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Main Parameters of Soil Quality and it's Management Under Changing Climate

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Reviewing Paper
Introduction: Malcolm summarised the topic of soil quality and it's management in a well synthetized form in 2000. So, the soils are fundamental to the well-being and productivity of agricultural and natural ecosystems. Soil quality is a concept being developed to characterize the usefulness and health of soils. Soil quality includes soil fertility, potential productivity, contaminant levels and their effects, resource sustainability and environmental quality. A general definition of soil quality is the degree of fitness of a soil for a specific use. The existence of multiple definitions suggests that the soil quality concept continues to evolve (Kádár, 1992; Várallyay, 1992, 1994, 2005; Németh, 1996; Malcolm, 2000; Márton, 2005; Márton et al. 2007). Recent attention has focused on the sustainability of human uses of soil, based on concerns that soil quality may be declining (Boehn and Anderson, 1997). We use sustainable to mean that a use or management of soil will sustain human well-being over time. Lal (1995) described the land resources of the world (of which soil is one component) as "finite, fragile, and nonrenewable," and reported that only about 22% (3.26 billion ha) of the total land area on the globe is suitable for cultivation and at present, only about 3% (450 million ha) has a high agricultural production capacity. Because soil is in large but finite supply, and some soil components cannot be renewed within a human time frame, the condition of soils in agriculture and the environment is an issue of global concern (Howard, 1993; FAO, 1997). Concerns include soil losses from erosion, maintaining agricultural productivity and system sustainability, protecting natural areas, and adverse effects of soil contamination on human health (Haberern, 1992; Howard, 1993; Sims et al., 1997). Parr et al. (1992) state, "...soil degradation is the single most destructive force diminishing the world's soil resource base." Soil quality guidelines are intended to protect the ability of ecosystems to function properly (Kádár, 1992; Várallyay, 1992, 1994, 2005; Cook and Hendershot, 1996; Németh, 1996; Malcolm, 2000; Márton, 2005; Márton et al. 2007). The Hungarian Ministry of Environment and Water (HMEW, 2004) suggests that the Hungarian Regions should adopt a national policy "...that seeks to conserve and enhance soil quality...".

Useful evaluation of soil quality requires agreement about why soil quality is important, how it is defined, how it should be measured, and how to respond to measurements with management, restoration, or conservation practices. Because determining soil quality requires one or more value judgments and because we have much to learn about soil, these issues are not easily addressed (Várallyay, 1992, 1994, 2005; Cook and Hendershot, 1996; Németh, 1996; Malcolm, 2000). Definitions of soil quality have been based both on human uses of soil and on the functions of soil within natural and agricultural ecosystems. For purposes of this work, we are showing soil quality within the context of managed agricultural ecosystems. To many in agriculture and agricultural research, productivity is analogous to soil quality. Maintaining soil quality is also a human health concern because air, groundwater and surface water consumed by humans can be adversely affected by mismanaged and contaminated soils, and because humans may be exposed to contaminated soils in residential areas (Kádár, 1992; Várallyay, 2005; Cook and Hendershot, 1996; Németh, 1996; Malcolm, 2000; Márton et al. 2007). Contamination may include heavy metals, toxic elements, excess nutrients, volatile and nonvolatile organics, explosives, radioactive isotopes and inhalable fibers (Sheppard et al., 1992; Cook and Hendershot, 1996).
Soil quality is not determined by any single conserving or degrading process or property, and soil has both dynamic and relatively static properties that also vary spatially (Carter et al., 1997). Gregorich et al. (1994) state that "soil quality is a composite measure of both a soil's ability to function and how well it functions, relative to a specific use." Increasingly, contemporary discussion of soil quality includes the environmental cost of production

and the potential for reclamation of degraded soils (Várallyay, 2005). Reasons for assessing soil quality in an agricultural or managed system may be somewhat different than reasons for assessing soil quality in a natural ecosystem. In an agricultural context, soil quality may be managed, to maximize production without adverse environmental effect, while in a natural ecosystem, soil quality may be observed, as a baseline value or set of values against which future changes in the system may be compared (Várallyay, 1994; Cook and Hendershot, 1996; Németh, 1996; Malcolm, 2000; Márton et al. 2007).

Soil quality has historically been equated with agricultural productivity, and thus is not a new idea. Soil conservation practices to maintain soil productivity are as old as agriculture itself, with documentation dating to the Roman Empire (Jenny, 1961). The Storie Index (Storie, 1932) and USDA Land Capability Classification (Klingebiel and Montgomery, 1973) were developed to separate soils into different quality classes. Soil quality is implied in many decisions farmers make about land purchases and management, and in the economic value rural assessors place on agricultural land for purposes of taxation. Beginning in the 1930s, soil productivity ratings were developed in the United States and elsewhere to help farmers select crops and management practices that would maximize production and minimize erosion or other adverse environmental effects (Huddleston, 1984). These rating systems are important predecessors of recent attempts to quantitatively assess soil quality. In the 1970s, attempts were made to identify and protect soils of the highest productive capacity by defining "prime agricultural lands" (Miller, 1979). An idea related to soil quality is "carrying capacity". Carrying capacity is the number of individuals that can be supported in a given area (Budd, 1992). Soils with high productivity have high carrying capacity, and are considered to be high quality. Sustainability implies that a system does not exceed its carrying capacity over time. Recent attempts to define soil quality and develop indices to measure it have many of the properties of the earlier soil productivity ratings (Doran and Jones, 1996; Snakin et al., 1996; Seybold et al., 1997).

Cox (1995) calls for national goals for soil quality that "... recognize the inherent links between soil, water and air quality." Haberern (1992) suggests that the decade of the 1990s is the time to study the soil as we have recognized and studied air quality and water quality in the preceding two decades. Air and water quality standards are generally based on maximum allowable concentrations of materials hazardous to human health. They are specified and enforced by regulators according to public uses of these resources. The result is that changes in air and water quality are now monitored to protect human health. With few exceptions, soil quality standards have not been set, nor have regulations been created regarding maintenance of soil quality (Várallyay, 2005; Cook and Hendershot, 1996; Malcolm, 2000; Márton et al. 2007). To the extent that soil has been the disposal site of hazardous wastes, as well as a pathway by which contamination or other applied chemicals may present a human health risk, sporadic 40 regulations of soil quality (in terms of contamination) does exist in the 27 European Union (EU) countries for not just new ones but an estimated 30 000 existing chemicals, today. These regulations are in the form of laws regulating hazardous waste, toxic substances, and pesticides. However, these standards are often contradictory, inconsistent with each other and with current methods of assessing risk. For example, in the United States, federal regulations supporting CERCLA (40 CFR) is a list of "hazardous substances" and the levels in various media (e.g., soil, water) to which the Environmental Protection Agency (EPA) must respond with a cleanup effort. However, EPA has fielded considerable controversy about contaminant levels and chemical forms that legitimately constitute a human health risk. Target cleanup levels have also been subject to debate and legislation.

Soil quality assessment requires definition of a "clean" soil (Sims et al., 1997). From this point of view, good quality soil has been defined as posing "...no harm to any normal use by humans, plants or animals; not adversely affecting natural cycles or functions; and not contaminating other components of the environment" (Moen, 1988). The parallel to air and water quality is easy to draw on a conceptual level, but designation of soil quality standards is significantly complicated by soil variability and heterogeneity (Smith et al., 1993).

Among the authors (Merker, 1956; Odell et al. 1984; Johnston et al., 1986; Reganold et al., 1990; Granatstein and Bezdicek, 1992; Kádár, 1992; Beke et al., 1994; Jenkinson et al., 1994; Schjenning et al., 1994; Murata et al., 1995; Biederbeck et al., 1996; Lindert et al., 1996; Romig et al., 1995; Warkentin, 1995; Carter et al., 1997; Gerzabeck et al., 1997; Seybold et al., 1997; Malcolm, 2000; Várallyay, 2005) and organizations defining soil quality are Larson and Pierce (1991), Karlen et al. (1997). The next section reviews some of the definitions and soil characteristics used to define soil quality. The reader should understand that the definition of soil quality and selection of soil characteristics needed to quantify soil quality are continuing to evolve. For example, Bouma (1989) recognized that an essential problem with definitions that produce carefully limited suitability classes is that empirical decisions must be made to separate the classes along what is essentially a continuum. That is, if soil organic matter is part of a soil quality definition, where on the continuum of soil organic matter content does one draw the line between a high quality and low quality soil? Does high organic matter content always indicate high soil quality? These are non-trivial questions under discussion by the soil science community.

Carter et al. (1997) suggest a framework for evaluating soil quality that includes:
1. describing each soil function on which quality is to be based,
2. selecting soil characteristics or properties that influence the capacity of the soil to provide each function,
3. choosing indicators of characteristics that can be measured, and
4. using methods that provide accurate measurement of those indicators.

The following soil functions appear frequently in the soil science literature:
1. soil maintains biological activity/productivity (Karlen et al., 1997), serves as medium for plant/crop growth (Arshad and Coen, 1992), supports plant productivity/yield (Arshad and Coen, 1992), supports human/animal health (Karlen et al., 1997);
2. partitions and regulates water/ solute flow through environment (Larson and Pierce, 1991; Arshad and Coen, 1992);
3. serves as an environmental buffer/filter (Larson and Pierce, 1991), maintains environmental quality (Arshad and Ccen, 1992);
4. cycles nutrients, water, energy and other elements through the biosphere (Anderson and Gregorich, 1984).
Clearly, these functions are interrelated. Later in this chapter, discussion focuses on the first and third functions (productivity and environmental buffering) as encompassing those aspects of soil quality most debated in the literature.

Larson and Pierce (1991) defined soil quality as "the capacity of a soil to function within the ecosystem boundaries and interact positively with the environment external to that ecosystem." Three soil functions are considered essential: provide a medium for plant growth, regulate and partition waterllow through the environment, and serve as an effective environmental filter. Arshad and Coen (1992) define soil quality as "the sustaining capability of a soil to accept, store and recycle water, minerals and energy for production of crops at optimum levels while preserving a healthy environment." They discuss terrain, climate and hydrology as site factors that contribute to soil quality and suggest that socioeconomic factors such as land use, operator and management should be included in a soil quality analysis. This approach is consistent with the FAO approach to land quality analysis (FAO, 1997). Karlen et al. (1992) define soil quality as "the ability of the soil to serve as a natural medium for the growth of plants that sustain human and animal life." Their definition is based on the role of soil quality in the long-term productivity of soil and maintenance of environmental quality. Doran and Parkin (1994) defined soil quality as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health." Gregorich et al. (1994) define soil quality as "a composite measure of both a soil's ability to function and how well it functions relative to a specific use" or "the degree of fitness of a soil for a specific use."

The Soil Science Society of America Ad Hoc Committee on Soil Health proposed that soil quality is "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al., 1997). This definition requires that five functions must be evaluated to describe soil quality: 1. sustaining biological activity, diversity, and productivity; 2. regulating and partitioning water and solute flow; 3. filtering, buffering, degrading, immobilizing and detoxifying organic and inorganic materials, including industrial and municipal byproducts and atmospheric deposition; 4. storing and cycling nutrients and other elements within the earth's biosphere; and 5. providing support of socioeconomic structures and protection for archeological treasures associated with human habitation. No soil is likely to successfully provide all of these functions, some of which occur in natural ecosystems and some of which are the result of human modification. We can summarize by saying that soil quality depends on the extent to which soil functions to benefit humans. Thus, for food production or mediation of contamination, soil quality means the extent to which a soil fulfills the role we have defined for it. Within agriculture, high quality equates to maintenance of high productivity without significant soil or environmental degradation.

The Glossary of Soil Science terms produced by the Soil Science Society of America (1996) states that soil quality is an inherent attribute of a soil that is inferred from soil characteristics or indirect observations. To proceed from a dictionary definition to a measure of soil quality, a minimum dataset (MDS) of soil characteristics that represents soil quality must be selected and quantified (Papendick et al., 1995). The MDS may include biological, chemical or physical soil characteristics [Organic matter (OM), Aggregation (A), Bulk density (BD), Depth to hardpan (DH), Electrical conductivity (EC), Fertility (F), Respiration (R), pH, Soil test (ST), Yield (Y), Infiltration (I), Mineralizable nitrogen potential (MNP), Water holding capacity (WHC)]. For agriculture, the measurement of properties should lead to a relatively simple and accurate way to rank soils based on potential plant production without soil degradation. Unfortunately, commonly identified soil quality parameters may not correlate well with yield (Reganold, 1988). In the next section, we consider these four points concerning the selection and quantification of soil characteristics: 1. soil characteristics may be desirable or undesirable, 2. soil renewability involves judgment of the extent to which soil characteristics can be controlled or managed, 3. rates of change in soil characteristics vary, and 4. there may be significant temporal or spatial variation in soil characteristics.

Components of soil quality definitions may include desirable and undesirable characteristics. Desirable soil characteristics may either be the presence of a property that benefits soil productivity and/or other important soil functions, or the absence of a property that is detrimental to these functions. A soil characteristic may include a range of values that contributes positively to quality and a range that contributes negatively. Soil pH, for example, may be a positive or negative characteristic depending on its value. Larson and Pierce (1991) suggest that ranges of property values can be defined as optimal, suboptimal or superoptimal. A pH range of 6 to 7.5 is optimal for production of most crops. Outside of this range, pH is suboptimal and soil quality is lower than at the optimal pH range. The complexity of the soil quality concept is illustrated by the fact that the choice of optimal pH range is crop or use dependent. Letey (1985) suggested that identification of a range of water content that is nonlimiting to plant productivity might be a good way of assessing the collective effect of soil physical characteristics that contribute to crop productivity. For soils of decreasing quality, the width of the nonlimiting water range decreases. Undesirable soil characteristics may be either the presence of contaminants or a range of values of soil characteristics that contribute negatively to soil quality. The presence of chemicals that inhibit plant root growth or the absence of nutrients that result in low yields or poor crop quality are examples of undesirable soil characteristics that lower soil quality.

The extent to which soil is viewed as a renewable resource shapes our approach to soil quality. "Soil" in this context is the natural, three-dimensional, horizonated individual, not something created by earth moving machinery. For the purpose of assessing human impact on sustainability of soil quality, it may be appropriate to use only those soil properties that are slowly or nonrenewable. Shorter term assessments may be based on those properties that change rapidly and are subject to easy management. Willis and Evans (1977) argued that soil is not renewable over the short term based on studies that suggest that 30 to more than 1,000 years are required to develop 25 mm of surface soil from parent material by natural processes. Jenny (1980) also argued that soil is not renewable over the time scale to which humans relate. Howard (1993) suggests defining soil quality based on undisturbed natural soils and to set quality standards based on changes in soils which cannot be reversed naturally or by ecological approaches. The renewability of soil depends on the soil property considered. For example, once soil depth is reduced by wind or water erosion so that it is too shallow to support crops, it is not renewable within a human or management time frame. Some important soil characteristics are slowly renewable. Organic matter, most nutrients and some physical properties may be renewed through careful long-term management. Certain chemical properties (pH, salinity, N, P, K content) may be altered to a more satisfactory range for agriculture within a growing season or two, while removal of unwanted chemicals may take much longer.

No soil property is permanent, but rates and frequency of change vary widely among properties. Soil properties also vary with ecosystem, arguably depending most on climate. In rangelands, for example, temporal variability is high and relatively unpredictable due to the strong dependence of soil properties on soil wetness (Herrick and Whitford, 1995). Variability in soil wetness is not restricted to rangelands and may be an especially important determinant of microbial community structure and function in both irrigated and rainfed agricultural systems. Arnold et al. (1990) suggest that changes in soil properties can be nonsystematic, periodic, or trend. Nonsystematic changes are short term and unpredictable. Periodic are predictable and trend changes tend to be in one direction over time. Carter et al. (1997) distinguish between dynamic soil properties that are most subject to change through human use and are strongly influenced by agronomic practices, and intrinsic or static properties that are not subject to rapid change or management. Examples of dynamic soil characteristics are the size, membership, distribution, and activity of a soil's microbiological community; the soil solution composition, pH, and nutrient ion concentrations, and the exchangeable cation population. Soils respond quickly to changes in conditions such as water content. As a result, the optimal frequency and distribution of soil measurements vary with the property being measured. Soil mineralogy, particle size distribution and soil depth are static soil quality indicators. Although changes occur continuously, they are slow under natural conditions. Organic matter content may be a dynamic variable, but the chemical properties of organic matter may change only over periods on the order of 100 to 1,500 years depending on texture. Soil properties that change quickly present a problem because many measurements are needed to know the average value and to determine if changes in the average indicate improvement or degradation of soil quality. Conversely, properties that change very slowly are insensitive measures of short-term changes in soil quality. Papendick et al. (1995) argue that the MDS required for soil quality analysis includes a mix of "dynamic" and relatively "static" properties.

A soil quality assessment must specify area. One could use the pedon (the three-dimensional soil individual) as the unit of measure, or a soil map unit, a landscape, a field or an entire watershed. The choice will depend to some degree on what property is of interest and the spatial variability of the property. Karlen et al. (1997) propose that soil quality can be evaluated at scales ranging from points to regional, national and international. They suggest that the more detailed scales provide an opportunity to "understand" soil quality while larger scale approaches provide interdisciplinary monitoring of soil quality and changes in soil quality. Pennock et al. (1994) discuss scaling up data from discrete sampling points to landscape and regional scales.

Soil physical characteristics [Aeration (A), Aggregate stability (AS), Bulk density (BD), Clay mineralogy (CM), Color (C), Consistence (dry (CD), moist (CM), wet (CW)), Depth to root limiting layer (DRLL), Hydraulic conductivity (HC), Oxygen diffusion rate (ODR), Particle size distribution (PSD), Penetration resistence (PR), Pore connectivity (PC), Pore size distribution (PSD), Soil strength (SS), Soil tilth (ST), Structure type (STY), Temperature (T), Total porosity (TP), Water-holding capacity (WHC)] are a necessary part of soil quality assessment because they often cannot be easily improved (Wagenet and Hutson, 1997). Larson and Pierce (1991) summarize the physical indicators of soil quality as those properties that influence crop production by determining: 1. whether a soil can accommodate unobstructed root growth and provide pore space of sufficient size and continuity for root penetration and expansion, 2. the extent to which the soil matrix will resist deformation, and 3. the capacity of soil for water supply and aeration. Factors such as effective rooting depth, porosity or pore size distribution, bulk density, hydraulic conductivity, soil strength and particle size distribution capture these soil functions (Malcolm, 2000; Várallyay, 2005).

Reganold and Palmer (1995) use texture, color, dry and moist consistence, structure type, a structure index, bulk density of the 0-5 cm zone, penetration resistance of 0 to 20 and 20 to 40 cm zones and topsoil thickness as physical determinants of soil quality. Letey (1994) suggests that structure, texture, bulk density, and profile characteristics affect management practices in agriculture but are not directly related to plant productivity. He proposes that water potential, oxygen diffusion rate, temperature, and mechanical resistance directly affect plant growth, and thus are the best indicators of the physical quality of a soil for production. Soil tilth, a poorly defined term that describes the physical condition of soil, also may be an indicator of a soil's ability to support crops. Farmers may assess soil tilth by kicking a soil clod. More formal measurements to describe soil ti]th include bulk density, porosity, structure, roughness and aggregate characteristics (Karlen et al., 1992). Many of the processes that contribute to soil structure, aggregate stability, bulk density and porosity are not well understood, making soil tilth a difficult parameter to quantify. Soil depth is an easily measured and independent property that provides direct information about a soil's ability to support plants. Effective soil depth is the depth available for roots to explore for water and nutrients. Layers that restrict root growth or water movement include hard rock, naturally dense soil layers such as fragipans, petrocalcic and, petroferric horizons, duripans, and human-induced layers of high bulk density such as plow pans and traffic pans. Effective soil depth is a problem for agricultural use of over 50% of soils in Africa (Eswaran et al., 1997). Soil depth requirements vary with crop or species. Many vegetable crops, for example, are notably shallow rooted while grain crops and some legumes like alfalfa are deep rooted. Variation will be even greater in unmanaged, natural systems. Wheat yield in Colorado was shown to decrease from 2,700 to 1,150 kg ha' over a 60-yr period of cultivation primarily due to decrease in soil depth (Bowman et al., 1990).

Assessment of soil quality based on soil chemistry, whether the property is a contaminant or part of a healthy system, requires a sampling protocol, a method of chemical analysis, an understanding of how its chemistry affects biological systems and interacts with mineral forms, methods for location of possible contamination, and standards for soil characterization (Várallyay, 2005; Németh, 1996; Malcolm, 2000). Some soil chemical properties suggested as soil quality indicators are: Base saturation percentage (BSP), Cation exchange capacity (CEC), Contaminant availability (CA), Contaminant concentration (CC), Contaminant mobility (CM), Contaminant presence (CP), Electrical conductivity (EC), ESP, Nutrient cycling rates (NCR), Ph, Plant nutrient availability (PNA), Plant nutrient content (PNC) and SAR. Nutrient availability depends on soil physical and chemical processes, such as weathering and buffering, and properties such as organic matter content, CEC and pH (Kádár, 1992; Várallyay, 1992, 1994, 2005; Németh, 1996; Malcolm, 2000; Márton, 2005; Márton et al. 2007). At low and high pH, for example, some nutrients become unavailable to plants and some toxic elements become more available. Larson and Pierce (1991) chose those chemical properties that either inhibit root growth or that affect nutrient supply due to the quantity present or the availability. Reganold and Palmer (1995) used chemical parameters related to nutrient availability as measures of soil quality, including CEC, total N and P, pH and extractable P, S, Ca, Mg and K. Karlen et al. (1992) suggest that total and available plant nutrients, and nutrient cycling rates, should be included in soil quality assessments. Soil properties may be severely compromised by intended or unintended human additions of chemical compounds and soil productivity reduced if unwanted chemicals exceed safe thresholds. Data are required to determine whether or not a site is significantly polluted and if it requires clean-up (Sims et al., 1997). International standard methods have been created to maintain the quality of measurements (Hortensius and Welling, 1996). A difficult determination is the level of each chemical that is considered an ecological risk. Beck et al. (1995) provide a list of levels for organic chemicals adopted by The Netherlands and Canada. EPA uses similar lists for compounds considered hazardous (e.g., 40 CFR). Sims et al. (1997) argue that clean and unclean are two extremes of a continuum and that it is more appropriate to define the physical, chemical and biological state of the soil as acceptable or unacceptable. In The Netherlands, soil quality reference values have been created for heavy metals and organic chemicals based on a linear relationship with soil clay and organic matter content. The Dutch Ministry of Housing, Physical Planning and Environment has used the maximum of a range of reference values for a given substance as a provisional reference value for good soil quality (Howard, 1993).

The focus of many soil quality definitions is soil biology [Organic carbon (OC), Microbial biomass (MB), C and N, Total bacterial biomass (TBB), Total fungal biomass (TFB), Potentially mineralizable N (PMN), Soil respiration (SR), Enzymes (Dehydrogenase, Phosphatase, Arlysulfatase), Biomass C/total organic carbon, Respiration/biomass, Microbial community fingerprinting (MCF), Substrate utilization (SU), Fatty acid analysis (FAA), Nucleic acid analysis (NAA)]. Soil supports a diverse population of organisms, ranging in size from viruses to large mammals, that usually interacts positively with plants and other system components (Paul and Clark, 1996). However, some soil organisms such as nematodes, bacterial and fungal pathogens reduce plant productivity. Many proposed soil quality definitions focus on the presence of beneficial rather than absence of detrimental organisms, although both are critically important. Various measures of microbial community viability have been suggested as measures or indices of soil quality. Community level studies consider species diversity and frequency of occurrence of species. Visser and Parkinson (1992) found that diverse soil microbiological criteria may be used to indicate deteriorating or improving soil quality. They suggested testing the biological criteria for soil quality at three levels: population, community and ecosystem. Microorganisms and microbial communities are dynamic and diverse, making them sensitive to changes in soil conditions (Kennedy and Papendick, 1995). Their populations include fungi, bacteria including actinomycetes, protozoa, and algae. Soil microorganisms form crucial symbiotic relationships with plants, including mycorrhizal infection for P and N acquisition and bacterial infection for fixation of atmospheric N.

Authors emphasizing use of biological factors as indicators of soil quality often equate soil quality with relatively dynamic properties such as microbial biomass, microbial respiration, organic matter mineralization and denitrification, and organic matter content (Yakovchenko et al., 1996; Franzluebbers and Arshad, 1997), or soil microbial C, phospholipid analyses and soil enzymes (Gregorich et al., 1997), or total organic C and N (Franco-Vizcaino, 1997). Visser and Parkinson (1992) question the suitability of enzyme assays for microbial activity and soil quality assessments. Waksman (1927), who studied measurements of soil microorganisms that could indicate soil fertility, found that physical and chemical factors as well as soil biology were needed to predict soil fertility. Meso- and macrofauna populations have also been considered as part of soil quality definitions (Berry, 1994). One could choose to use presence or absence of a particular species or population of a particular species as a measure of soil quality. Stork and Eggleton (1992) discuss species richness as a powerful indicator of invertebrate community and soil quality, although determining the number of species is a problem. They suggest that keystone species, taxonomic diversity at the group level, and species richness of several dominant groups of invertebrates can be used as part of a soil quality definition. Measuring soil fauna populations involves decisions about which organisms to measure and how to measure them. An example is the earthworm population, the size of which is frequently mentioned as an important measure of soil quality. Measurement choices include numbers of organisms per volume or weight of soil, number of species, or a combination of numbers of organisms and species. Reganold and Palmer (1995) use total earthworms per square meter, total earthworm weight (g m-’) and average individual earthworm weight as biological indicators of soil quality.

Measurement of one or more components of the N cycle including ammonification, nitrification and nitrogen fixation, may be used to assess soil fertility and soil quality (Visser and Parkinson, 1992). Presumably, high rates of N turnover may infer a dynamic and healthy soil biological community. In contrast, low soil quality or poor soil health may be inferred from lack of N turnover. The interpretation of N turnover rates is highly dependent on the kinds of substrates added to soils and climate variables such as soil temperature and moisture. One needs to be careful when comparing N turnover rates within soils and among different soils to be sure that the cause of differences is a soil quality parameter and not natural variability. Presence of pesticide residues, for example, may reduce N turnover rate. In such an instance, both the presence of the pesticide and the N turnover rate would be needed to determine that the soil quality had been impaired.

Production incorporates use of and need for functioning soil resources in agriculture, and environmental buffering incorporates the direct and indirect effects of human use on ecosystem function and human health (Kádár, 1992; Várallyay, 1992, 1994, 2005; Németh, 1996; Malcolm, 2000; Márton, 2005; Márton et al. 2007).

Worldwide agriculture is the most extensive human land use, and soil characteristics are a critical determinant of agricultural productivity. Agriculture includes irrigated and rainfed cultivated cropland, permanent crops such as orchards and vineyards, irrigated pasture, range, and forestry. Each cropping system has distinct soil and soil management conditions for optimal production. It has been suggested that soil productivity is the net resultant of soil degradation processes and soil conservation practices (Parr et al., 1990). An appropriate definition of soil quality and the criteria necessary to evaluate and monitor soil quality is a step toward "the development of systematic criteria of sustainability". Issues to be considered when discussing soil quality for agriculture include: 1. How are productivity and sustainability related? 2. Is the cropping system in question cultivated or non-cultivated? 3. Is the cropping system in question an irrigated or dryland system? Sustainability of agricultural systems is critical to human welfare and is an a subject of research and debate (Letey, 1994). High productivity and sustainability must be converging goals if the growing human population is to be fed without destroying the resources necessary to produce food. Sustainability implies that a system is at a desirable steady state. Thermodynamically, soil is an open system through which matter and energy flow and a steady state is characterized by a minimum production of entropy (Andiscott, 1995). Ellert et al. (1997) review related literature on ways of assessing soil function on an ecosystem scale, commenting that the complexity and organization of living systems, which seem to defy the second law of thermodynamics (increasing disorder/entropy), may provide a means to broadly assess ecosystem function.

The purpose of agriculture is to provide products for human sustenance and by definition is not sustainable unless the nutrients removed in the products are returned to the soil. Many of the arguments about the sustainability of agricultural systems relate to the form in which nutrients are most sustainably returned. No agricultural system will be sustainable in the long run without management that considers nutrient cycling and energy budgets. The more intense the agricultural system, the more energy and resources must be expended to maintain the system. The relative quality of a soil for agriculture can depend on the resources available to farmers. In the United States, resources may be readily available for management of dynamic soil properties such as nutrient or water status. In other countries, farmers may be resource poor, and agricultural systems are generally low input, meaning that large-scale irrigation is absent, use of fertilizers, pesticides, and herbicides is minimal, and high energy, mechanized equipment is not available (Eswaran et a1.,1997). This means, for example, that soil quality for agriculture will be more dependent on climate than if the same soils were part of a highly managed, irrigated system. Similarly, sustainability is more dependent on maintenance of dynamic soil properties because resources may not exist to remedy losses (Várallyay, 2005; Malcolm, 2000; Márton et al. 2007). It is difficult to overstate the importance of irrigation to food production. One-third of the total global harvest of food comes from the 17% (250 million ha) of the world's cropland that is irrigated (Hoffman et al., 1990); three-quarters of which are in developing countries (Tribe, 1994). India, China, the former Soviet Union, the United States and Pakistan have the greatest area of irrigated land. Should soil quality criteria be the same for irrigated and dryland agriculture? Sojka (1996) suggests that the arid and semi-arid soils that support most irrigated agriculture have thin erodible surfaces, characteristics that would classify such soils as having poor quality. Yet under irrigation, they feed much of the world. Without irrigation, for example, in many African soils, moisture stress becomes a significant factor limiting production, and the water-holding capacity of a soil becomes crucial (Eswaran et al., 1997). This suggests that a standard set of criteria based on potential productivity is not a sufficient definition of soil quality.

Soils that are not cultivated are a much larger component of agriculture, broadly defined, than those that are cultivated. About 65% of the land in the United States is forest (284 million ha) or range land (312 million ha), with only about 284 million hacultivated (NRC,1994). Herrick and Whitford (1995) suggest that range land soils, which often serve multiple uses, present unique challenges and opportunities for assessing soil quality because spatial and temporal variability are higher than in cropped systems. On range lands and forest lands, food, fiber, timber production, biomass for fuel, wildlife, biodiversity, recreation, and water supply are all potential uses that may have diverse criteria for quality soils. Herrick and Whitford (1995) give the example of a thick O horizon that may be an indicator of good timber production but has no predictive value of soil quality for the rancher. The National Research Council (NRC, 1994) recommends that range land health be determined using three criteria: degree of soil stability and watershed function, integrity of nutrient cycles and energy flows, and presence of functioning recovery mechanisms. Soil erosion by wind and water and infiltration or capture of precipitation were selected as processes that could be used as indicators of soil stability and watershed function. Specific indicators or properties need to be related to these two broad processes. The amount of nutrients available, the speed with which nutrients cycle, and measures of the integrity of energy flow through the system were considered fundamental components of range land health. Finally, the capacity of range land ecosystems to react to change depends on recovery mechanisms that result in capture and cycling of nutrients, capture of energy, conservation of nutrients, energy and water, and resilience to change. Specific indicators include status of vegetation, age class and distribution (Kádár, 1992; Várallyay, 1992, 1994, 2005; Németh, 1996; Malcolm, 2000; Márton et al. 2007).

The evaluation of land quality for forestry is a well-known practice. Indices range from quantitative through semi-quantitative to qualitative. Quantitative evaluations, such as site index, use regression equations to predict tree height at a predetermined tree age based on soil and climate data. Qualitative evaluations assign land to classes based on soil and climate properties.

In soil science, the term "buffer" refers collectively to processes that constrain shifts in the dissolved concentration of any ion when it is added to or removed from the soil system (Singer and Munns, 1996). Soils "buffer" nutrients as well as contaminants and other solutes, via sorption to or incorporation into clay and organic materials.

The extent to which a soil immobilizes or chemically alters substances that are toxic, thus effectively detoxifying them, reflects "quality" in the sense that humans or other biological components of the system are protected from harm. This is the basis for the European concept of soil quality (Moen, 1988; Siegrist, 1989; Denneman and Robberse, 1990). Lack of soil function in this category is reflected as direct toxicity or as contamination of air or water. Identifying substances that qualify as "contaminants" can be challenging because some, such as nitrates and phosphates, are important plant nutrients as well as potential water pollutants. An example is agricultural runoff containing N03 or soluble P (Yli-Halla et al., 1995). This chapter does not attempt a comprehensive review of research in this area, which is covered in an earlier chapter, but instead presents a few sample articles pertinent to this aspect of soil quality.

Holden and Firestone (1997) define soil quality in this context as "the degree to which the physical, chemical, and biological characteristics of the soil serve to attenuate environmental pollution." Howard (1993) defines the ecological risk of a chemical in the environment as "the probability that a random species in a large community is exposed to a concentration of the chemical greater than its no-effect level." The extent to which a soil is capable of reducing the probability of exposure is a measure of its quality. A well-studied example of a common soil contaminant is Pb (McBride et al., 1997). Although legislated limits may be on a concentration basis in soil (e.g., 500 ftg kg-’), risk assessment techniques have attempted to account for the chemical form of Pb present, as well as the observed relative relationship between the amount of Pb present in soil and blood levels in local residents (Bowers and Gauthier, 1994). Critics have questioned analytical techniques used to determine bioavailable levels of Pb in soil, as well as the degree to which toxicity data account for its chemical fate and ecologically damaging properties (Cook and Hendershot, 1996). Natural variability of soils and variation within a soil series make average values or average background values inadequate for soil quality assessments. In addition, bioaccumulation and toxicity need to be considered when establishing levels of toxicants that may not be exceeded in a "high quality" soil for a given use (Traas et al. 1996). Another example is the effect of heavy metals such as Cr(VI) on soil biological properties. Based on a study of three New Zealand soils of contrasting texture, organic matter content, and CEC, Speir et al. (1995) propose an "ecological dose value" that represents the inhibitory effects of a heavy metal (in this case, Cr(VI)) on the kinetics of soil biological properties, and serves as a generic index for determination of permissible concentration levels for heavy metals in soils.

A single soil characteristic is of limited use in evaluating differences in soil quality (Reganold and Palmer, 1995). Using more than one quantitative variable requires some system for combining the measurements into a useful index (Halvorson et al., 1996). The region, crop, or general soil use for which an index was created will likely limit its effectiveness outside the scope of its intended application. Even an index designed only to rate productivity is not likely to be useful for all crops and soils, leading Gersmehl and Brown (1990) to advocate regionally targeted systems. Rice is a good example of a crop requiring significantly different soil properties than other crops. It is a food staple for a large proportion of the world population. Approximately 146 million ha were in rice production in 1989 (FAO, 1989) mainly (90%) in Asia. High quality soils for paddy rice may be poor quality for most other irrigated and dryland crops because they may be saline or sodic, and high in clay with slow infiltration and permeability. These physical and chemical properties often constrain production of other crops. Although they are not reviewed here, various land suitability classifications specifically for rice have been developed since the turn of the century (Dent, 1978). Examples of several soil quality indexing systems are presented in the following sections. To some extent, recent attempts to enumerate the factors of soil quality resemble Jenny’s (1941) introduction of the interrelated factors of soil formation.

An index is categorized here as nonquantitative if it does not combine evaluated parameters into a numerical index that rates soils along a continuous scale. Examples are the USDA Land Capability Classification and the US Bureau of Reclamation (USBR) Irrigation Suitability.

The purpose of the Land Capability Classification (LCC) was to place arable soils into groups based on their ability to sustain common cultivated crops that do not require specialized site conditioning or treatment (Klingebiel and Montgomery, 1973). Nonarable soils, unsuitable for long-term, sustained cultivation, are grouped according to their ability to support permanent vegetation, and according to the risk of soil damage if mismanaged. The LCC combines three rating values at different levels of abstraction: capability class, subclass, and unit. At the most general level, soils are placed in eight classes according to whether they (a) are capable of producing adapted plants under good management (classes I to N), (b) are capable of producing specialized crops under highly intensive management involving "elaborate practices for soil and water conservation" (classes V to VII), or (c) do not return on-site benefits as a result of management inputs for crops, grasses or trees without major reclamation (Klingebiel and Montgomery, 1973). The four possible limitations/hazards under the subclass rating are erosion hazard, wetness, rooting zone limitations and climate. The capability unit groups soils that have about the same responses to systems of management and have longtime estimated yields that do not vary by more than 25% under comparable management. The issue of critical limits is a difficult one in soils because of the range of potential uses and the interactions among variables (Arshad and Ccen, 1992). Several studies have shown that lands of higher LCC have higher productivity than lands of lower LCC (Patterson and Mackintosh, 1976; van Vliet et al., 1979; Reganold and Singer, 1984). In a study of 744 alfalfa, corn, cotton, sugar beet and wheat growing fields in the San Joaquin Valley of California, those with LCC ratings between 1 and 3 had significantly lower input/output ratios than fields with ratings between 3.01 and 6 (Reganold and Singer, 1984). This suggests that use of the LCC system provides an economically meaningful assessment of soil quality for agriculture.

This was a frequently used system of land evaluation for irrigation in the Western US during the period of rapid expansion of water delivery systems (McRae and Burnham, 1981). It combines social and economic evaluations of the land with soil and other ecological variables to determine if the land has the productive capacity, once irrigated, to repay the investment necessary to bring water to an area. It recognizes the unique importance of irrigation to agriculture and the special qualities of soils that make them irrigable.

Quantitative systems result in a numerical index, typically with the highest number being assigned to the best quality soils. Systems may be additive, multiplicative or more complex functions. They have two important advantages over nonquantitative systems: 1. they are easier to use with GIS and other automated data retrieval and display systems, and 2. they typically provide a continuous scale of assessment. No single national system is presently in use but several state or regional systems exist.

Although he considered the productivity of the land to be dependent on 32 soil, climate and vegetative properties [Surface conditions: Physiographic position, Slope, Microrelief, Erosion deposition, External drainage, runoff. Soil physical conditions: Soil color, Soil depth, Soil density and porosity, Soil permeability, Soil texture, Stoniness, Soil structure, Soil workability-consistence, Internal drainage, Water-holding capacity, Plant-available water. Soil chemical conditions: Organic matter, Nitrogen, Reaction, Calcium carbonate, bases, Exchange capacity, Salts: Cl, SO Na, Toxicities, e.g., B, Available P, Available K, Minor elements, e.g., Zn, Fe, Fertility. Mineralogical conditions: Mineralogy. Climate: Precipitation Temperature Growing season Winds. Vegetativé cover: Natural vegetation], only nine properties were used in the SIR, because incorporating a greater number of factors made the system unwieldy. The nine factors are soil morphology (A), surface texture (B), slope (C), and six variables (X.) that rate drainage class, sodicity, acidity, erosion, microrelief and fertility; rated from 1% to 100%. These are converted to their decimal value and multiplied together (Storie, 1964). Values for each factor were derived from Storie's experience mapping and evaluating soils in California, and in soil productivity studies in cooperation with the California Agricultural Experiment Station cost-efficiency projects relating to orchard crops, grapes and cotton. In describing the SIR (SIR= [AxBxCxIIXi]x100), Storie (1932, 1964) explicitly mentioned "soil quality". Soils that were deep, had no restricting subsoil horizons, and held water well had the greatest potential for the widest range of crops. The usefulness of the SIR as a soil quality index would be greatest if there was a statistically significant relationship between SIR values and an economic indicator of land value. Reganold and Singer (1984) found that area-weighted average SIR values between 60 and 100 for 744 fields in the San Joaquin Valley of California had lower but statistically insignificant input/output ratios than fields with indices < 60. The lack of statistical significance does not mean that better quality lands could not be farmed at economically lower cost or at higher cost and higher output than the lower quality lands.

We productivity index model (PI) was developed to evaluate soil productivity in the top 100 cm, especially with reference to potential productivity loss due to soil erosion (Neill, 1979; Kiniry et al., 1983). The PI model rates soils on the sufficiency for root growth based on potential available water storage capacity, bulk density, aeration, pH, and electrical conductivity. A value from zero to one is assigned to each property describing the importance of that parameter for root development. The product of these five index values is used to describe the fractional sufficiency of any soil layer for root development. Pierce et al. (1983) modified the PI to include the assumption that nutrients were not limiting and that climate, management and plant differences are constant. A number of authors found that it is useful to various degrees (Gantzer and McCarty, 1987; Lindstrom et al., 1992).

Parr et al. (1992) suggest that a SQI could take the form of Equation: SQI = f (SP, P, E, H, ER, BD, FQ, MI) where SQI is a function of soil properties (SP), potential productivity (P), environmental factors (E), human and animal health (H), erodibility (ER), biological diversity (BD), food quality and safety (FQ) and management inputs (MI). Determination of the specific measurable indicators of each variable and the interactions among these diverse variables is a daunting task. Moreover, the mathematical method of combining these factors, as well as the resulting value that would indicate a high quality soil, is not specified. The inclusion of variables BD, FQ and MI make this a land quality index as suggested by FAO (1997).

Larson and Pierce (1991) defined soil quality (Q) as the state of existence of soil relative to a standard or in terms of a degree of excellence. They argue that defining Q in terms of productivity is too limiting and does not serve us well. Rather, Q is defined as the sum of individual soil qualities q. and expressed as Equation: Q=f(qi ...qn). These authors do not identify the best subset of properties or their functional and quantitative relationship, but do suggest that a MDS should be selected from those soil characteristics in which changes are measurable and relatively rapid (i.e., "dynamic" properties), arguing that it is more important to know about changes in soil quality (dQ) than the magnitude of Q (Larson and Pierce, 1991). Changes in soil quality are a function of changes in soil characteristics (q) over time (t): dQ = f[(qi.t – qit0)... (qn.t-qnt0)]. If dQ/dt is ≥ 0, the soil or ecosystem is improving relative to the standard at time to. If dQ/dt <0, soil degradation is occurring. Time zero can be selected to meet management needs or goals. If there is a drastic change in management, time zero can be defined as prior to the change. If a longer time period of comparison is considered more appropriate, properties of an uncultivated or pristine soil could be used.

The MDS recommended by Larson and Pierce (1991) includes N mineralization potential or P buffering capacity, total organic C, labile organic C, texture, plant-available water capacity, structure (bulk density is recommended as a surrogate variable), strength, maximum rooting depth, pH and EC. In instances when data are unavailable, pedotransfer functions (Bouma, 1989) can be used to estimate values of soil characteristics. These estimates can then be used as part of the minimum dataset to estimate soil quality or changes in soil quality brought about by management. Although this is a quantitative system, some qualitative judgments are needed to make decisions about changes in soil quality. In particular, interpretation of the meaning of magnitude of changes in a characteristic or the number of characteristics to change from time zero to the time of the measurement is qualitative. The authors do not address how large a change in pH, soil depth, bulk density or organic C represents serious soil degradation, or the values that define soil as high or low quality.

Karlen et al. (1994) developed QI based on a 10-year crop residue management study. QI is based on four soil functions: (1) accommodating water entry, (2) retaining and supplying water to plants, (3) resisting degradation, and (4) supporting plant growth. Numerous properties were measured and values normalized based on standard scoring functions. One function is based on the concept that more of a property is better, one that less is better and the third that an optimum is better. Lower threshold values receive a score of zero, upper threshold values receive a score of one, and baseline values receive a score of one-half. Priorities are then assigned to each value. For example, aggregate stability was given the highest weight among factors important in water entry. After normalizing, each value is then multiplied by its weighting factor (wt) and products are summed Equation: QI=qwe (wt) + qwt (wt)+qrd (wt) + qspg (wt). Subscripts refer to the four main functions described earlier. It should also be noted that resisting degradation (rd) and sustaining plant growth (spg) are assigned secondary and tertiary levels of properties that themselves are normalized and weighted before a final value is calculated and incorporated into Equation. The resulting index resulted in values between zero and one. Of the three systems in the study, the one with the highest rate of organic matter return to the soil had the highest index value, and the soil with the lowest had the lowest value. The authors suggest that this demonstrates the usefulness of the index for monitoring the status and change in status of a soil as a function of management. They also suggest that the index and the soil characteristics that go into the index may change as the index is refined (Karlen et al. 1994).

Snakin et al. (1996) developed an index of soil degradation that assigns three separate values from one to five reflecting the degree to which a soil's physical, chemical, and biological properties are degraded, as well as the rate of degradation. The Canadian soil capability classification system is similar to the older US systems and is quantitative. In a study in southwestern Ontario, Patterson and Mackintosh (1976) found that high gross returns per ha were three times as likely if the productivity index of land, based on the soil capability classification, was between 90 and 100 than if it fell between 80 and 89. Smith et al. (1993) and Halvorson et al. (1996) propose a multiple-variable indicator transform procedure to combine values or ranges of values that represent the best estimate of soil quality. Their system converts measured data values into a single value according to specified criteria. They do not attempt to define soil quality or specify what soil characteristics are to be used. They combine this procedure with kriging to develop maps that indicate the probabilities of meeting a soil quality criterion on a landscape level. Critical threshold values must be known, assumed, or determined in order to separate different soil qualities. Numerous additive productivity rating systems have been developed for specific states, as reviewed by Huddleston (1984). In these systems, soil properties are assigned numerical values according to their expected impact on plant growth. The index is usually calculated as the sum of the values assigned to each property with 100 the maximum value. Huddleston (1984) notes advantages and disadvantages to such a system which are similar to those for many of the soil quality indices previously discussed. Additive systems become complex as the number of factors, cropping systems, and soil and climatic conditions increases. A unique problem of subtractive systems (one in which 100 is the starting point and values are deducted for problem conditions) is that negative values result when multiple factors are less than satisfactory.

Soil quality is a concept being developed to characterize the usefulness and health of soils, because soils are fundamental to the well-being and productivity of agricultural and natural ecosystems. It is a compound characteristic that cannot be directly measured. Many definitions of soil quality can be found in the literature and no set of soil characteristics has been universally adopted to quantify definitions. Soil quality is often equated with agricultural productivity and sustainability. An approach toward developing soil quality definitions is one that assesses soil quality in the context of a soil's potential to perform given functions in a system; e.g., maintains productivity, partitions and regulates water and solute flow through an ecosystem, serves as an environmental buffer, and cycles nutrients, water, and energy through the biosphere. Air and water quality standards are usually based on maximum allowable concentrations of materials hazardous to human health. A definition of soil quality based on this concept would encompass only a fraction of the important roles soils play in agriculture and the environment but could be essential to soil remediation. To proceed from a definition to a measure of soil quality, a minimum dataset of soil characteristics that represent soil quality must be selected and quantified. Many soil physical, chemical and biological properties have been suggested to separate soils of different quality. These include desirable and undesirable properties. Desirable soil characteristics may either be the presence of a property that benefits crop productivity and environmental buffering and/or other important soil functions, or the absence of a property that is detrimental to these functions. In particular, absence of contaminants is an important soil quality characteristic. In selecting characteristics, it is necessary to recognize that some soil properties are static, in the sense that they change slowly over time and others are dynamic. In addition, spatial and temporal variability of soil properties must be considered when selecting the properties used to assess soil quality. A single soil property is of limited use in evaluating soil quality. Qualitative and quantitative soil quality indices have been suggested that combine quantitative values of soil properties. Quantitative systems may be additive, multiplicative or more complex functions. Regardless of the definition or suite of soil variables chosen to define and quantify soil quality, it is critical to human welfare that soils be managed to provide for human health and well-being while minimizing soil and environmental degradation.

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