PROCEDURE

2. Soil Texture

Equipment needed:

- Water bottle

Note: As an indicator of soil quality, soil texture is judged mostly in the context of its influence on productivity and the ease of soil management. Unlike other indicators of soil quality, soil texture is a fixed soil property that is not readily altered (except over long time periods or in extreme cases of erosion or sediment deposition), and therefore is not a property which needs to be monitored through time. Nevertheless, it is important to be knowledgeable about soil texture because it often sets limits on the maximum soil quality that management practices can achieve.

Procedure: The “feel” or hand texture method can be used for determining soil texture. Relative proportions of sand, silt and clay can be estimated by manipulating a moistened sample between the thumb and forefinger. Accuracy depends mainly on experience, however, flow diagrams and guides (such as the one provided below) which describe the method for determining texture by feel can be used to aid interpretation.

Guide for Determining Texture by Feel (Adopted from Brady and Weil, 1999, p. 128)

Start by kneading a walnut-sized sample of moist sample into a uniform puttylike consistency, slowing adding water if necessary. The soil should be moist but not glistening.

While manipulating the sample, note its malleability, stickiness, and stiffness, all properties associated with clay content. A high silt content makes the sample feel smooth, with little stickiness or resistance to deformation. A soil with a high sand content feels rough and gritty, and makes a grinding noise when rubbed next to ones ear.

To estimate the amount of clay, attempt to squeeze a ball of moistened soil between your thumb and the side of your forefinger, making a ribbon of soil. Make the ribbon as long as possible until it breaks from its own weight. Interpret your observations as follows:

1. Soil will not cohere into a ball, falls apart: **SAND**

2. Soil forms a ball, but will not form a ribbon: **LOAMY SAND**
3. Soil ribbon is dull and breaks off when less than 2.5 cm long and
 - a. Grinding noise is audible; grittiness is prominent feel: **SANDY LOAM**
 - b. Smooth, floury feel prominent; no grinding audible: **SILT LOAM**
 - c. Only slight grittiness and smoothness; grinding not clearly audible: **LOAM**
4. Soil exhibits moderate stickiness and firmness, forms ribbons 2.5 to 5 cm long, and
 - a. Grinding noise is audible; grittiness is prominent feel: **SANDY CLAY LOAM**
 - b. Smooth floury feel prominent; no grinding audible: **SILTY CLAY LOAM**
 - c. Only slight grittiness and smoothness; grinding not clearly audible: **CLAY LOAM**
5. Soil exhibits dominant stickiness and firmness, forms shiny ribbons longer than 5 cm, and
 - a. Grinding noise is audible; grittiness is dominant feel: **SANDY CLAY**
 - b. Smooth, floury feel prominent; no grinding audible: **SILTY CLAY**
 - c. Only slight grittiness and smoothness; grinding not clearly audible: **CLAY**

3. Soil Compaction Test-Penetrometer

Equipment needed:

- Penetrometer

Considerations: Penetrometer readings are influenced by soil moisture status and should not be taken if the soil is saturated or too dry. They are best taken 24 to 48 hours after a rainfall or irrigation event.

Note: The number of blows required to penetrate the soil to a given depth increases as the pore space of the soil decreases or as it becomes more compacted.

Procedure:

At each test site:

- Gently press the penetrometer tip into the soil surface until it just becomes buried (i.e., soil surface is level with the base of the cone), while holding the penetrometer upright, lift the weight up to the collar and hold it in this position.
- Use the bubble level, located on the shaft of the penetrometer, to bring the penetrometer to the vertical position (the bubble is in the center of the bubble level). Release the weight; this is counted as blow number 1.
- While maintaining the penetrometer in the vertical position, continue to lift and drop the weight until the penetrometer has penetrated to 15 cm (marked on the shaft). Record the number of blows required to reach 15 cm on the *Compaction Test Monitoring Card*.
- Continue lifting and dropping the weight until the penetrometer tip reaches 30 cm. Record the number of blows required to penetrate from 15-30 cm on the *Compaction Test Monitoring Card*.
- Carefully remove the penetrometer from the soil. To avoid injury to your back, be sure to lift with your legs. Extraction of the penetrometer is easier if the handle is rotated slightly back and forth at the same time as the lifting force is applied. If the penetrometer will not come out with reasonable effort, obtain assistance, or use a shovel to disturb the soil around the upper part of the penetrometer shaft in the ground.

Alternate Procedure

- Record the penetration depth after each blow. This method will more accurately locate the depths of maximum or changing soil resistance.

4. Infiltration Test¹

Material needed to measure infiltration:

- 15 cm (6-inch) diameter, metal infiltration ring
- Plastic wrap
- 500 mL graduated cylinder
- Gallon jugs or 5 gallon buckets to carry water
- Stopwatch or timer
- Water
- Hand sledge and wood block

Considerations: Infiltration is best taken 24-48 hours after a rainfall or irrigation event. If the soil is saturated infiltration will not occur. Conversely, if soil is very dry, such that it cracks at the soil surface, water entry is enhanced, thus yielding falsely high values for the infiltration rate.

Procedure:

At each test site:

- Clear the sampling area of surface residue. If the site is covered with vegetation, use scissors to remove or trim the vegetation as close to the soil surface as possible.
- Using the hand sledge and block of wood, drive the infiltration ring, beveled edge down, to a depth of three inches (7.5 cm) (line marked on outside of ring).
- Gently firm the soil surface around the inside wall of the infiltration ring with your finger to prevent extra seepage.
- Line the soil surface inside the ring with a sheet of plastic wrap to completely cover the soil and ring. This procedure prevents disturbance to the soil surface when adding water.
- Fill the graduated cylinder to the 444 mL mark with water *from or near* the site. For instance, you can use the same water the crop might be irrigated with, or rainwater. You can also use tap water if your water source is well water. However, if your water source is not a well, do not use tap water. The water chemistry will likely be different. This can change the interactions with the soil and affect the infiltration rate (USDA, 1999).

¹ Method was adopted from the USDA Soil Quality Test Kit, 1999.

- Pour the water into the ring lined with plastic; the water will be 2.54 cm (1 inch) deep.
- Remove the plastic wrap by gently pulling it out, leaving the water in the ring. Note the time.
- Record the amount of time (in minutes) it takes for the 2.54 cm of water to infiltrate the soil. Stop timing when the surface is glistening.
- Record the amount of time in minutes on the *Infiltration Monitoring Card*.
- **Repeat the infiltration test:** In the same ring, perform a second addition of 444 mL of water. On the *Infiltration Monitoring Card*, enter the number of minutes elapsed for the second infiltration measurement.

Comment: Infiltration measurements on heavy clay soils may take a very long time. In such instances, watch the progress of the first measurement site closely. For subsequent sites on the same soil, you may use this test as a guideline as to when you should periodically check their progress. If all of the water has still not infiltrated after 1 hour, record the depth of water left, in mm, using the marks on the inside of the ring. Subtract that number from the original 2.54 cm that you poured in, and you will have the amount of water infiltrated.

5. Slake Resistance Test²

Material needed for slake test:

- Soil stability kit
- Hand trowel
- Distilled water or rainwater (1 L)

Considerations: the soil should be air-dry when performing this test. If the soil is not dry, collect surface fragments as outlined in Step 1 and allow them to dry.

Procedure:

At each test site:

- Clear the sampling area of surface residue.
- Carefully select 12 soil aggregates from the soil surface zone (top 15 cm). Fragments should be approximately 1 cm across. Be careful not to damage the soil fragments while sampling.
- If there is a surface crust, collect 3 fragments of the crust and 3 from just below the crust.
- Remove all the sieve baskets from the stability kit
- Fill the compartments in the box with water. The water should be 2 cm deep and at approximately the same temperature as the soil.
- Place soil fragments in the sieve baskets
- Lower one of the sieves into a box compartment filled with water.
- Observe the soil fragments for 5 minutes. Refer to Table 1 below to determine classes 1 and 2.
- After 5 minutes, raise the basket out of the water, and then lower it to the bottom. It should take one second for the basket to clear the surface and one second to return to the bottom.
- Repeat the lifting and immersion sequence four more times (total of five immersions). Refer to Table 1 below to determine classes 3 to 6.

² Method is a modified version of methods used in USDA Soil Quality Test Kit, 1999.

- Soil stability is rated according to the time required for the fragment to disintegrate to 50% of its original size during the immersion procedure and to the proportion of the soil fragments remaining on the mesh after the 5 extraction-immersion cycles.

Record the stability ratings for all 12 soil fragments on the ***Soil Slaking/Soil's Resistance to Water Erosion Monitoring Card***. (NOTE: the aggregates in stability classes 4, 5 and 6 must have remained more than 50% intact after the 5 minutes of immersion.)

Table 1: Stability Class Table (adopted from USDA, 1999).

Stability class	Criteria for assignment to stability class
0	Soil too unstable to sample (falls through sieve).
1	50% of original shape lost within 5 seconds of insertion in water.
2	50% of original shape lost 5-30 seconds after insertion.
3	50% of original shape lost 30-300 seconds after insertion or less than 10% of soil remains on the sieve after 5 dipping cycles.
4	10-25% of soil remaining on sieve after 5 dipping cycles.
5	25-75% of soil remaining on sieve after 5 dipping cycles.
6	75-100% of soil remaining on sieve after 5 dipping cycles.

6. Habitat Quality/Earthworms³

Materials needed to measure earthworms:

- Tarp or sturdy plastic ground sheet.
- Container to collect the worms
- Shovel
- Measuring tape

Considerations: In eastern Ontario, we recommend that earthworm populations are measured in early spring or late fall, when earthworm activity near the surface is at its greatest. During the summer, they typically retreat from the hot dry soil to cooler places. Earthworms also prefer soil moisture contents that are desirable for good plant growth; sampling after long periods of saturation or of drought should be avoided.

Note:

- Dig the hole first, and then sort for earthworms.
- Upon excavation of the earthworm pit, put the topsoil portion (top 6-7 cm) into a separate pile to use for the *Soil Color Assessment*.

Procedure:

- At each site, measure a 30 cm square plot and dig down approximately 15 cm (6 inches) with the shovel.
- Place the soil from the pit on the tarp or ground sheet.
- Sort through the soil, one handful and a time, and place all of the earthworms in a container.
- Count the earthworms and record the total number on the *Worm Sampling Monitoring Card*.

³ Method was adopted from USDA Soil Quality Test Kit, 1999.

7. Soil pH Test

Materials needed to measure pH:

- Shovel or hand trowel.
- pH test kit (Chlorphenol Red indicator dye, glass rod, test plate, pH color chart)

At each site:

- Remove a sample of soil from the wall of the earthworm count pit, approximately 5-10 cm below the surface.
- Fill the large depression of the spot plate approximately $\frac{1}{2}$ full of soil.
- Add sufficient Chlorphenol Red indicator dye to saturate the sample, then add 2-3 drops more. Gently tip and rotate the plate so the excess dye has good contact with the soil; do not get the dye muddy.
- Using the glass rod, draw a thin layer of the dye into the groove on the test plate.
- Compare color of the dye with the pH color chart.
- Record value on the *Soil pH Monitoring Card*.

8. Soil Color/Organic Matter Monitoring card (OMMC)

Materials needed to assess soil color:

- Munsell color sheet/OMMC
- Hand trowel
- Water bottle

Procedure:

- Using the topsoil (top 6-7 cm) removed from the earthworm pit, select a representative sample of this topsoil layer.
- If the soil is dry moisten the sample by adding water drop by drop.
- Wait for the water to seep into the soil.
- Using the Munsell color sheet/OMMC provided in the test kit, determine which color corresponds best with your soil sample. Record this color on the *Soil Color/Organic Matter Monitoring Card*. Record the soil as Value/Chroma value.
- It may be useful to compare the topsoil's of long term cropping land with tree lines and fence lines (this may give you an indication of your soils natural state). Generally, the darker the soil (i.e., the lower the Munsell Value) the greater the organic matter content.

SOIL QUALITY MONITORING KIT

BACKGROUND AND INTERPRETATIVE GUIDE FOR INDIVIDUAL KIT TESTS

TEST INTERPRETATION

1. SOIL TEXTURE

Soil texture refers to a soil's relative proportion of sand, silt and clay. It is one of the key variables influencing many soil processes, particularly those involved in soil-water interactions (i.e., accepting, holding and transmitting air and water) and in supplying nutrients to plants. Generally speaking, coarse-textured (i.e., sandy) soils tend to be low in organic matter content and native fertility, they have low water and nutrient holding capacity, low cation exchange and buffering capacities and high infiltration rates. Coarse-textured soils usually require careful attention to water management (i.e., generally including frequent irrigation and/or artificial drainage to suit the needs of specific crops) and proper fertilization (usually more frequent but lower quantities of nutrients per application) (Brady and Weil, 1999). In contrast, fine-textured (i.e., clayey) soils generally are more fertile, have higher organic matter content, high cation and buffering capacities, have better water and nutrient holding capacities, and have lower infiltration rates. Greater microporosity of fine-textured soils, results in reduced aeration and therefore lower rates of organic matter oxidation. Lastly, the formation of clay-humus complexes protects organic matter from degradation (Brady and Weil, 1999).

Soil texture governs many soil management practices. Often when soils have high clay content, they are difficult to manage. Such soils are often sticky when wet and hard when dry, and thus are difficult to cultivate except within a narrow water content range. The ideal soil is often considered to be a loam, which contains relatively equal proportions of clay, sand, and silt. Fine-textured soils are more susceptible to compaction when the moisture content at the time of field operations (e.g., harvesting) is high. Thus in fine to medium textured soils tillage should be limited to periods when the soil is moist but not near saturation. Sandy soils are more prone to drought than clay soils, due to lower water holding capacity. Therefore, such soils may require irrigation and/or mulch to maintain adequate soil moisture content (USDA, 1996). Thus the relative proportions of sand, silt and clay is one of the most important characteristics of soil. It influences many soil processes that are of great significance to land management such as ease of tillage, porosity, aeration and fertility.

2. PENETROMETER-PENETRATION RESISTANCE/COMPACTION

Introduction

Penetration resistance is a common measure of soil compaction (Vanags, 2006). It is measured by determining cone index values using a dynamic cone penetrometer. The number of blows required to penetrate the soil to a given depth increases as the pore space of the soil decreases or as it becomes more compacted.

Penetrometer readings are influenced by soil moisture status and should not be taken if the soil is saturated or too dry: the dryer the soil, the greater the penetration resistance. Penetration resistance is best determined when the soil is at field capacity (24 to 48 hours after a rainfall or irrigation event), which is a uniform condition that can be reproduced from season to season (USDA, 1999).

Interpretations

Areas of compaction or crust formation can be expected to show greater soil penetration resistance (higher number of blows to reach desired soil depth) than areas within the same field with lesser or no structural deterioration (i.e., compaction) (assuming water content and texture are held constant). When assessing compacted layers or problem areas within your field, it may be useful to take readings along a nearby fence line (providing the soil type and moisture conditions are similar to the area you are comparing it with), this should give you some idea of the natural state of your soil.

Soil compaction can be defined as the packing together of soil particles by forces exerted at the soil surface, resulting in increased soil density (USDA, 2004). Compaction has been reported as one of the largest challenges facing farmers of eastern Canada today (McBride et al., 2002). Compaction is mainly caused by repeated passes of heavy machinery on wet soils during tillage and harvesting. Fine textured soils in humid climates are the most susceptible to compaction (Topp et al., 1995). Compaction can reduce crop yield through its effects on a wide variety of plant growth factors. For example, compaction; (1) reduces seedling emergence, thus decreasing crop stand; (2) destroys macropores and thereby decreases oxygen supply to crop roots which restricts their growth and increases risk of root diseases; (3) reduces macroporosity and thereby reduces water infiltration which limits plant available water (Topp et al., 1995) (Table 2). Figure 2 shows typical locations of compacted zones in cultivated soils (USDA, 1999).

Table2: Some of the impacts of soil compaction on soil properties and soil's physical, biological, and chemical functions (University of Minnesota, 2002).

Impact of Compaction on Soil Properties	Impact on Soil Function
Shallower rooting	<ul style="list-style-type: none"> • Reduced nutrient and water uptake
Decreased infiltration	<ul style="list-style-type: none"> • Increased runoff (i.e., erosion) • Drought susceptibility
Slowed drainage	<ul style="list-style-type: none"> • Reduced soil temperature, and therefore slower seed germination, low microbial activity and associated reduced nutrient availability • Low oxygen and therefore growth of anaerobic bacteria and the associated loss of N to the atmosphere through denitrification
Decreased water-holding capacity	<ul style="list-style-type: none"> • Drought susceptibility
Fewer macropores	<ul style="list-style-type: none"> • Fewer large organisms • Decreased biodiversity. Potential changes in nutrient cycling

Figure 2: Typical locations of compacted zones in cultivated soils (Source: USDA, 1999).

Note: above does not reflect no-till soils

3. INFILTRATION

Introduction

Infiltration rate provides a measurement of the rate at which water enters the soil surface. Infiltration rate is dependent on the soil type, soil structure, and the soil water content. The initial soil water content at time of measurement affects the ability of the soil to absorb additional water. Thus, infiltration rate will be higher when the soil is dry than when it is wet. Consequently, when comparing infiltration rates between different soils, soils should have similar moisture contents (USDA, 1999).

The infiltration rate is sensitive to near-surface conditions and is subject to significant change with soil use, management, and time. It is affected by plant root development, earthworm burrows, soil aggregation, and increases in stable organic matter. Tillage has been shown to affect infiltration rates. Immediately following tillage infiltration may be high due to loosening of surface crusts and compact areas. However, over the long-term, tillage disrupts aggregates and soil structure, increasing the risk of compaction, crusting and loss of continuous surface connected pores. Compacted soils have less pore space, resulting in reduced infiltration rates (USDA, 1999).

Interpretations

Due to the influence of the initial soil water content at the time of measurement, it is important that soil water contents be similar when comparing infiltration rates from different sites. If the soil is not at field capacity when the test is performed, a second infiltration test immediately follows. The first application of water wets the soil and the second application provides a more accurate measurement of the infiltration rate of the soil. Wetting the soil prior to measurement aims to standardize the soils for differences in soil water content. Previously disturbed areas should be avoided. Soil infiltration rate/hr is calculated by the equation: $(1/\text{second infiltration time (minutes)}) \times 60$ (USDA, 1999).

The rate at which water enters the soil surface is dependent upon soil texture, structure and initial soil water content. Generally sandy soils will have rapid infiltration rates, while clayey soils have lower rates of infiltration (Table 3 and 4). However, infiltration rates may be high in expanding type clays, as water infiltrates into shrinkage cracks. As infiltration proceeds, macropores generally fill with water and shrinkage cracks close up (Brady and Weil, 1999). Soil structure (i.e., the arrangement and binding together of soil particles (by natural processes) into peds (soil units such as soil aggregates, prisms or blocks (Brady and Weil, 1999))) is important for maintaining soil porosity and therefore infiltration. Channels between peds (interped pores) are important for infiltration. Well-structured soils generally have more interped pores than soils with poor or massive soil structures. Finer soils usually have a stronger, more defined structure than coarser soils due to shrink/swell processes dominating in clay-rich soils and more cohesive strength between particles (McCauley et al., 2005). If aggregates are stable, the structure remains intact throughout a rainstorm.

Table 3. Steady Infiltration rates for general soil textures in very deeply wetted soil
(Cited by USDA, 1999, p. 55)

Soil Type	Steady Infiltration Rate (inches per hour)
Sand	>0.8
Sandy and silty soils	0.4-0.8
Loams	0.2-0.4
Clayey soils	0.04-0.2

Table 4: Infiltration Rates and Classes (Cited by USDA, 1999, p. 56)

Infiltration Rate (in/hr)	Infiltration class
> 20	Very rapid
6 to 20	Rapid
2 to 6	Moderately rapid
0.6 to 2	Moderate
0.2 to 0.6	Moderately slow
0.06 to 0.2	Slow
0.0015 to 0.06	Very slow
<0.0015	Impermeable

4. SLAKE RESISTANCE RATING

Introduction

Soil slaking is an indicator of soil tensile strength; an important influence on soil's resistance to soil erosion. Slaking is the process of fragmentation that occurs when dry aggregates are suddenly immersed in water. Slaking occurs because the aggregates are not strong enough to withstand the internal stresses that arise from differential swelling and air entrapment in the soil aggregate during rapid water intake. These stresses may be released through creation of an increasingly extensive network of failure zones in the soil aggregates (USDA, 1999).

Interpretations

Soil stability is rated according to the time required for the fragments to disintegrate during the 5-minute immersion and the proportion of soil fragment remaining on the mesh after the 5 extraction-immersion cycles (Table 5). The stability rating is recorded for all 12-soil fragments. The slake test yields a rating of 0 to 6. Soil fragments or aggregates which fall into classes 0 to 3 are relatively unstable. Class 4 indicates some stability, but very little strength. Classes 5 and 6 represent relatively stable soil fragments or aggregates (USDA, 1999).

Stability ratings of soil surface crust fragments are interpreted differently. Soils with weak and unstable aggregates are susceptible to accelerated structural damage. The breakdown of aggregates at the surface of fine-textured soils can result in surface crust formation. Surface crusts can prevent seedling emergence and impede soil infiltration (and therefore increase risk of erosion) and aeration (Topp et al., 1995). In general, unstable crusts are better than very strong crusts, which have a greater potential to lower soil quality. The subsurface aggregates underlying the crust are tested to assess the potential for future slaking and surface crust formation.

Slake resistance rating is affected by:

- soil water content
- rate of wetting
- soil texture
- clay mineralogy
- organic matter content

Organic matter has been shown to protect soil aggregates from slaking by reducing the wetting rate. Degradation of organic matter leads to less stable aggregates and soil crust formation in many soils, particularly those high in silt content and with low organic matter content at or near the surface. Soil organic matter can be increased through soil management practices such as reduced tillage and the application of organic residues (Govers et al., 2004). In general, the greater the aggregation of the soil and the greater the aggregate stability, the less erodible the soil will be.

Table 5: Stability Class Table (adopted from USDA, 1999).

Stability class	Criteria for assignment to stability class
0	Soil too unstable to sample (falls through sieve).
1	50% of original shape lost within 5 seconds of insertion in water.
2	50% of original shape lost 5-30 seconds after insertion.
3	50% of original shape lost 30-300 seconds after insertion or less than 10% of soil remains on the sieve after 5 dipping cycles.
4	10-25% of soil remaining on sieve after 5 dipping cycles.
5	25-75% of soil remaining on sieve after 5 dipping cycles.
6	75-100% of soil remaining on sieve after 5 dipping cycles.

6. HABITAT QUALITY/EARTHWORMS

Introduction

Earthworm numbers are a key indicator of soil habitat quality (Ivask et al., 2006). Their presence, in large numbers throughout the soil profile represents two inter-related phenomena. Not only are they excellent indicators of a soil's general habitat quality but also by their presence they improve soil condition. Earthworms affect important soil processes such as: the suitability for seed germination and root growth/development; the capacity to accept, hold, and transmit water; and the capacity to supply plant nutrients. Earthworms affect such processes through their influence on key soil properties such as aggregate stability, macroporosity, drainage, aeration and organic matter decomposition. They affect the soil environment through their burrowing, fecal excretion (casts), and feeding and digestion.

When earthworms burrow, they create tunnels in the soil, which increases infiltration capacity and improves soil aeration. Earthworm burrows also affect chemical transport during water flow. The burrows drain quickly, and soil aeration after wetting occurs rapidly, which keeps the soil well oxygenated (Linden et al., 1994). Earthworm burrows also provide paths for roots. In compacted soil, recent earthworm burrows may be the only paths for plant root growth. In addition, burrow walls are nutrient rich, which may promote root growth (Linden et al., 1994). Earthworms ingest, transport, and excrete both organic and mineral matter, which affects soil properties. They enhance the rate of residue breakdown and nutrient release. For instance, some species of earthworms forage on the soil surface and pull residue into their burrows for later consumption. As residue passes through an earthworm's gut, soil minerals, water and microbes are mixed with residue matter. Within the gut and after excretion, this material has been shown to be metabolically active. Thus, earthworms play a significant part in the cycling of organic material in soils (Linden et al., 1994). Earthworms also mix soil. Soil near the surface is often mixed into the subsoil. Similarly, subsoil can be deposited on, or close to, the surface.

Interpretations

The presence of a large number of earthworms reflects and integrates many positive aspects of soil condition: good aeration, porosity (i.e., not compact), abundant food supply (organic residues), and lack of disturbance by tillage (Table 6).

Important, is the recognition that earthworms are seasonal and migratory biota (i.e., seeking warmth, food and moisture). Thus, sampling should be performed at the same time each year. Preferably when conditions are most favorable for earthworms, such as in the early spring or late fall, and when the soil is at field capacity (24-48 hours after a rainfall event). If no earthworms are found during an inspection take note of evidence of their activity, namely earthworm burrows in the soil profile and casts (faecal) on the soil surface (McGarry, 1984).

Table 6: Interpretation of earthworm numbers per 20 cm cube of soil (provided conditions support earthworm populations) (Shepherd, 2000).

Earthworm Numbers	Interpretation
>20	good habitat quality
10-20	Moderate habitat quality
<10	poor habitat quality

Conditions influencing earthworm numbers in agricultural settings include (USDA, 1999):

Tillage

-Tillage generally kills about 25% of the earthworm population. The indirect effects of tillage (i.e., increase in surface temperature, decreased soil moisture, and more rapid decomposition of crop residues) affect the remaining population.

Temperature

-The optimal temperature range for earthworms is 1 to 20°C.

Soil Properties

- Generally medium soils are more favorable for earthworms than sandy and clayey soils.

Food Source

-The primary food source for earthworms is organic residues from the soil surface. Dead roots and root exudates can also be important food sources. In soils supporting earthworm populations, the quantity and quality of residue input frequently determines earthworm abundance.

Soil Disturbance

-Earthworm numbers are generally greater in undisturbed soil systems (i.e., no or reduced tillage).
-Earthworm populations can recover fairly rapidly (with in a few years) once soil disturbance is stopped.

Soil Moisture

-soil moisture restrictions generally determine earthworm distributions and their activity.

Agrochemicals

- Pesticides, particularly insecticides, can affect earthworm populations. The majority of triazine herbicides (i.e., atrazine, simazine, and cyanazine) are slightly toxic. Carbamate-based herbicides (i.e., carbendazim, benomyl, and thiophanate-methyl) are very toxic. Organophosphates (i.e., phorate, isozophos, chlorpyrifos, and ethoprophos) and most of the carbamate-based insecticides (i.e., carbaryl, carbofuran, methomy, and methylcarb) are toxic. Most of the nematicides (i.e., D-

D, metham-sodium, and methyl bromide) have been reported as toxic to earthworms.

6. Soil pH

Introduction

The degree of acidity or alkalinity (i.e., soil pH) is an important control on the availability of nutrients to plants and of potentially adverse chemical conditions. This is because the pH of a soil influences the rate of plant nutrient release by weathering, the solubility of all soil materials, the amounts of nutrient ions stored on the cation-exchange sites, and the likelihood that potential toxicities exist (e.g., Al and Mn). Major factors affecting soil pH include temperature and rainfall, which control the intensity of leaching and soil mineral weathering. Strong acidity is generally associated with leached soils of humid regions; alkalinity generally occurs in semi-arid and arid climates. Agricultural practices such as liming or addition of ammonium fertilizers can alter soil pH (USDA, 1999). Many soils formed from limestone till contain lime and are naturally slightly alkaline. Due to the presence of lime in these soils, their pH changes very slowly. Soils formed from other rock types contain little lime and their pH may change relatively quickly. This is especially true for sandy soils (Agriculture and Agri-Food Canada, 1994).

Acidic soils are often associated with deficiencies of the basic nutrients (Ca, Mg, and K) and deficiencies of P (Figure 4). Some trace elements and soluble Al may be present at high enough concentrations to cause toxicity to plants in strongly acidic soils. Alkaline soils are associated with deficiencies of trace elements, in particular Fe and Zn, and deficiencies of P (Hillel, 1998). The optimal availability for most nutrients is between pH 6 and 7. Soil pH also affects the activity of beneficial microorganisms, which affects nutrient availability. Fungi generally function at a wide pH range, while bacteria and actinomycetes function better at intermediate and higher pH (USDA, 1999). Through its influence on the quantity and types of organism responsible for organic matter formation, pH also affects aggregate stability and, in turn, the transfer of air and water in the soil (Brady and Weil, 1999).

Interpretation

In general, soil pH values between 6 and 7.5 are optimum for crop growth. Site specific interpretations for soil quality depend on specific land use and crop tolerance (Figure 3).

Figure 3: preferred pH ranges for crops commonly grown in Ontario (Agriculture and Agri-Food Canada, 1994).

Figure 4: Soil pH and nutrient availability to plants (USDA, 1999, p. 66). The wider the bar the greater the availability.

7. SOIL COLOR/ORGANIC MATTER MONITORING CARD (OMMC)

Introduction

Soil organic matter is considered a key property affecting plant growth, through its control of many essential physical, chemical, and biological soil processes. Soil organic matter in general terms can be defined as “that fraction of the soil composed of anything that once lived” (USDA, 1996).

Some of the effects of soil organic matter on plant growth include:

- (1) It ensures a suitable medium for seed germination, root growth/development and controls the soil's capacity to accept, hold and transmit water. It affects such processes through its influence on biological properties such as earthworm numbers and on soil physical properties such as soil aggregation, erosion, drainage, tilth, aeration, water-holding capacity, bulk density, evaporation, and permeability.
- (2) It affects chemical properties such as the absence or presence of adverse chemical conditions and the supply of plant nutrients. It affects such processes through its influence on properties such as cation exchange capacity, metal complexing, buffering capacity, supply and availability of N, P, S, and micronutrients, and adsorption of pesticides and other added chemicals.

Organic matter is considered one of the key soil properties affecting plant growth, through its control of many essential physical, chemical and biological soil processes (Fenton, 1994; Doran and Parkin, 1994). A “good” quality soil must therefore have sufficient amounts of soil organic matter. It is an essential component of soil that stores and supplies nutrients. It plays a key biological function in that it greatly affects the activities of microflora and microfaunal organisms, and a physical function in that it promotes good soil structure, thereby improving tilth, aeration, aggregate stability, and water-holding capacity (Stevenson, 1994, p. 14).

Interpretation

In the field, soil color changes can give a general indication of trends in soil organic matter levels under cropping (Shepherd, 2000). Generally darker soil colors near the soil surface are associated with higher organic matter levels. Schulze et al. (1993) found that within similar landscapes and soil texture classes, there was a good linear correlation between Munsell soil color and soil organic matter for Ap horizons (Cited by Krull et al., 2004). While there are large regional differences in soil organic matter content because of climate and other soil factors, soil color changes within a farmer's field can provide important information on the effect of cropland management on soil organic matter levels (Definition of Soil Organic Matter, 2005). Generally, a farmer should aim for his/her soil color to decrease in Munsell value, which is indicative of increasing organic matter content (at constant soil moisture contents). Soil color may also be useful when comparing the topsoil's of long term cropping land with tree lines and fence lines.

**SOIL QUALITY
MONITORING DATA SHEETS**

COMPACTION TEST MONITORING CARD

Location (field): _____

Field size: _____

Date: _____ Time: _____

Sample site No.	Depth	No. of blows	Average blows to reach 15 cm (A+C+E/3)
	0 to 15 cm (A)		
	15 to 30 cm (B)		
	0 to 15 cm (C)		Average blows to reach 30 cm (B+D+F/3)
	15 to 30 cm (D)		
	0 to 15 cm (E)		
	15 to 30 cm (F)		

Date: _____ Time: _____

Sample site No.	Depth	No. of blows	Average blows to reach 15 cm (A+C+E/3)
	0 to 15 cm (A)		
	15 to 30 cm (B)		
	0 to 15 cm (C)		Average blows to reach 30 cm (B+D+F/3)
	15 to 30 cm (D)		
	0 to 15 cm (E)		
	15 to 30 cm (F)		

Date: _____ Time: _____

Sample site No.	Depth	No. of blows	Average blows to reach 15 cm (A+C+E/3)
	0 to 15 cm (A)		
	15 to 30 cm (B)		
	0 to 15 cm (C)		Average blows to reach 30 cm (B+D+F/3)
	15 to 30 cm (D)		
	0 to 15 cm (E)		
	15 to 30 cm (F)		

INFILTRATION MONITORING CARD

Location (field): _____

Field size: _____

Date: _____ Time: _____

Sample site No.	Site location	Start time	End time	Infiltration time (mins. or hrs)	Infiltration rate/hr (cm/hr)*
	1 st 2.54 cm (1") of water				
	2 nd 2.54 cm (1") of water				
	1 st 2.54 cm (1") of water				
	2 nd 2.54 cm (1") of water				
	1 st 2.54 cm (1") of water				
	2 nd 2.54 cm (1") of water				

* Infiltration rate / hr = (1 / second infiltration time (minutes))* 60)

WORM SAMPLING MONITORING CARD

Location (field): _____

Field size: _____

Date: _____ Time: _____

Sample Site No.	Total Earthworms

Date: _____ Time: _____

Sample Site No.	Total Earthworms

Date: _____ Time: _____

Sample Site No.	Total Earthworms

Date: _____ Time: _____

Sample Site No.	Total Earthworms

Date: _____ Time: _____

Sample Site No.	Total Earthworms

SOIL COLOR/ORGANIC MATTER ASSESSMENT MONITORING CARD

Location (field): _____

Field size: _____

Date: _____ Time: _____

Sample site No.	Munsell color (Value/Chroma)

Date: _____ Time: _____

Sample site No.	Munsell color (Value/Chroma)

Date: _____ Time: _____

Sample site No.	Munsell color (Value/Chroma)

Date: _____ Time: _____

Sample site No.	Munsell color (Value/Chroma)

Date: _____ Time: _____

Sample site No.	Munsell color (Value/Chroma)

SOIL pH MONITORING CARD

Location (field): _____

Field size: _____

Date: _____ Time: _____

Sample site No.	pH

Date: _____ Time: _____

Sample site No.	pH

Date: _____ Time: _____

Sample site No.	pH

Date: _____ Time: _____

Sample site No.	pH

Date: _____ Time: _____

Sample site No.	pH

Date: _____ Time: _____

Sample site No.	pH

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