LITERATURE REVIEW: SOIL QUALITY

1.1 INTRODUCTION

Throughout the 1990's interest in soil quality and understanding its importance has come to the forefront of environmental sustainability. Over $25 billion is spent in the United States annually for soil care and improvement (Wallace & Terry, 1998). The terms soil quality, soil degradation, soil health, and soil resilience are being used more frequently and with greater urgency in connection with strategies to protect our global environment. The needs to improve our quality of life and protect many scarce natural resources are forcing society to recognize the importance of their soil resource. Soil quality is frequently over-looked in a society that places more emphasis on water and air quality, likely because these resources have a more apparent connection to human health and existence. However, soil quality and land management both have a direct influence on water and atmospheric quality and, by extension, to human and animal health (Doran and Parkin, 1994; Kennedy & Papendick, 1995). Soil is a vital resource for producing the food and fiber needed to support an increasing world population (Pappendick & Parr, 1992). While seemingly a straight-forward concept, soil quality has been difficult to define and more difficult to quantify (Karlen et al., 1997). Many feel that soil quality can not be defined for a complex system as diverse and dynamic as soils. "Quality" and "soil quality" are seen by some to have infinite meanings and basically are indefinable (Sojka & Upchurch, 1999). Others, however, have taken on the challenge of converting a subjective term such as "soil quality" into an objective characterizeable term. The difficulty in establishing a definition comes from the variety of land uses, locations, environments, types of soils and general lack of understanding between the interactions of a multitude of processes occurring within the soil (Kennedy & Papendick, 1995). The definition of soil quality (and some may argue soil) is controlled by a multitude of variables.

Additionally, not all involved accept the same terminology. Soil quality and soil health are often considered to have the same meaning (Chen, 1999). The term soil health is often preferred to soil quality by farmers, while scientists relate the term "soil health" to the status of various biological properties in the soil (Haberern, 1992; Romig et al., 1995; Harris et al., 1996).

A sound definition of soil quality will find application over a broad range of situations. Initially, the definition of soil quality has been agriculturally based. Some have defined soil quality by the ability of the soil to serve as a natural medium for the growth of plants to maintain human and animal life (Karlen et al., 1992; Jazen et al., 1992). Parr et al. (1992) defined soil quality as :

> Capability of soil to produce safe and nutritious foods and crops in a sustainable manner over the long term, and to enhance human and animal health without adversely impairing the natural resource base or adversely affecting the environment.

While agriculture is a vital use of our soil resource other environmental and recreational functions of soil also need to be considered. Soils serve as a medium for the global cycle of nutrients and energy. The soil plays an ecological role in the purification, detoxification, and decomposition of wastes and hazardous materials (Jazen et al., 1992). The role soils play in an urban environment have also been recognized with concern for the quality of soils used on golf courses, lawns, and athletic fields (Koolen & Rossignol, 1998; Huinink, 1998; Thien et al., 2001). Doran and Parkin (1994) presented a function-based definition of soil quality that was adopted by the Soil Science Society of America. They define soil quality as:

> The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintains environmental quality, and promotes plant and animal health.

This definition focuses more on the general function of the soil rather then one specific use (i.e. agriculture).

Soil quality has also been described as the balance between soil degradation and soil resilience (Kennedy & Papendick, 1992; Lal, 1998). Soil resilience is the ability of soil to return to a dynamic equilibrium after being disturbed (Blum & Santelises, 1994). Soil resilience is controlled by inherent soil properties governed by the factors affecting soil formation (Blum, 1998). Soil degradation is the short to medium term deterioration of soil caused by land use, soil management, and the soil's susceptibility to soil processes that promote loss of function (Blum, 1998; Lal, 1998). As a soil quality definition is reached, it needs to be flexible to account for the numerous functions that soil may perform.

Interactions among the basic soil forming factors of parent material, climate, organisms, topography, time and human activity produce an inherent and baseline soil quality parameter (Karlen et al., 1992; Gregorich et al., 1994). Through measurement of various biological, physical and chemical indicators and their response to prevailing environmental conditions over time, an idea of soil quality emerges. However, a composite value of all soil quality indicators is difficult to conceptualize since interactions between indicators are sometimes unknown and often difficult to quantify. Since integration of analytical results into one composite value can be overly complex, it remains difficult to assess whether the soil has improved, degraded, or remained unchanged (Granatstein and Bezdicek, 1992). Thus, it seems more realistic to measure soil characteristics that evaluate quality based on the soil's intended function. When any of the proposed indicators lie outside an ideal range, more specific tests can be conducted and/or trigger remediation steps.

Assessing soil quality raises many questions. How is soil quality managed? What criteria should be used to evaluate soil quality? Which soil quality indicators should be used? How many indicators are needed to assess soil quality? What are the ideal conditions or values for each indicator? Can a composite value or status be determined? These questions illustrate just how difficult it can be to assess the quality of soil in one specific location. For example, a soil with high clay content may be ideal in a semiarid region where soil moisture retention is beneficial but, in a humid region the same property might cause poor drainage and limit plant growth. Basically, there is no universally accepted definition of soil quality or set of soil quality criteria and optimum values. Further research needs to be conducted on smaller, local scales to produce parameters leading to a universal soil quality evaluation.

1.2 STEPS IN SOIL QUALITY EVALUATION

Little information is available on the quality standards of every soil type under every environmental condition (Snakin et al., 1996). Environmental quality research is a continual process. Thien (1998) listed six steps basic to a soil quality management program:

1. Identification of critical soil-use functions,
2. Selection of indicators to evaluate these functions,
3. Analysis of indicators through soil sampling and testing,
4. Assessment of indicator status,
5. Recommendation of remedial management if needed, and
6. Monitoring changes to indicators.

While these steps seem straightforward they don't produce a composite value of soil quality. Some of the steps still require subjective inputs and establishment of arbitrary standards.

1.2.1 Identification of Critical Soil-Use Functions

Understanding soil function and land use is the first step in the determination of soil quality. The common component of the soil quality definitions previously stated is that they relate soil quality to the capacity of the soil to function effectively. Confusion over defining soil quality is often the result of not identifying major issues of concern with respond to soil function (Doran and Parkin, 1994). Soil functions can be classed into four general categories; productivity and sustainability, environmental quality, biodiversity, and human welfare (Doran and Parkin, 1994; Lal, 1998). Ultimately, when monitoring soil quality, it is important to identify the specific and detailed functions a soil will perform. Identification of the soil function(s) will allow for easier identification of appropriate indicators to reflect soil quality.

1.2.2 Selection of Indicators to Evaluate Soil Function

Establishing the soil's function leads to selection of soil quality indicators. Any indicator criteria used to assess soil quality should be practical and useful across a range of ecological and socio-economic situations (Doran and Parkin, 1996). Soil quality indicators should meet the following criteria (Doran & Parkin, 1996; Chen,1999):

1. Correlate and encompass natural processes in the environment,
2. Integrate soil physical, chemical and biological characteristics and processes,
3. Be easy to use and accessible for a broad range of users and field conditions,
4. Be sensitive to changes in management or environmental conditions, and
5. Be present in existing environmental databases when possible.

Cameron et al. (1998) proposed applying these steps to a simple scoring system to decide whether to accept a possible soil quality indicator in the assessment of polluted soils. Their formula was:

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

where:

A = Acceptance level of the indicator

S = Sensitivity of the indicator to changes from degradation or remediation

U = Ease of use and/or understanding

M = Cost effectiveness of measurement of the indicator

I = Predictable influence of properties on soil, plant and animal health

R = correlation and relationship to ecosystem processes

In this equation each parameter is rated between 1 and 5 based on the user's understanding of that parameter. The sum of all the parameters gives the acceptance level, which can then be compared to other indicators. Such as system helps in screening the most useful and robust soil quality indicators for a specific assessment. A soil quality indicator with an acceptance level of 23 would be more useful compared to an indicator with a level of 15. While of some benefit, the rating system is subjective to the experience and knowledge of the user. Scientists would place greater value on analytical indicators such as physical, chemical, and biological soil properties while farmers would prefer descriptive, easily understandable indicators such as smell, feel, and look (Harris and Bezdicek, 1994). With the above criteria in mind, basic indicators selected should ultimately relate back to the function of the soil and its environmental conditions.

Using some of the criteria previously stated, Larson and Pierce (1991) proposed a minimum data set for assessing the quality of the world's soils. These indicators are defined in Table 1.1, and are divided into three categories; biological, chemical, and physical soil quality indicators.

Table 1.1. Proposed basic soil biological, chemical, and physical indicators to measure soil quality (taken from Doran and Parkin, 1994)

	---Soil Characteristic---	
Biological	**Physical**	**Chemical**
Microbial biomass C and N	Soil texture	Total organic C and N
Potentially mineralizable N	Depth of soil and rooting	pH
Soil respieration	Soil bulk density and infiltration	Electrical conductivity
Biomass C/Total org. C ratio	Water holding capacity	Mineral N, P, and K
Respiration/biomass ratio	Water retention characteristics	
	Water content	
	Soil temperature	

Doran and Parkin (1996) developed a minimum data set for assessing soil quality using the minimal data set suggested by Larson and Pierce (1991).

Table 1.2. List of soil characteristics that can be estimated from basic input variables using pedotransfer function or simple models (taken from Doran and Parkin, 1996)

Soil Attribute	**Soil Quality Indicator**
Cation exchange capacity	Organic C + clay type and content
Water retension characteristic	soil texture + organic C + bulk density
Hydraulic conductivity	soil texture
Aerobic and anaerobic microbial activity	water-filled pore space
C and N cycling	soil respiration
Plant/microbial activity or pollution potential	soil pH + electrical conductivity
Soil productivity	bulk density, available water holding capacity, pH, electrical conductivity, and aeration
Rooting depth	bulk density, available water holding capacity, pH,
Leaching potential	soil texture, pH, organic C (hydraulic conductivity, cation exchange capacity, soil depth)

Table 1.2 is the minimal data set and the respective soil processes they measure proposed by Doran and Parkin. Of the indicators reported, soil organic matter (SOM) content is often considered to be the single most important soil quality indicator (Larson & Pierce, 1991). Often, minimal data sets establish soil organic matter as one characteristic. However, some studies relate the importance of soil organic matter as not one entity, but rather a set of characteristics (Gregorich et al., 1994). Soil characteristics such as: total soil organic carbon and nitrogen, light fraction and macro-organic matter, mineralizable carbon and nitrogen, microbial biomass carbon and nitrogen, soil respiration, and soil carbohydrates and enzymes are included within the soil organic fraction (Gregorich et al., 1994; Sikora et al., 1996). A notable limitation in using individual soil quality indicators lies in being able to show or establish their interconnection. Soil organic matter is one attribute of soil that has considerable influence on not only soil biological characteristics, but also physical and chemical characteristics.

Table 1.3. Soil physical, chemical, biological indicators for assessing soil quality and their relationship to soil organic matter (taken from Sikora et al., 1996)

Soil characteristic	**Relationship to soil condition - function**	**Relation to soil organic matter**
Physical indicators		
Texture	Retention and transport of water and chemicals	Determines degree of SOM
Topsoil and rooting depth	Estimate of productivity potential and erosion	Positive correlation with SOM
Soil bulk density and infiltration	Indicators of compaction and potential for leaching productivity and erosivity	Positive correlation with SOM
Water holding capactiy	Related to water retention, transport, and erosivity	Positive correlation with SOM
Temperature	Determines plant productivity, microbial activity, and SOM level	
Chemical indicators		
Total organic C and N (SOM)	Defines soil fertility, stability, and erosion extent	Stability of SOM related to C/N ratio
Electrical conductivity	Defines plant and microbial activity thresholds	Effect varies with SOM content
pH	Defines biological and chemical activity thresholds	Stability and activity of SOM fractions
Cation-exchange capacity	Defines equilibrium levels of cation nutrients and H^+	Positive correlation with SOM and clay content
Extractable N, P	Productivity and potential N loss indicators	Influenced by SOM transformations
Biological indicators		
Microbial biomass C and N	Flux of nutrients and pool of active N and C	Early warning indicator of SOM change
Potentially mineralizable N	Soil productivity and N supplying potential	Active SOM pool
Soil respiration	Indicator of biomass activity	Indicator of SOM turnover, early warning indicator of SOM change

The relationship between soil organic matter and the minimal data set proposed by Doran & Parkin (1994) and Larson & Pierce (1991) is presented in Table 1.3. Ultimately, the appropriate use of indicators to monitor soil quality ecosystem they are part (Doran & Parkin, 1996).

1.2.2.1 Selection of Physical Soil Quality Indicators

The soil's physical state directly influences environmental quality and crop production (Arshad et al., 1996). Well-aggregated soils in good physical condition maintain the balance of air and water required to promote many other soil properties (Lowery et al., 1996). Physical soil quality indicators include soil texture, bulk density, porosity, topsoil depth, water holding capacity, soil temperature, and aggregate stability. Soil texture has considerable influence on moisture retention and hydraulic conductivity as well as bulk density (Arshad and Coen, 1992). Soils with a fine texture will have greater moisture retention and hydraulic conductivity and will exhibit a lower bulk density. Soil texture can also be used in estimating and modeling the potential for soil erosion (Chen, 1999). Spain (1990) found a positive correlation between the soil texture and the amount of soil organic carbon. Soil organic matter is protected from decomposition through the sorption of organic matter onto clay particles and entrapment of organic matter in small pores of aggregates (Oades, 1989; Sikora & Stott, 1996). The structural condition, texture, and packing of the soil all affect bulk density (Blake & Hartge, 1986). Soils with coarse (sand) textures tend to have a higher bulk density then soils with fine (clay) textures. The bulk density of a particular soil may vary related to the degree of packing, and thus, is often used as a measure of soil structure. In turf soils, compaction is often a problem from foot and vehicle traffic (Brede, 2000). Bulk density is an important measurement used to assess the amount of compaction on golf courses. Soil properties and processes such as moisture retention, water flow, root development, nutrient cycling, and the sustainability of micro and macro organisms are negatively influenced by high bulk density values (Arshad et al., 1996; Arshad & Coen, 1992). The depth of the A-horizon or depth to any subsurface soil layer that restricts root growth is related to the productivity potential and stability of the soil surface (Chen, 1999; Rhoton and Lindbo, 1997). The depth of topsoil also has a positive correlation to the amount of soil organic matter and microbial populations (Doran et al., 1996; Sikora et al., 1996). An increase in soil temperature tends to have a positive impact on plant and microorganism growth and can also accelerate critical biological and chemical soil processes (Brady & Weil, 2000). However, extremely high soil temperatures can have a negative effect such as a decline in microbial activity and root development. In turf soils this can be important when areas are planted with cool season grasses (Brede, 2000). Microbial biomass is a soil property influenced by extreme high and/or low temperatures through low respiration rates, long turnover time and inducing dormancy (Joergensen et al., 1990; Carter et al., 1999; Insam et al., 1989). The influence temperature has on microbial biomass impacts physical properties such as organic matter content, depth of A-horizon and porosity. Aggregate stability or the distribution of stabile aggregates is important when trying to maintain a balance of air and water in the soil system and the development of plant roots. Often, other physical properties such as depth of the A horizon and the amount of organic matter is positively correlated to aggregate stability. In golf course soils the stability or aggregate size distribution is fairly high due to the a well developed root zone from the grass vegetation (Haynes, 1999; Wright & Anderson, 2000). A decline in stability could be an indicator of changes from freezing and thawing or other natural processes.

1.2.2.2 Selection of Chemical Soil Quality Indicators

Chemical indicators of soil quality show profound interaction with biological properties and processes in soil. Chemical indicators of soil quality include, total carbon and nitrogen, pH, electrical conductivity, cation exchange capacity (CEC) and extractable nitrogen and phosphorus. Total carbon and nitrogen correlate to the amount of SOM content. The amount of organic matter in a soil may be estimated by multiplying the organic C concentration by a constant factor based on the percentage of C in organic matter. This conversion assumes that there are little or no free calcium carbonates present. The organic C-organic matter conversion factors for surface soils have varied from 1.72 to 2.0 (Nelson & Sommers, 1996). Soil organic matter is often considered the key quality factor in soil and is highly correlated to numerous factors influencing productivity and environmental sustainability (Stott & Martin, 1990). Soil organic matter is a sink and source for plant nutrients and is functional in maintaining soil fertility, reducing erosion, influencing aggregation, and improving water infiltration and retention (Sikora & Stott, 1996; Doran et al., 1996). Organic matter improves soil quality by improving other properties such as nutrient and water storage, buffering capacity and microbial activity/diversity (Arshad and Coen, 1992). In turf soils such as high-sand greens the amount of organic matter or development of organic matter is critical in the development of the highly managed turf. The addition of well-decomposed organic

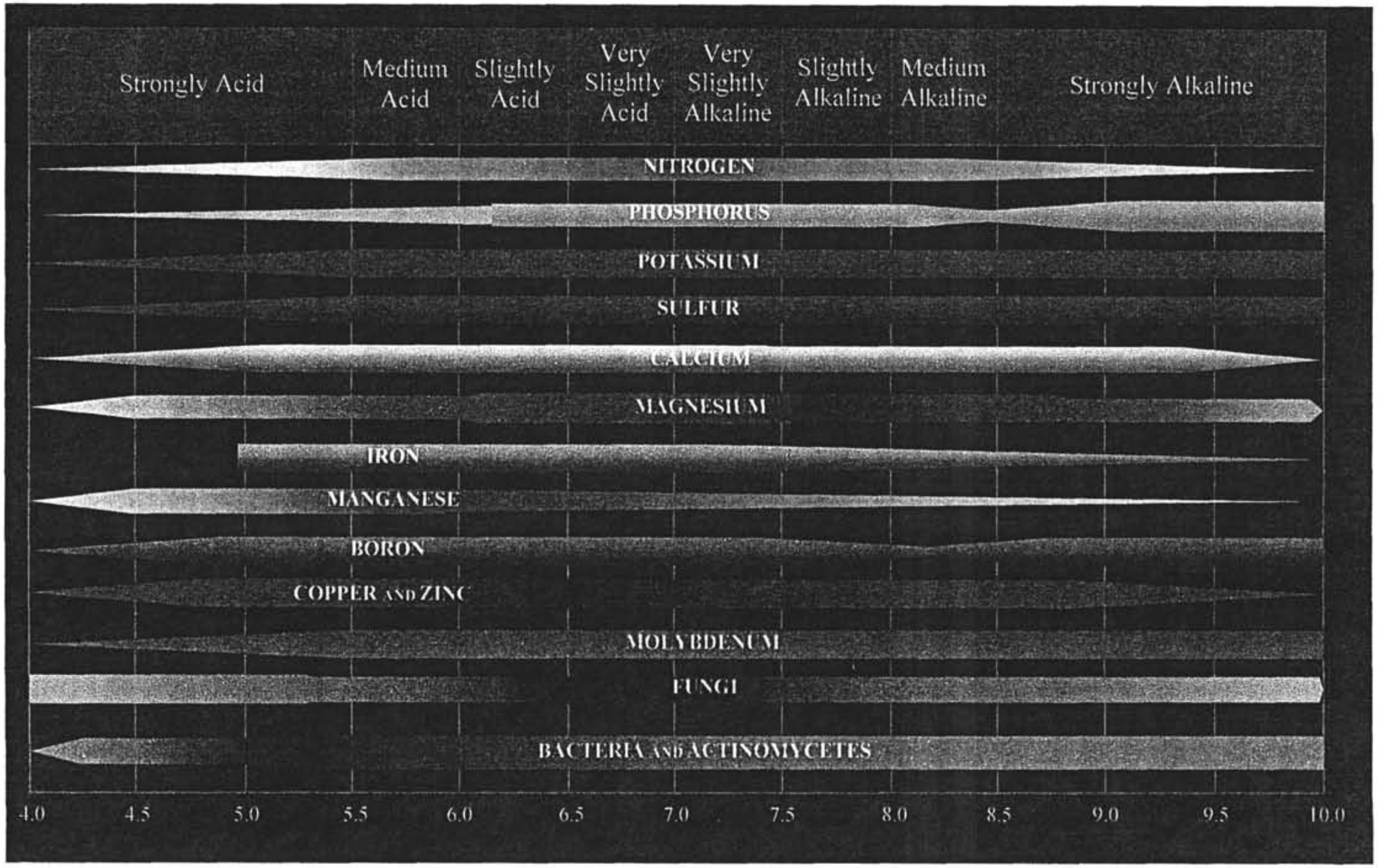

Figure 1.1. Relationship between soil pH and availability or abundance of soil nutrients and microbes. (modified from Musser, 1950; USDA-NRCS, 1996)

matter (such as humus) can have a significant positive influence on the CEC of a sandy soil (Carrow et al., 2001). As previously shown in Table 1.3 soil organic matter is connected to numerous soil physical, chemical and biological soil properties.

Soil acidity (pH) reflects the hydrogen ion (H^+) activity in the soil solution and defines most chemical and biological activity thresholds. Soil pH is a function of the base saturation (%BS), colloid type, and cation type within the soil. Indirectly, soil pH is influenced by inherent properties of the soil due to the five soil forming factors of time, climate, biota, topography and parent material. Soil pH is also influenced by the cropping or management system and use of chemicals such as fertilizers, sludge and liquid manures, and pesticides (Smith & Doran, 1996). Nutrient availability depends highly on soil pH (Arshad and Coen, 1992). At low pH some metallic elements like zinc and aluminum are overly abundant and highly mobile causing metal toxicity while reducing the availability of elements like calcium and phosphorus which may react to form precipitants (Brady & Weil, 2000; Musser, 1950). Adversely, at high pH elements such as magnesium and calcium tend to be abundant in the soil solution while micronutrients such as iron, manganese, phosphorus and boron become unavailable. The diagram in Figure 1.1 illustrates the availability of various nutrients and organisms based on the soil pH. The kind of vegetation as well as the productivity and health is highly correlated to the soil pH and the ability of the plant to tolerate acidic or alkaline environments (Smith & Doran, 1996). Turf varieties such as bentgrasses and Zoysiagrasses are tolerant to excessive acidity ($pH < 5.0$) while perennial ryegrasses and buffalograss are tolerant to excessive alkalinity ($pH > 8.0$) (Carrow et al., 2001). The size and diversity of the microbial community in a soil is also pH dependent. A soil pH between 6.6 and 7.3 is considered ideal for most microbial activities that contribute to nutrient cycling (N, P, and S) and pH values between 5 and 8 is considered ideal for most soil microorganisms (Smith & Doran, 1996; USDA-NRCS, 1998). Finally the environmental fate of xenobiotics such as pesticides rely on the soil pH. If the pH is outside the acceptable range, pesticides may be ineffective, changed to an undesirable form, or may not be available for microbial decomposition (Koskinen & Harper, 1990).

Electrical conductivity (EC) is a measure of soil salinity and can also be used to estimate soluble nutrients present (Rhoades, 1996). Microbial and plant activity responds to soil electrical conductivity of the soil. Highly saline soils cause considerable stress and constraint to plant growth and development. Golf courses tend to have consistant problems with salinity as salt in irrigation water or effluent water used to water the golf course is fairly high (Brede, 2000). Likewise, soil salinity significantly impacts microbial respiration, decomposition and other processes involved in nitrogen cycling (Smith & Doran, 1996). Especially in arid regions of the world, soil salinity usually becomes a crucial factor in the determination of soil quality. Often the soil drainage, type of parent material and irrigation water quality contributes considerably to soil salinity.

Cation exchange capacity is a property that is often defined as the "sum total of the exchangeable cations that a soil can absorb" (Brady & Weil, 2000). CEC has been more recently defined as:

$$\mathrm{CEC} = \mathrm{M}^{x+}_{\mathrm{Excess}} + \mathrm{A}^{x-}_{\mathrm{Deficit}}$$

where M^{x+} and A^{x-} are the cations and anions in the system. However, the magnitude of the anion deficit is small and is often ignored (Sumner & Miller, 1996). The retention of and release of nutrients and the buffering capacity of the soil depends on the soil's cation exchange capacity. Cation exchange capacity is a function of the amount and type of clay minerals and the amount of organic matter present in the soil. Clay minerals such as smectite and other 2:1 expanding clay minerals tend to have a higher CEC then 1:1 and non-expanding clay minerals. The amount of organic matter has a positive influence on the CEC.

Extractable nutrients such as nitrogen and phosphorus present an indication of plant available nutrients and the potential for nutrient loss (i.e. N loss). Turf soils which receive frequent applications of N, P, and K require careful monitoring of the soil's nutrient status. A slight change in soil pH or a significant increase in a particular nutrient such as Ca can often lead to deficiencies in other nutrients such as phosphorus or micronutrients such as zinc and iron (Brede, 2000; Carrow et al., 2001). Often these characteristics have been determined through the analysis of the soil's cation exchange capacity. The abundance or lack of nutrients can significantly impact microbial populations and diversity as well as plant growth and development.

1.2.2.3 Selection of Biological Soil Quality Indicators

Microorganisms in the soil contribute to the improvement and maintenance of soil quality. Soil organisms control the decomposition of plant and animal materials, the rate of biogeochemical cycling, aid in the formation of soil structure, and control the fate of organic chemicals in the soil (Turco et al., 1994; Kelly and Tate, 1998). The dynamic nature of soil organisms makes them sensitive to natural or management-related soil changes and thus make excellent assessors of soil quality (Kennedy and Papendick, 1995). The complexity of the soil biological component yields a multitude of potential biological indicators of soil quality. Kennedy and Papendick (1995) cited fourteen different microbial indicators of soil quality. Doran and Parkin (1994) selected microbial biomass carbon and nitrogen, potential mineralizable nitrogen and soil respiration as biological soil quality indicators for use in a minimal data set.

Microbial biomass is the living component of soil organic matter (Rice et al., 1996). Microbial biomass has a relatively short turnover time of less than one year and can therefore be a sensitive indicator to conditions that alter soil organic matter levels such as climate and pollutant toxicity (Paul, 1984). As the active component of organic matter, microbial biomass influences nutrient transformations, cycling, and storage (Insam and Parkinson 1989; Rice et al., 1996). Gallardo and Schlesinger (1990) found a significant decrease in microbial biomass with soil depth. Microbial biomass carbon is stored energy for microbial activity and processes and indicates potential microbial activity (Rice et al., 1996). Some perceive the ratio of microbial biomass carbon to total carbon can be useful in measuring SOM and provides a more sensitive index of changes to SOM than total carbon or microbial biomass carbon measured alone (Anderson & Domsch, 1989; Sparline, 1992). Biomass nitrogen indicates potentially available nitrogen and is a significant sink for nitrogen (Insam and Parkinson, 1989). Nitrogen present in the microbial biomass is a rather large part of the potentially mineralizable-N that is available to plants. A significant increase in available N can help to improve turf quality in golf courses. However, too much available N can increase the thatch layer in some grasses which lead to a decrease in turf quality (Mienhold et al., 1973; White & Dickens, 1984). Similar to microbial biomass carbon, the ratio of biomass nitrogen to total nitrogen may give a more sensitive indication of soil quality compared to total nitrogen or microbial biomass nitrogen alone. Microbial biomass nitrogen has also been related to nitrogen mineralization to estimate the quality of organic matter (Bonde et al., 1998). Other properties can influence the microbial biomass such as soil pH, texture, soil water content, and aggregate stability (Rice et al., 1996).

Mineralizable nitrogen is a useful soil quality indicator when used in connection with total nitrogen, total carbon, and microbial biomass (Drinkwater et al., 1996). Potentially mineralizable nitrogen is considered to be a single pool of nitrogen, or can be divided into three components, biomass N, active non-biomass N, and stabilized N (Duxbury and Nkambule, 1994). The passive nitrogen pool along with the stabilized soil nitrogen is virtually inaccessible to soil organisms and enzymes due to its relation with clay and organic soil colloids (Duxbury and Nkambule, 1994). The active soil organic nitrogen, or the mineralizable nitrogen is the biologically dynamic and labile organic nitrogen that can be mineralized within a one year. This is an indicator of potential nutrient availability and microbial activity. Mineralizable nitrogen is influenced by a wide array of soil properties, most notably soil temperature and water content (Cabrera & Kissel, 1998; Duxbury & Nkambule, 1994).

Soil respiration is one of the most frequently used soil biological indicators to reflect biological activity within the soil (Kieft & Rosacker, 1991; Parkin et al., 1996). While microbial respiration is often used synonymously with soil respiration a distinction between the two can be made. Microbial respiration is the net or total production of CO_2 (or consumption of O_2) through microbial metabolism. Soil respiration is the production of CO_2 (or consumption of O_2) through the metabolic processes of all living organisms in the soil. Soil respiration includes the biological activity of microorganisms, macroorganisms, and plant roots (Parkin, 1996). A high degree of microbial respiration can indicate or lead to the loss of organic carbon within the soil. The status of nutrient cycling can also be determined through the measurement of soil respiration (Alef, 1995; Parkin, 1996). Low microbial respiration could indicate the presences of pollutants such as fungicides or other pesticides.

Soil microbes perform many beneficial functions as well as some detrimental impacts. The impact of soil biota is complex and difficult considering the same activity may be positive or negative depending on its location in the soil profile. Soil respiration and other microbial indicators need to be interpreted with respect to the specific function carried out by the soil microorganisms (Parkin, 1996).

1.2.3 Analysis and Assessment of Critical Threshold Values for Soil Quality Indicators

The capability of making soil quality indicators quantifiable can assist land-managers with identifying problems and making management decisions. However, it can be difficult to develop ideal values or ranges for soil quality indicators because of the numerous functions of soil (Larson & Pierce, 1994). Two approaches can be used to establish an ideal range for soil quality. The first approach is to set the ideal soil quality as the native condition of the soil. The second approach is considering what conditions are needed to maximize production, environmental performance, or any function (Granatstein & Bezdicek, 1992). Initial control limits will most likely come from a wide array of resources such as; state extension services, literature surveys, management experience, model predictions, consultants, regulations, or other sources. Then, research can establish definitive boundaries and critical control limits, even to the point of being applicable to a case-by-case basis.

Pierce and Larson (1993) suggested using statistical control charts to help establish critical control limits and monitor changes in soil quality. Critical control limits outline the upper and lower limits allowable for a particular soil property to sustain or promote good soil quality. Figure 1.2 illustrates a control chart that can be used in soil quality assessment. The upper control limit (UCL) and the lower control limit (LCL) delineate the critical threshold range. Upper and lower control limits are selected based on known tolerances, mean variation obtained from average measurements, or personal experience (Larson & Pierce, 1994).

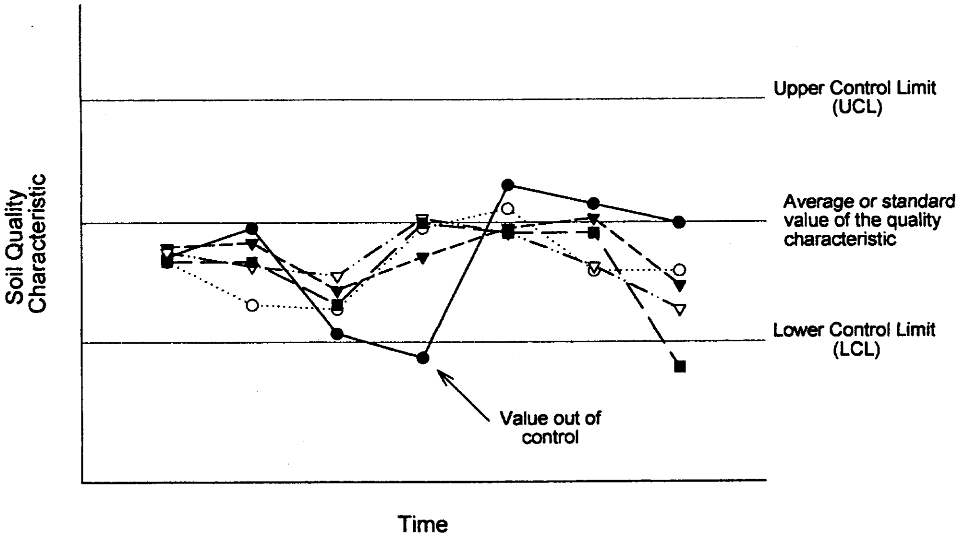

Figure 1.2. A control chart illustrating upper control limits and lower control limits to set an acceptable range for monitoring soil quality (from Pierce & Larson, 1994).

In general, if values are located within the control limits, the system is considered to be in control or of acceptable quality. When a sample value is located outside the limits, the system is considered to be in a state of degradation. Trends within the chart indicate potential problems and signal areas requiring additional management. Even if values are within the critical threshold limits but showing a trend toward moving out of the control zone, action may be warranted. The concept of control charts shows promise for assessing the status of soil quality indicators, but becomes complex when too many indicators are included.

1.2.4 Development and Implementation of Soil Quality Indices

The complexity of co-evaluating the status of many chemical, physical, and biological parameters has prompted investigators to integrate multiple indicators into a soil quality index (Smith et al., 1993). Researchers, farmers, and policymakers could use an integrated soil quality index to assist with management and environmental decisions related to estimations of potential food production, identification of problem areas, and guidance with the formulation of regulatory policies (Granatstein & Bezdicek, 1992; Papendick et al., 1994). As previously stated, soil quality encompasses four broad functions; productivity and sustainability, environmental quality, biodiversity, and human welfare (Parr et al., 1992; Granatstein & Bezdicek, 1992; Doran and Parkin, 1994; Lal, 1998). Any general soil quality index must accommodate these four functions and yielding quantitative evaluation and unambiguous interpretation (Doran & Parkin, 1994). Of the numerous proposals for a quantitative soil quality value, the most common approach suggests that soil quality is a function of a set number of specific soil quality elements. Doran and Parkin (1994) suggested one approached using an index system that is based on conditions that maximize production and environmental performance. The index system they proposed considered three of the four broad functions stated previously; sustainable production, environmental quality and human and animal health. Sustainable production was defined in respect to plant production and resistance to erosion. Environmental quality was determined in respect to ground and surface water quality as well as air quality. Finally, human and animal health was defined in terms of food quality, safety, and nutritional composition. Under those three issues the following index was proposed:

$$SQ = f(SQ_{E1}, SQ_{E2}, SQ_{E3}, SQ_{E4}, SQ_{E5}, SQ_{E6})$$

where the specific soil quality elements (SQ_{Ei}) are defined as follows:

SQ_{E1} = food and fiber production

SQ_{E2} = erosivity

SQ_{E3} = groundwater quality

SQ_{E4} = surface water quality

SQ_{E5} = air quality

SQ_{E6} = food quality

The advantage of this method is that the functions of soil can be assessed based on specific performance criteria for each element in each ecosystem. However, one negative aspect is that each element is given equal weight. One way to correct for this is to add a weighting function to each element, creating the following equation:

$$SQ = f(K_1 SQ_{E1}, K_2 SQ_{E2}, K_3 SQ_{E3}, K_4 SQ_{E4}, K_5 SQ_{E5}, K_6 SQ_{E6})$$

where K_n is the weighting coefficient.

Weighting factors are assigned to each soil quality element based on geographical, societal, and economic concerns. Another advantage of this method is that the elements in this index can be grouped and evaluated with regard to specific soil functions. However, this approach becomes complicated by the duplicitous roles of the indicators. For instance, the presence of a clay pan, may slow water flow and the leaching of chemicals from the rooting zone, which would be seen as beneficial from an environmental standpoint, but the same clay pan might restrict the development of plant rooting systems, which is a negative attribute from the productivity standpoint. This method also requires reducing each soil function down to a mathematical expression. While this method can quantify soil quality, it often relies on extensive databases making it overly complex and difficult to implement for non-scientists such as farmers, extension agents, and land use managers. Also, the interpretation of each soil function and related mathematical expression for that given function is rather subjective and depends on the expertise of the user.

Larson and Pierce (1994) proposed a similar modeling system that would score or rate soil quality based on the productivity. They produced a productivity index (PI) described as:

$$\mathrm{PI} = \sum_{i=1}^{r} (A_i x C_i x D_i x \mathrm{WF})$$

where A_i is the sufficiency of the available water content, C_i is the sufficiency of bulk density, D_i is the sufficiency of pH, WF is a weighting factor, and r is the number of horizons in the depth of rooting (Larson & Pierce, 1994). While the method leads to a quantitative rating of soil quality for agricultural soils, other environmental functions such as environmental protection and promotion of human health are not considered.

Smith et al. (1993) developed a multiple-variable indicator-kriging procedure (MVIK) that could integrate numerous soil quality indicators into an index. The index could then be used to produce soil quality maps based on the local topography. This method uses the science of applied statistics known as geostatistics. Through various univariate and bivariate analyses the similarity between soil samples is determined based on a function of their distance from one another. This process can then be modeled and the procedure known as kriging can be used to estimate the values for unsampled locations (Warrick et al., 1986). The index that is produced from "kriging" can be used to develop a soil quality map. A contour map is used and shows values indicating the probability that the soil in a particular location meets the threshold criteria for good soil quality. Lowering or increasing thresholds can greatly alter the soil quality map. Also, another important step is the determination of how many soil parameters must meet their thresholds or acceptable ranges before the soil at a given location is considered to be in a state of good quality (Smith et al., 1993). As more indicators are incorporated in the index, the more unlikely it is that all the parameters will meet their threshold values. While seemingly difficult to produce, graphs and soil maps are easily understandable and consider interactive effects between soil quality indicators. Snakin et al. (1996) proposed a similar method in which the degree of degradation was determined and mapped. Instead of mapping the soils that have a high probability of having good soil quality, the soils were mapped based on their degree (or rate) of degradation.

These procedures used similar principles with the establishment of soil quality indicators and critical thresholds. There are two important steps that need to be made in the modeling process. First, it is important to establish the critical thresholds for each parameter and clearly state the reasons that a particular value is chosen as the upper or lower control limits (Harris et al., 1996). The second step is quantifying soil functions and processes. Often, the addition of more functions or processes can greatly alter the outcome or final value/rating of a soil quality index.

1.2.5 Selection of Appropriate Remedial Management for Degraded Indicators

Based on which soil quality indicators are in a state of degradation, appropriate changes in management such as the application of fertilizers, additional irrigation, or reduction in pesticides may be needed to correct various soil parameters and to reach ideal or acceptable conditions.

Successful remediation of soil degradation can be determined by continuous monitoring of soil quality indicators. Monitoring indicators over a long period of time will allow for better interpretation of trends and changes in management practices on the soil and water resource. Additionally, monitoring over time may allow or stress the addition of other soil or environmental parameters that need to be monitored.

1.3 APPLICATION OF ORGANIC COMPOST TO IMPROVE SOIL QUALITY

Around 1 billion tons (0.9 billion Mg) of organic and inorganic agricultural by-products are produced annually in the United States (Edwards & Someshwar, 2000). Agricultural organic by-products include crop residues and animal (poultry, swine, dairy, etc.) manures. The increased demand for animal production for food has significantly increased the amount of manure produced. In addition, with the increase of urban sprawl and the human population the amount of sewage sludge and solid waste will also continue to grow (Zhu, 1998).

Agricultural by-products have the potential to be recycled and used to help improve soil quality. Animal manures have long been used to help recycle nutrients and improve soil tilth on agricultural fields (Edwards et al., 1995). Composted materials have also been used to improve soil and turf quality on golf courses and other recreational sites since the early 1900's (Piper & Oakley, 1917; Welton, 1930). They are an excellent source of nutrients such as N, P, K, Ca, and Mg and have a high content of organic carbon (Zhu, 1998). Recently use of land-applied, composted animal waste has become a more attractive option for enhancing soil quality in turf management (golf courses and home lawns), the forestry industry and the reclamation of soils contaminated by mining (Zhu, 1998; Delschen, 1999; Dinelli, 1999; Garling et al., 2001).

Organic composts such as dairy and swine manures are land-applied because they can improve soil quality by modifying various physical, chemical and biological soil properties. The main benefit of organic amendments is the addition of organic carbon and organic matter. Organic matter, in turn, influences many soil properties including aggregation, pH, nutrient retention and microbial diversity. The typical impacts of compost application for various soil physical, chemical and biological soil properties under compost application are shown in Table 1.4.

1.3.1 Influence of Compost Application on Physical Properties

Organic amendments improve physical properties by mainly increasing soil organic matter and increasing biological activity (Stewart et al., 2000). A reduction in bulk

Table 1.4. Changes in soil properties due to organic compost application (taken from He et al., 1992)

Physical propterties	Change	Biological properties	Change	Chemical properties	Change
Bulk denisty	decreased	Bacteria population	increased	Total C content	increased
Porosity	increased	Fungi and actinomycetes population	increased	Total salt content	increased
Water holding capacity	increased			CEC	increased
Aggregation	stabilized	Celluloytic activity	increased	N,P and S	conflicting
		Autotrophic nitrifier	increased	Ca, Mg, and K	increased
		Vesicular-arbuscular-mycorrhizae	increased	pH	increased
				Total trace metals	increased
		Urease activity	increased	Trace metal extractability	increased
				Trace metal bioavailability	increased

density and increased soil porosity and infiltration are very common when organic amendments are used (Mathers & Steward, 1984; He et al., 1992; Herrick & Lal, 1995). Benefits to physical properties can occur with both short and long term application. A decrease in bulk density within the top 3 cm was reported in a tropical pasture, which received patches of cattle manure. The bulk density within 60 days of application was less than 0.93 g cm^{-3} compared with 1.05 g cm^{-3} in the control (Herrick & Lal, 1995). Other studies reported improvement to physical properties over a 1 to 2 year period from application of organic wastes. These studies found that bulk density decreased while the amount of soil carbon and available water capacity increased with increased application of organic wastes (Table 1.5). Benefits have also been reported over a longer time period ranging between 5 to 85 years (Khaleel et al., 1981). Tester (1990) reported a decrease

Table 1.5. Soil Physical properties as affected by various waste applications. (numbers in parentheses are control values)

Carbon application rate	Study Period	Net increase in soil C	Bulk density	Available water capacity	Reference
metric tons C ha^{-1} yr^{-1}	years	%	g cm^{-3}	% by weight	Kaldivko and
4.3	1	0.63	1.27 (1.35)	13.5 (12.2)	Nelson (1979)
10.9		1.07	1.29	13.5	
17.4		1.14	1.21	14.8	
69.6	1	0.59	1.25 (1.38)	12.0 (10.8)	Webber (1978)
15.5	1	0.05			Haghiri et al.
49.9		0.78			(1978)
99.9		1.81			
9.4	1	0.2			Epstein et al.
56.4		0.47			(1976)
15.7	2	0.44	1.37 (1.43)	3.0 (2.6)	Gupta et al.
31.5		1.3	1.24	2.3	(1977)
63		2.69	1.03	3.9	
28.8	2	0.5	1.00 (1.02)		Tiarks et al.
64		1.05	1.00		(1974)
132.8		2.55	0.85		

in bulk density over 5 years from 1.4 g cm^{-3} to 0.8 g cm^{-3} with an application of 240 Mg ha^{-1} of sewage sludge compost. Azevedo and Stout (1974) found that the application of animal manures improved soil physical properties by enhancing aggregate crumb structure in the surface horizons. Hall and Coker (1981) reported that the application of sewage sludge increased the proportion of stable soil aggregates from 16% to 33%. Improvement in these properties has been linked to increases in both microporosity and macroporosity following the application of animal manure (Pagliai & Vignozzi, 1998). The enhancement in aggregation and porosity contributes to improvements in other properties such as CEC, water holding capacity and microbial diversity (Gallardo-Lara & Nogales, 1987; Raveendran et al., 1994).

1.3.2 Influence of Compost Application on Chemical Properties

Miller et al. (1985) reported changes to soil chemical properties following applications of swine manure, namely an increase in soil pH from 5.2 up to 8.0 and a decrease in redox potential (Eh). Olness et al. (1998) observed an increase in soil pH from 4.9 to 6.3 following the application of animal waste compost. However, soils with high pH, excess calcium carbonate or those already receiving liming applications showed no significant change in soil pH (Gallardo-Lara & Nogales, 1987; Ndayegamiye & Cote, 1989; Raveendran et al., 1994). Generally, acidic soils tend to see the greatest increase in soil pH with compost application (He et al., 1992). Cation exchange capacity can also be increased from application of organic amendments. Ndayegamiye and Cote (1989) reported an increase in CEC from 10.5 cmol kg^{-1} to 12.1 cmol kg^{-1} from long-term (>9yr) application of 60 Mg ha^{-1} of solid cattle manure. Raveendran et al. (1994) reported substantial increases in CEC from 1.30 to 4.9 cmol kg^{-1} on soils receiving 40 Mg ha^{-1} of organic amendments. Table 1.6 below can be used to help estimate increases to CEC in high sand golf greens with various organic amendments. It is feasible to increase CEC by as much as 4 cmol kg^{-1} depending on the CEC of the amendment used (Carrow et al., 2001).

Table 1.6 Effect of amendment CEC on the amount of amendment required to increase the CEC of a typical sand used for turfgrass root zones by 1, 2, 3, and 4 cmol kg^{-1}. (Modified from Carrow et al., 2001)

		Amendment (dry weight basis) to be added to 14,000 kg sand to obtain the following increases in CEC			
Amendment	**Increased (cmol kg^{-1}):**	**1**	**2**	**3**	**4**
		kg Amendment			
10		1562	3515	6026	9374
20		740	1562	2481	3515
40		361	740	1140	1562
80		178	361	548	740
120		118	238	361	485
160		88	178	269	361
200		70	142	214	287

Organic amendments have also been used to supplement and reduce fertilizer applications. Nutrients such as N, P, and K found in animal manures can be used by plants and soil microbes, however, most occur in the organic form and must be mineralized first (Table 1.7). Raveendran et al. (1994) reported that cow and chicken manure contained 0.46% and 1.78% total P and 0.69% and 2.66% total K respectively. Steward et al. (2000) reported an increase in soil N, P and K from manure application, however as much as 60 to 80% of the N and P was found in an organic form. Over a 5 year period, annual applications of 240 Mg ha^{-1} increased total N from 0.456 to 3.552 g kg^{-1} and total P from 0.250 to 4.390 g kg^{-1} dry weight in the top 3.5 cm of soil.

Table 1.7. Assumed N and P mineralization rates and cumulative availability in composted cattle manure (taken from DeLuca & DeLuca, 1997)

Year following first compost application	Annual N mineralization rate, %	Cumulative N availability, kg/ha ∓	Annual P mineralization rate, %	Cumulative P availability, kg/ha ∓
0	20	27	60	27
1	20	54	20	36
2	10	67	10	40
3	5	74	5	43
4	5	81	5	45
5	5	87	0	45
6	5	94	0	45
7	5	101	0	45
8	5	108	0	45
9	5	114	0	45
10	5	121	0	45
11	5	128	0	45
12	5	136	0	45
13	0	136	0	45

∓ The total amount of N made available to plants by current plus previous applications of composted manure with annual compost applications of 15.02 Mg/ha wet weight (0.9% N and 0.3% P)

While high amounts of N, P, and K may be tied up in the organic form, the availability of P and K in animal manure often approaches 90 or 100% (Azevedo & Stout, 1974). It is difficult to predict the influence organic amendments will have on N, P, K, and S due to the maturity, source, and application rate of the compost (He et al., 1992).

1.3.3 Influence of Compost Application on Biological Properties

The impact of organic amendments on biological soil properties can be seen in both soil quality indicators and human pathogens such as fecal coliform or *Streptococcus* (Ottolenghi, 1987). Various studies have shown that application of organic amendments will increase microflora populations over short and long periods of time (Table 1.8).

Table 1.8. Microflora populations for soil applied with organic amendments

Treatment	Study Duration	Application Rate	Bacteria	Fungi	Actinomycetes	Reference
				— x 10^6 CFU g^{-1}—		
Cattle Manure	2 mo	60 Mg ha^{-1}	280 (39)†	3.1 (0.6)	2.8 (0.9)	Ndayegamiye & Cote (1989)
Pig Slurry	2 mo	120 m^3 ha^{-1}	260 (39)	2.5 (0.6)	2.3 (0.9)	Ndayegamiye & Cote (1989)
Sewer Sludge	3 yr	1.5 kg ha^{-1}	49 (39)	0.22 (0.23)		Liu et al. (1995)
City Refuse	6 d	45 Mg ha^{-1}	150 (3.3)		44 (7.3)	Miyashita et al. (1982)

† Numbers in parentheses are control values

Liu et al. (1995) reported a significant but temporary increase in the population of microflora over a short period of time when sewage sledge was applied to Kentucky bluegrass and creeping bentgrass. This was explained by the high amount of living organisms present in fresh sludge. However, with time, the microflora populations decrease and reach a state of equilibrium. Nutrient mineralization and microbial biomass can be improved through the application of organic amendments. Hassen et al. (1998) observed an increase in nitrogen mineralization due to compost amendments (Table 1.9). Fauci & Dick (1994) reported an 80 – 400% increase in microbial biomass in soils treated with organic amendments.

Table 1.9 Evolution of the total mineral nitrogen content (mg N kg^{-1} dry soil) in soil amended with organic wastes (modified from Hassen et al. 1998)

Treatment	Time (weeks)		N min. rate	Net min. rate
	0	16	(%)	(%)
Soil	53.43	41.51	24.9	-11.67
Soil + Compost	83.88	72.54	40.1	-11.32
Soil + Manure	49.75	69.07	32.6	19.35
Soil + Sludges	129.5	162.87	77.1	33.61

Green house soils receiving an equivalent of 22 Mg (dry wt.) beef manure ha^{-1} contained a microbial biomass of 300 mg C kg^{-1} compared to the control soil that had a microbial biomass of 100 mg C kg^{-1} after 306 days. Organic amendments have also helped prevent disease to vegetation while increasing plant growth (Wallace & Terry, 1998). Organic turf amendments composed of hydrolysed poultry meal contain microorganisms that are critical to the biological control of diseases caused by *Phytophthora, Pythium, Rhizoctonia, and Sclerotium* (Liu et al., 1995). Measuring the impact of organic amendments on soil biological properties can be difficult as the climate can have a significant impact on microbial activity. Temperature and moisture conditions have considerable influence on mineralization of nutrients such as nitrogen and phosphorus, oxidation rates of carbon, and the emergence or suppression of plant pathogens such as dollar spot disease (Ndayegamiye & Cote, 1989; Liu et al., 1995; Fauci & Dick, 1996).

1.3.4 Negative Effects of Compost Application on Soil Quality

While providing many beneficial properties to enhancing soil quality, the application of organic amendments often has negative impacts. The addition of biosolids have increased nitrification rates, however, amendments having pH values that differ from the soil have decreased the rate of nitrification (Olness et al., 1998). The application of organic wastes also tends to increase the total, extractable, and bioavailable trace metals (He et al., 1992). Metal toxicity to the microbial biomass resulting from compost application is a potential risk. Cu, Zn, Ni and Cd reduce microbial biomass and nitrogen mineralization if present at high concentrations (Chander & Brookes, 1991; Hassen et. al., 1998). Rice et al. (1996) reported that when levels of Cu or Zn alone were 1.4 times the permitted limits microbial biomass carbon decreased by 12%. When Cu and Zn were combined they decreased the microbial biomass by up to 53%. Studies have also shown that applications of organic amendments can increase salinity. While soluble salts may not be present initially in organic amendments, they can arise during the decomposition process (Steward & Meek, 1977). Ca and Mg salts in particular may be released during the decomposition of farm manures (Barker et al., 2000). Soils high in soluble salts can see negative impacts on infiltration rates and subsurface water movement. Increases in bioavailable nitrogen and other nutrients from organic composts also prevent the microbial breakdown of xenobitoics. The presence of excess nitrogen can prevent soil microbes from using xenobiotics such as pesticides as an energy source (Abdelhafid-Rahima et al., 2000). Contrasting studies, though, have stated that the application of organic amendments increased microbial degradation of some pesticides such as Atrazine through stimulation of the microbial biomass (Hance, 1973). The application of organic wastes can also have negative effects on plant life. Applications of activated sewage sludge on bermudagrass can cause decreased thatch and lignin content, however, contrasting studies have shown that sewage sludge increased thatch compared to inorganic N treatments (Mienhold et al., 1973; White & Dickens, 1984).

While the positives tend to outweigh the negatives, the potential of metal toxicity, high concentrations of soluble salts, and fluxuations in soil pH pose significant threats to soil quality and application of organic compounds should be monitored carefully. The public opinion of organic amendments is in a state of flux and changes often (Sims & Pierzynski, 2000). There is wide spread concern about the impact of over-application, bio-pathogens, and odors from compost production and application. Sims and Pierzynski (2000) suggested additional soil quality indicators should be added to the minimal data set when organic amendments are used (Table 1.10). These additional indicators account for possible negative interactions organic amendments may have with soil, water, and/or vegetative quality.

Organic compost and manure use provides a viable and attractive method for recycling wastes while eliminating an environmental nuisance. Composting can lower both operational costs and environmental contamination compared to landfill and incineration practices (He et al., 1992). The potential use of organic compost as a method to enhance soil quality is not limited to agriculture. The use of compost on turf, home lawns and gardens, and reclamation of mine-contaminated soils has increased significantly in recent years (Delschen, 1999; Dinelli, 1999; Garling et al., 2001).
The overall impact of organic amendments to soil physical, chemical, and biological properties depends highly on the type of by-product, the method of production, and application rate (He et al., 1992). While there are benefits the potential negative impacts illustrates the importance of monitoring the soil quality of soils amended with organic composts.

Table 1.10. Minimal data set of soil quality indicators proposed by Doran and Parkin (1996) with suggested additional indicators for application of agricultural, municipal or industrial by-products (taken from Sims & Pierzynski, 2000)

Soil quality indicator in the MDS (Doran & Parkin 1996)	Rationale for inclusion of soil quality indicators in the MDS	Suggested additions to the MDS when by-products are used †	Rationale for addition of indicators to the MDS
Physical Texture Topsoil depth Rooting zone depth Infiltration Bulk density Water holding capacity	Indicators of retention and transport of water and chmicals, soil erosion, leaching, surface and subsurface runoff, and soil productivity; also related to water availability and useful in models that seek to integrate soil, land-scape, and geographic variability into soil quality	Erodibility (RUSLE) Runoff potential Leachability index Compaction Heat capacity Porosity Soil color Drainage, MHW depth	Provide more direct, quantitative measures of the potential for transport of by-products or of solutes and soil particles from by-product amended soils to water; aid in assessing the potential for loss from soils of volatile compounds that can affect air quality
Chemical Soil organic matter pH Electrical conductivity Extractable N, P, and K	Define soil fertility, stability, and erosion extent, potential for N loss, biological and chemical activity, thresholds of microbial activity; useful as productivity and environmental quality indicators	CEC/AEC Sorption capacity Total, extractable, bioavailable, soluble and desorbable nutrients and nonessential elements; environmental tests for N and P (DPS, PSNT, LCM, stalk nitrate)	Better assessment of potential of soil to retain or release elements and/or organic compounds to leaching or runoff waters; quantify buildup of elements and degree of saturation of soil sorption capacity, predict plant response to N and evaluate success of N management programs
Biological Microbial biomass C, N Mineralizable N Soil respiration	Microbial catalytic potential, repository for C and N, indications of effects on soil organic matter (OM), measures of N supply and soil productivity, changes in biomass and total C Pool	Microbial diversity Biodegradation potential in surface and subsoils Redox potential	Evaluate changes in microbial population diversity and size of various communities; assess capacity of entire soil profile to degrade organic pollutants in aerobic vs. anaerobic zones

† RULE = revised universal soil loss equation, MHW = mean high water table, CEC/AEC = cation/anion exchange capacity, DPS = degree of P saturation, PSNT = pre-sidedress soil nitrate test, LCM = leaf chlorophyll meter.

1.4 LITERATURE CITED

Abdelhafid, R., S. Houtot, and E. Barriuso. 2000. Dependence of atrazine degradation on C and N availability in adapted and non-adapted soils. Soil Biol. Biochem. 35:389-401

Alef, K. 1995. Soil respiration. p. 214-219 *In* K. Alef and P. Nannipieri (ed.) Methods in applied soil microbiology and biochemistry. Harcourt Brace & Company, New York.

Anderson, J.P.E., and K.H. Domsch. 1978. A physiological method for quantitative measurement of microbial biomass in soils. Soil Biol. Biochem. 10:215-221.

Anderson, J.P.E., K.H. Domsch. 1989. Ratios of microbial biomass carbon to total organic carbon in arable soils. Soil Biol. Biochem. 21:471-479

Arshad, M.A., and G.M. Coen. 1992. Characterization of soil quality: Physical and chemical criteria. Amer. J. Alter. Agric. 7:25-31

Arshad, M.A., B. Lowery, and B. Grossman. 1996. Physical tests for monitoring soil quality. p.123-141. *In* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Azevedo, J., and P.R. Stout. 1974. Farm animal manures: An overview of their role in the agricultural environment. California Agric. Exp. Stn. Manual 44.

Barker, A.V., M.L. Stratton, and J.E. Rechcigl. 2000. Soil and by-product characteristics that impact the beneficial use of by-products. p. 169-213. *In* D.L. Karlen et al. (ed.) Agricultural utilization of urban and industrial by-products. ASA Spec. Publ. 58. ASA, CSSA, and SSSA, Madison, WI.

Blake, G.R., and K.H. Hartge. 1986. Bulk Density. p. 363-375. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Blum, W.E.H. 1998. Basic concepts: Degradation, resilience, and rehabilitation. p. 1-16 *In* R.Lal et al. (ed.) Methods for assessment of soil degradation. CRC Press, Boca Raton, FL.

Blum, W.E.H., and A.A. Santelises. 1994. A concept of sustainability and resilience based on soil functions. p. 535-542. *In*. D.J. Greenland and I Szabolcs (ed.) Soil resilience and sustainable land use. CAB Int., Wallingford, Oxon, England.

Bonde, T.A., J. Schnurer, and T. Rosswall. 1998. Microbial biomass as a fraction of potentially mineralizable nitrogen in soils from long-term field experiments. Soil Biol. Biochem. 20:447-452

Brady, N.C., and R.R. Weil. 2000. Elements of the nature and properties of soils. 12th ed. Prentice Hall, New Jersey

Cabrera, M.L., and D.E. Kissel. 1988. Potentially mineralizable nitrogen in disturbed and undisturbed soil samples. Soil Sci. Soc. Am. J. 52:1010-1015

Cameron, K., M.H. Beare, R.P. McLaren, and H. Di. 1998. Selecting physical, cnemical, and biological indicators of soil quality for degraded or polluted soils. Proceedings of 16th World Congress of Soil Science. Scientific registration No. 2516. Symposium No. 37. August 20-26, 1998. Montpelier, France

Carrow, R.N., D.V. Waddington, and P.E. Rieke. 2001. Turfgrass soil fertility and chemical problems: assessment and management. Ann Arbor Press, Michigan.

Carter, M.R., E.G. Gregorich, D.A. Angers, M.H. Beare, G.P. Sparling, D.A. Wardle, and R.P Voroney. 1999. Interpretation of microbial biomass measurements for soil quality assessment in humid temperate regions. Can. J. Soil. Sci. 79:507-520

Chander, K., and Brookes, P.C. 1991. Effects of heavy metals from past applications of sewage sludge on microbial biomass and organic matter accumulation in a sandy loam and silty loam U.K. soil. Soil Biol. Biochem. 23-927-932

Chen, Z.S. 1999. Selecting indicators to evaluate soil quality. Exten. Bull. 473. Dept. of Agric. Chem. Nat. Taiwan Univ.

Delschen, T. 1999. Impacts of long-term application of organic fertilizers on soil quality parameters in reclaimed loess soils of the Rhineland lignite mining area. Plant Soil 213: 43-54

Deluca, T.H., and D.K. DeLuca. 1997. Composting for feedlot manure management and soil quality. J. Prod. Agric. 10:235-241

Dinelli, F.D. 1999 Using composts to improve turf ecology. USGA Green Section Record 36(4):16-18

Doran, J.W., and T.B. Parkin. 1994. Defining and assessing soil quality. p. 1-22. *In* J.W. Doran et al. (ed) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Doran, J.W., and T.B. Parkin. 1996. Quantitative indicators of soil quality: A minimum data set. p. 25-37 *In.* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Doran, J.W., M. Sarrantonio, and M.A. Leibig. 1996. Soil health and sustainability. P. 1-54. *In* D.L. Sparks (ed). Advances in agronomy. Vol. 56. Academic Press, New - York.

Drinkwater, L.E., C.A. Cambardella, J.D. Reeder, and C.W. Rice. 1996. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. p. 217-229 *In*. J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Special Publication 49. Madison, WI.

Duxbury, J.M., and S.V. Nkambule. 1994. Assessment and significance of biologically active soil organic nitrogen. p. 125-146 *In.* J.W. Doran et al. (ed) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Edwards., J.H., and A.V. Someshwar. 2000. Chemical, physical, and biological characteristics of agricultural and forest by-products for land application. p. 1-62. *In* J.F Power and W.A. Dick (ed.) Land application of agricultural, industrial, and municipal by-products. SSSA Book Ser. 6. SSSA Madison, WI.

Edwards, J.H., R.H. Walker, E.C. Burt, and R.L. Raper. 1995. Issues affecting application of noncomposted organic waste to agricultural land. p. 225-249. *In* D.L. Karlen et al. (ed.) Agricultural utilization of urban and industrial by-products. ASA Spec. Publ. 58. ASA, CSSA, and SSSA, Madison, WI.

Epstein, E., J.M. Taylor, and R.L. Chaney. 1976. Effects of sewage sludge and sludge compost applied to soil on some soil physical and chemical properties. J. Environ. Qual. 5:422-426

Fauci, M.F., and R.P. Dick. 1994. Microbial biomass as an indicator of soil quality: Effects of long-term management and recent soil amendments. p. 229-234 *In* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Gallardo, A., and W.H. Schlesinger. 1990. Estimating microbial biomass nitrogen using the fumigation-incubation and fumigation-extraction methods in a warm-temperate forest soil. Soil Biol. Biochem. 22:927-932

Gallardo-Lara, F., and R. Nogales. 1987. Effect of the application of town refuse compost on the soil-plant system: A review. Biol. Wastes 19:35-62

Garling, D., M. Boehm, and J. Rimelspach. 2001. Organic materials boost fairways. Golf Course Management. 69:61-64

Granatstein, D., and D.F. Bezdicek. 1992. The need for a soil quality index: Local and regional perspectives. Amer. J. of Alter. Agric. 7:12-16

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367-385

Gupta, S.C., R.H. Dowdy, and W.E. Larson. 1977. Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. Soil Sci. Soc. Am. Proc. 41:601-605

Haberern, J. 1992. Viewpoint: A soil health index. J. Soil Water Conserv. 47:6

Haghiri, F., R.H. Miller, and T.J. Logan. 1978. Crop response and quality of soil leachate as affected by land application of beef cattle waste. J. Environ. Qual. 7:406-412

Hall, J.E., and E.G. Coker. 1981. Some effects of sewage sludge on soil physical conditions and plant growth p. 43-64. *In* C. Catroux, P. L'Hermite, and E. Suess (ed.) The influence of sewage sludge application on physical and biological properties of soils. D. Reidel Publishing Company, Boston, USA.

Hance, R. J. 1973. The Effect of nutrients on the decomposition of the herbicides Atrazine and Linuron incubated with soil. Pest. Sci. 4:817-822

Harris, R.F., and D.F. Bezdicek. 1994. Descriptive Aspects of Soil Quality/Health. p. 23-36. *In* J.W. Doran et al. (ed) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Harris, R.F., D.L. Karlen, and D.J. Mulla. 1996. A conceptual framework for assessment and management of soil quality and health. p. 61-82. *In.* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Hassen, A., N. Jedidi, M. Cherif, A. M'Hiri, A. Boudabous, and O. Cleemput. 1998. Mineralization of nitrogen in a clayey loamy soil amended with organic wastes enriched with Zn, Cu and Cd. Bioresource Technology 64:39-45

Haynes, R.J., 1999. Labile organic matter fractions and aggregate stability under short-term, grass-based leys. Soil Bio. Biochem. 31:1821-1830

He., X., S.J. Traina, and T.J. Logan. 1992. Chemical properties of municipal solid waste composts. J. Environ. Qual. 21:318-329

Herrick, J.E., and R. Lal. 1995. Soil physical property changes during dung decomposition in a tropical pasture. Soil Sci. Soc. Am. J. 59:908-912.

Huinink, J.Th.M. 1998. Soil quality requirements for use in urban environments. Soil Till. Res. 47:157-162

Insam, H., D. Parkinson, and K.H. Domsch. 1989. Influence of macroclimate on soil microbial biomass. Soil Biol. Biochem. 21:211-221

Joergensen, R.G., P.C. Brookes, and D.S. Jenkinson. 1990. Survival of the soil microbial biomass at elevated temperatures. Soil Biol. Biochem. 22:1129-1136

Karlen, D.L., N.S. Eash, and P.W. Unger. 1992. Soil and crop management effects on soil quality indicators. Amer. J. Alter. Agric. 7:48-55

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil Quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61:4-10

Kieft T.L., and L.L. Rosacker. 1991. Application of respiration and adenylate-based soil microbiological assay to deep subsurface terrestrial sediments. Soil Biol. Biochem. 12:119-126

Kelly, J.J., and R.L. Tate. 1998. Effects of heavy metal contamination and remediation on soil microbial communities in the vicinity of a zinc smelter. J. Environ. Qual. 27:609-617

Kennedy, A.C., and R.I. Papendick. 1995. Microbial characteristics of soil quality. J. Soil and Water Cons. May-June. 243-248

Khaleel, R., K.R. Reddy, and M.R. Overcash. 1981. Changes in soil physical properties due to organic waste applications: A review. J. Environ. Qual. 10:133-141

Kladivko, E.J., and D.W. Nelson. 1979. Changes in soil properties from application of anaerobic sludge. J. Water Pollut. Control-Fed. 51:325-332

Koolen, A.J., and J.P. Rossignol. 1998. Introduction to symposium 19: Construction and use of artificial soils. Soil Till. Res. 47:151-155

Koskinen, W.C., and S.S. Harper. 1990. The retention process: mechanisms p. 51-77 *In* H.H. Cheng (ed.) Pesticides in the soil environment: Processes, impacts, and modeling. SSSA Book Ser. 2. SSSA. Madison, WI.

Lal. R. 1998. Soil quality and sustainability p. 17-30. *In* R. Lal et al. (ed.) Methods for assessment of soil degradation. CRC Press, Boca Raton, FL.

Larson, W.E., and F.J. Pierce. 1991. Conservation and enhancement of soil quality. *In.* Evaluation for sustainable land management in the developing world. Vol. 2. IBSRAM Proc. 12 (2). Bangkok, Thailand. Int. Board for Soil Res. And Management.

Larson, W.E., and F.J. Pierce. 1994. The dynamics of soil quality as a measure of sustainable management. p. 37-51 *In* J.W. Doran et al. (ed) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

Liu, L.X., T. Hsiang, K. Carey, and J.L. Eggens. 1995. Microbial populations and suppression of dollar spot disease in creeping bentgrass with inorganic and organic amendments. Plant Disease 79:144-147

Lowery, B., W.J. Hickey, M.A. Arshad, and R. Lal. 1996. Soil water parameters and soil quality. p. 143-156 *In.* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Mathers, A.C., and B.A. Stewart. 1984. Manure effects on crop yields and soil properties. Trans. ASAE 27:1022-1026.

Meinhold, V.H., R.L. Duble, R.W. Weaver, and E.C. Holt. 1973. Thatch accumulation in bermudagrass turf in relation to management. Agron. J. 65:833-835

Miller, W.P., D.C. Martens, and L.W. Zelazny. 1985. Effects of manure amendment on soil chemical properties and hydrous oxides. Soil Sci. Soc. Am. J. 49:856-861

Miyashita, K., T. Kato, and S. Tsuru. 1982. Actinomycetes occurring in soil applied with compost. Soil Sci. Plant. Nutr. 28:303-313

Musser, H.B. 1950. Turf Management. McGraw-Hill Book Company, New York

Ndayegamiye, A., and D. Cote. 1989. Effect of long-term pig slurry and solid cattle manure application on soil chemical and biological properties. Can. J. Soil Sci. 69:39-47

Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. p. 961-1010 *In* J.M. Bartels et al. (ed.) Methods of soil analysis. Part 3 Chemical methods. SSSA Book Ser No. 5. SSSA, Madison, WI.

Olness, A., C.E. Clapp, R. Liu, and A.J. Palazzo. 1998. Biosolids and their effects on soil properties. p. 141-165 *In* A. Wallace and R. Terry (ed.) Handbook of soil conditions: Substances that enhance the physical properties of soil. Marcel Dekker, New York.

Ottolenghi, A.C., and V.V. Hamparian. 1987. Multiyear study of sludge application to farmland: prevalence of bacterial enteric pathogens and antibody status of farm families. Appl. Environ. Microb. 53:1118-1124

Ouedraogo, E., A. Mando, and N.P. Zombre. 2001. Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa. Agric. Ecosys. Environ. 84:259-266

Pagliai, M., and N. Vignozzi. 1998. Use of manures for soil improvement. p. 119-139. *In* A. Wallace and R. Terry (ed.) Handbook of soil conditions: substances that enhance the physical properties of soil. Marcel Dekker, New York.

Parkin, T.B., J.W. Doran, and E.F. Vizcaino. 1996. Field and laboratory tests of soil respiration p. 231-246 *In.* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Papendick, R.I., and J.F. Parr. 1992. Soil quality: The key to sustainable agriculture. Am. J. Altern. Agric. 7:2-3

Papendick, R.I., J.F. Parr, and J. van Schilfgaarde. 1995. Soil quality: New perspective for a sustainable agriculture. *In.* Proceedings for International Soil Conservation Organization. New Delhi, India December 4-8,1994

Parr, J.F., R.I Papendick, S.B. Hornick, and R.E. Meyer. 1992. Soil quality: Attributes and relationship to alternative and sustainable agriculture. Amer. J. Alter. Agric. 7:5-11

Paul, E.A. 1984. Dynamics of organic matter in soils. Plant Soil 76:275-285

Pierce, F.J., and W.E. Larson. 1993. Developing criteria to evaluate sustainable land management. p. 7-14. *In* J.M. Kimble (ed.) Proc. Of the 8th Int. Soil Management Workshop: Utilization of Soil Survey Information for Sustainable Land Use. May 1993. USDA-SCS, National Soil Survey, Lincoln, NE.

Piper, C.V., and R.A. Oakley. 1917. Turf for golf courses. Macmillan, New York.

Raveendran, E., I.C. Grieve, and I.M. Madany. 1994. Effects of organic amendments and irrigation waters on the physical and chemical properties of two calcareous soils in Bahrain. Environ. Monitor. Assess. 30:177-196

Rhoades, J.D. 1996. Salinity: Electrical conductivity and total dissolved solids. p. 417-435 *In.* D.L. Sparks et al. (ed.) Methods of soil analysis. Part 3. SSSA Book Series no. 5, Madison, WI.

Rhoton, F.E., and D.L. Lindbo. 1997. A soil depth approach to soil quality assessment. J. Soil and Water Cons. 52(1):66-72

Rice, C.W., T.B. Moorman, and M. Beare. 1996. Role of microbial biomass carbon and nitrogen in soil quality. p. 203-215. *In.* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Sikora, L.J., and D.E. Stott. 1996. Soil organic carbon and nitrogen. p. 157-167 *In.* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Sims, J.T., and G.M. Pierzynski. 2000. Assessing the impacts of agricultural, municipal, and industrial by-products on soil quality. p. 237-262. *In* D.L. Karlen et al. (ed.) Agricultural utilization of urban and industrial by-products. ASA Spec. Publ. 58. ASA, CSSA, and SSSA, Madison, WI.

Smith, J.L., and J.W. Doran. 1996. Measurement and use of pH and electrical Conductivity for soil quality analysis. p. 169-186 *In.* J.W. Doran and A.J. Jones (ed.) Methods for assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Smith, J.L., J.J. Halvorson, and R.I. Papendick. 1993. Using multiple-variable indicator kriging for evaluating soil quality. Soil Sci. Soc. Am. J. 57:743-749

Snakin, V.V., P.P. Krechetov, T.A. Kuzovnikova, I.O. Alyabina, A.F. Gurov, and A.V. Stepichev. 1996. The system of assessment of soil degradation. Soil Tech. 8:331-343

Sojka, R.E., and D.R. Upchurch. 1999. Reservations regarding the soil quality concept. Soil Sci. Soc. Am. J. 63:1039-1054

Spain, A. 1990. Influence of environmental conditions and some soil chemical properties on the carbon and nitrogen contents of some tropical Australian rain-forest soils. Aust. J. Soil Sci. Res. 28:825-839

Sparling, G.P. 1992. Ratio of microbial biomass carbon to soil organic carbon as a sensitive indicator of changes in soil organic matter. Aust. J. Soil Res. 30:195-207

Stewart, B.A., and B.D. Meek. 1977. Soluble salt considerations with waste applications. p. 219-232. *In* L.F. Elliot and F.J. Stevenson (ed.) Soils for management of organic wastes and waste waters. ASA, CSSA, SSSA, Madison WI.

Stewart, B.A., C.A. Robinson, and D.B. Parker. 2000. Examples and case studies of beneficial reuse of beef cattle by-products. p. 387-407. *In* D.L. Karlen et al. (ed.) Agricultural utilization of urban and industrial by-products. ASA Spec. Publ. 58. ASA, CSSA, and SSSA, Madison, WI.

Stott, D.E., and J.P. Martin. 1989. Organic matter decomposition and retention in arid soils. Arid Soil Res. Rehabil. 3:115-148

Sumner, M.E., and W.P. Miller. 1996. Cation exchange capacity and exchange coefficients. p. 1201-1253. *In* J.M. Bartels et al. (ed.) Methods of soil analysis. Part 3 Chemical methods. SSSA Book Ser No. 5. SSSA, Madison, WI.

Thien, S.J. 1998. Soil quality and sustainable turfgrass management. Golf Course Management. 66:56-60

Thien, S., S. Starrett, R. Robel, P. Shea, D. Gourlay, and C. Roth. 2001. A multiple index environmental quality evaluation and management system. USGA Green Section Record. 39:12-18

Tiarks, A.E., A.P. Mazurak, and L. Chesnin. 1974. Physical and chemical properties of soil associated with heavy applications of manure from cattle feedlots. Soil Sci. Soc. Am. Proc. 38:826-830

Turco, R.F., A.C. Kennedy, and M.D. Jawson. 1994. Microbial indicators of soil quality. p. 73-90 *In* J.W. Doran et al. (ed) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA, Madison, WI.

United States Department of Agriculture, Natural Resource Conservation Service. 1996. Indicators for soil quality evaluation [Online]. Soil Quality Institute: Soil Quality Worksheets. Retrieved February 3, 2002 from http://www.statlab.iastate.edu/survey/SQI/pdf/sq_thr_2.pdf

Wallace, A., and R.E. Terry. 1998. Soil conditioners p. 1-42 *In* A. Wallace and R. Terry (ed.) Handbook of soil conditions: Substances that enhance the physical properties of soil. Marcel Dekker, New York.

Warrick, A.W., D.E. Myers, and D.R. Nielsen. 1986. p. 53-82. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Webber, L.R. 1978. Incorporation of nonsegregated, noncomposted solid waste and soil physical properties. J. Environ. Qual. 7:397-400

Welton, K. 1930. Preparation of compost. USGA Green Section Bulletin 10:162-172.

White, R.H., and R. Dickens. 1984. Thatch accumulation in bermudagrass as influenced by cultural practices. Agron. J. 76:19-22

Wright., S.F., and R.L. Anderson. 2000. Aggregate stability and glomalin in alternative crop rotations for the central Great Plains. Bio. Fertil. Soils 31:249-253.

Wu, J., and P.C. Brookes. 1988. Microbial biomass and organic matter relationships in arable soil. J. Sci. Food. Agric. 45:138-139

Yakovchenko, V., L.J. Sikora, and D.D. Kaufman. 1996. A biologically based indicator of soil quality. Biol Fertil Soils 21:245-251

Zhu, D. 1998. Heavy metal transport in soils as influenced by plants, organic amendments and organic compounds. Ph.D Thesis. Kansas State University, Manhattan, Kansas.