Soil Quality: A Concept, Definition, and Framework for Evaluation
(A Guest Editorial)

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ABSTRACT

This essay summarizes deliberation by the Soil Science Society of America (SSSA) Ad Hoc Committee on Soil Quality (S-581) and was written to spur discussion among SSSA members. Varying perceptions of soil quality have emerged since the concept was suggested in the early 1990s, and dialogue among members is important because, unlike air and water quality, legislative standards for soil quality have not been and perhaps should not be defined. In simplest terms, soil quality is "the capacity (of soil) to function". This definition, based on function, reflects the living and dynamic nature of soil. Soil quality can be conceptualized as a three-legged stool, the function and balance of which requires an integration of three major components – sustained biological productivity, environmental quality, and plant and animal health. The concept attempts to balance multiple soil uses (e.g., for agricultural production, remediation of wastes, urban development, forest, range, or recreation) with goals for environmental quality. Assessing soil quality will require collaboration among all disciplines of science to examine and interpret their results in the context of land management strategies, interactions, and trade-offs. Society is demanding solutions from science. Simply measuring and reporting the response of an individual soil parameter to a given perturbation or management practice is no longer sufficient. The soil resource must be recognized as a dynamic living system that emerges through a unique balance and interaction of its biological, chemical, and physical components. We encourage SSSA members to consider the concept of soil quality (perhaps as a marketing tool) and to debate how it might enable us to more effectively meet the diverse natural resource needs and concerns of our rural, urban, and suburban clientele of today and tomorrow.

INQUIRIES from policymakers, natural resource conservationists, scientists, and administrators regarding the concept of soil quality increased rapidly after the National Academy of Sciences published the book entitled *Soil and Water Quality: An Agenda for Agriculture* (National Research Council, 1993). In response, Dr. L.P. Wilding, 1994 president of the SSSA, appointed a 14-person committee (S-581) with representatives from all divisions. Appointees were asked to define the concept of soil quality, examine its rationale and justification, and identify the soil and plant attributes that would be useful for describing and evaluating soil quality.

The SSSA president and members accepting this committee appointment recognized the emotion and high public visibility being attached to the subject. Simultaneously, several committee members were being asked to provide information to groups within the Natural Resources Conservation Service, to congressional staff and others at meetings such as "Soil Quality: The State of the Science – A 1995 Farm Bill Forum" sponsored by the Soil and Water Conservation Society, to the Forest Service (specifically through the "Montreal Process", where indicators of sustainability for temperate and boreal forests were to be established), to the U.S. Environmental Protection Agency, and to leaders within the Society for Range Management (where guidelines for assessing rangeland health were being formulated). Based on this demand for information and the fact that soil is a complex medium that must be understood at many levels, it appeared that members of the SSSA should engage in dialogue concerning the concept of soil quality. The primary goal for this essay is to bring the topic of soil quality forward for active discussion and debate by members of the SSSA.

This essay does not represent a final statement on soil quality for the SSSA, but was written to encourage more dialogue among our members. Defining soil quality and identifying appropriate criteria and methods for evaluating it with respect to various soil functions will be an evolving process. Soil quality, like sustainable agriculture, appears to be a high-profile issue that, by its very nature, evokes human emotions and value systems. While uncomfortable for some, the concept of soil quality is reflective of the challenges that lie ahead for professionals in organizations such as the SSSA. We encourage the SSSA members to respond to issues raised by this report.

Soil Quality Perceptions

To some, the concept of soil quality seems unnecessary and redundant among the soil science profession. After all, "everyone" knows what constitutes good soil and where good soils are found. To others, quantifying soil quality is impossible because of "natural differences" among soil orders and even between the same soil series found in different places. One reason for these opinions is that the process of evaluating soil is not new. As noted by Warkentin (1995), evaluations for crop growth appear in the first written literature and certainly predate those records. Keen (1931) reported on studies made with regard to draft requirements for tillage and the fitness of soils as seedbeds for crop production. Productivity indices based on plant-available water capacity, bulk density, acidity, and a factor for plant root distribution were developed (Pierce et al., 1983, 1984) and used to evaluate soil erosion effects on crop productivity throughout the Midwest.

To facilitate the use of soil maps and classification information, soil survey interpretations have been written to predict the behavior of each soil under defined situations. Examples include productivity estimates for rural land appraisal; suitability ratings for crop production with or without drainage; suitability for highway subgrade or

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building sites; and estimates of erosion hazard, permeability to water, and water storage capacity (Kellogg, 1955; Klingebiel, 1991). In California, the Storie and Land Inventory and Monitoring indices used soil survey interpretations to define and protect "prime farmland" (Singer, 1978; Reganold and Singer, 1979, 1984). However, soil survey interpretations and guidelines are not the same as soil quality evaluations, primarily because the former fail to address most biological components of soils.

General concern about soil resources is not new. Lowdermilk (1953), stated that, "if soil is destroyed, then our liberty of choice and action is gone, condemning this and future generations to needless privations and dangers". He went on to say that it is the responsibility of the nation to protect the physical body of the soil resource, while it is the landowner's or manager's responsibility to protect attributes such as its fertility. Hillel (1991) began by recognizing that soil and water resources are so commonplace and seemingly abundant that society treats them contemptuously with terms like "dirty", "soiled", "muddled", and "watered down". With such emotion attached to the soil resource, it is not surprising that many highly visible groups around the world are asking similar questions under the headings of soil quality, soil health, soil care, soil resiliency, and sustainable land management.

Some people have suggested that soil quality is simply related to the quantity of crops produced. Others have emphasized the importance of demonstrating how soil quality affects feed and food quality (Hornick, 1992), or how soil quality affects the habitat provided for a wide array of biota (Warkentin, 1995). This illustrates the breadth of ideas we have encountered while examining soil quality primarily in relation to agricultural production. Numerous other aspects associated with the living and dynamic nature of soil will undoubtedly be encountered if the concept is assessed with regard to soils that are supporting forest and rangeland ecosystems, soils that are used for remediation of urban and industrial by-products with various contaminant loads, or for soils affected by mining, smelting, or refining industries, landfill operations, ecosystem preservation, or development of recreational opportunities. Because of the diversity in potential land uses, we suggest that soil quality evaluations should be viewed as relational rather than absolute. This recognizes that soils are different and that for a specific function, the quality of soils can be different without necessarily being limiting.

A relational approach for resource evaluation was also advocated by Aldo Leopold, in his book *A Sand County Almanac*. He suggested that land evaluations should be based on the number and type of plant or animal species inhabiting that land (Steinhardt, 1995). Leopold's assessments differed from traditional methods of rating soils because he accounted for several different factors and considered the total impact of management practices and land uses on the environment. Thomas (1991a) also favored multifactor evaluations and advocated community studies rather than those focused on indicator species when evaluating the ecology of old-growth forests.

Another perception of soil quality encountered by the committee was that related to the intrinsic value of soil. This perception focuses primarily on the unique and irreplaceable characteristics of soil resources, apart from their value for crop growth, land use, or ecosystem function. Assigning intrinsic value to soil is not widely explored by professional soil scientists or included in economic models of resources. However, intrinsic values associated with many natural resources, including soil, are held in various forms by naturalists and people who see a special relationship with the earth (Warkentin and Fletcher, 1977; Warkentin, 1995). We suggest that discussion by the SSSA is also warranted to address issues related to the intrinsic soil quality supporting natural ecosystems and with regard to the characteristics that meet user requirements for managed or fabricated agro- or urban-ecosystems.

Rationale for Addressing Soil Quality

With such varied perceptions of soil quality, what has brought the concept forward for public debate? One reason is that conservationists, clergy, scientists, and politicians have written thought-provoking articles (Gibbons and Wilson, 1984; Bhagat, 1990; Hillel, 1991; Sagan, 1992; Gore, 1993) that raised public concern regarding the sustainability of all natural resources. What has prompted these articles? One suggestion is that although post-World War II agricultural development was highly successful and resulted in dramatic yield increases that enabled farmers to feed more people than ever before, conservation efforts to protect soil resources were not always given appropriate attention and practices were often not adopted without legislative requirements such as cross-compliance.

With regard to post-World War II agriculture, Pesek (1994) stated that "technological fixes" worked to produce more food, feed, and fiber, but everyone associated with agricultural expansion was so caught up in change that side effects were not always noticed and experimentally unverified conclusions were sometimes drawn. Soil and crop management practices were rapidly adopted without recognizing consequences on long-term productivity and environmental quality (Doran et al., 1996). Off-site impacts including sedimentation of streams, rivers, lakes, and road ditches, loss of habitat for wildlife, appearance of pesticides and increased N and P concentrations in our water resources (National Research Council, 1993), and contamination by urban and industrial by-products were often overlooked. Cline and Ruark (1995) suggested that the neglect of such issues may reflect humankind's incomplete understanding of ecosystems. This may also explain why humankind is not capable of "controlling" natural systems, including soils, and understanding all of their functions.

The SSSA is well suited to address a concept such as soil quality because of its exemplary research and education record in soil physics, chemistry, biology, biochemistry, pedology, fertility, mineralogy, and plant nutrition. Members of the SSSA also have a very good understanding of the functions that soils perform in crop, forest, range, wetland, and urban ecosystems. The concept of soil quality could be used to increase collaborative efforts among soil science disciplines, and to synthesize available information into functional and proven practices that are readily available and useful to land managers and decision makers. For applications related to urban ecosystems or for contaminated soils, soil quality assessments may help identify knowledge gaps and critical research needs.

Defining Soil Quality

As stated in the June 1995 issue of *Agronomy News*, the simplest definition for soil quality is "the capacity (of soil) to function". An expanded version of this definition presents soil quality as "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." During the committee's deliberation it was suggested that "capacity" be replaced with either "ability" or "fitness". The use of "fitness" was criticized during the review process for this essay because in biology "fitness" has a well-recognized meaning – the measure of niche spaces taken up by the offspring of an individual. This experience illustrates how communication, specifically what would seem to be a relatively simple choice of words, can result in very different messages when delivered to our clients. It also demonstrates why conceptual topics such as soil quality warrant more discussion among members of the SSSA.

The proposed definition for soil quality was thought to be similar to those suggested by Acton and Gregorich (1995), Doran and Parkin (1994), and Larson and Pierce (1991). The S-581 committee was also willing to accept a protocol similar to that in the Canadian report entitled "The Health of Our Soils" (Acton and Gregorich, 1995), in which, with respect to agriculture, the terms *soil quality* and *soil health* are used interchangeably to mean "the soil's fitness to support crop growth without becoming degraded or otherwise harming the environment".

Surveys by Romig et al. (1995) supported using soil health and soil quality interchangeably. They found that farmers favored soil health and characterized it based on descriptive and qualitative properties by using direct value judgements (unhealthy to healthy), while scientists favored soil quality because of their focus on the analytical and quantitative properties of soil and the quantitative linkages between those properties and various soil functions. During the review process, however, the committee encountered strong opinions that *soil health* and *soil quality* should not be used interchangeably. This led the committee to conclude that more active debate by the SSSA members was needed to distinguish between these two terms.

Our recommendation is that soil quality should be evaluated based on soil function (Doran et al., 1996). By focusing on how well a specific soil functions within a defined ecosystem, the concept of soil quality can be used as a bridge between the interests and concerns of our rural, urban, and suburban clientele. For example, when evaluating soil quality with regard to partitioning water flow and storage within the environment (Larson and Pierce, 1991, 1994), issues related to both quantity and quality of surface water and groundwater resources can be addressed. Water that runs over the soil surface, whether from rainfall or irrigation, can carry sediment and potential pollutants into drainage areas. This can have both on-site and off-site impacts that affect many different groups of people. Water that infiltrates, in the absence of excessive nutrient or contaminant loads, supports biological productivity and is generally purified before contributing to groundwater recharge or returning to the surface as base flow. Therefore, when examined as part of an ecosystem, soil quality assessments provide an effective method for evaluating direct and indirect environmental impacts of human management decisions.

Evaluation of Soil Quality

A conceptual framework for evaluating soil quality is provided in Fig. 1. This framework illustrates that soil quality can be evaluated at several different scales. It also recognizes that soil quality can be viewed in two distinct ways: (i) as an inherent characteristic of a soil, or (ii) as the condition or "health" of the soil. Inherent soil quality is governed by soil-forming processes. As a result, each soil has a natural ability to function. This inherent characteristic can be defined by a range of parameter values that reflect the full (ideal) potential of a soil to perform a specific function. The second method for evaluating soil quality assumes that if a soil is functioning at full potential for a specific land use (perhaps through adoption of "best management practices"), it has excellent quality; whereas, if a soil is functioning well below its potential, it can be concluded to have impaired or poor quality. Implicit in this assumption is that ecosystem processes are understood well enough that the system is truly sustainable. For this situation, soil quality assessments require measuring the current state of an indicator and comparing the results to known or desired values. This approach can also be used to follow temporal trends associated with specific land-use decisions.

The common theme within the framework (Fig. 1) is that, regardless of scale, the two primary questions that must be answered are (i) how does the soil function, and (ii) what indicators are appropriate for making the evaluation? After answering those questions, a range of parameter values that indicate a soil is functioning at full potential can be developed using landscape characteristics (Pennock et al., 1994), knowledge of pedogenesis, and a more complete understanding of the dynamic processes occurring within a soil. The potential values can be represented in simple ranges, scoring functions (Karlen et al., 1994a), or fuzzy logic membership groups (Mays et al., 1995).

Within the conceptual framework, "point scale" evaluations of soil quality would be made primarily at a subdisciplinary level. Soil function would be defined in terms of physical, chemical, or biological properties and processes. For example, soil quality parameters that might be used to evaluate how well a specific soil accepts, retains, and transmits water to crops could include measurements of soil structure, pore space size and distribu-

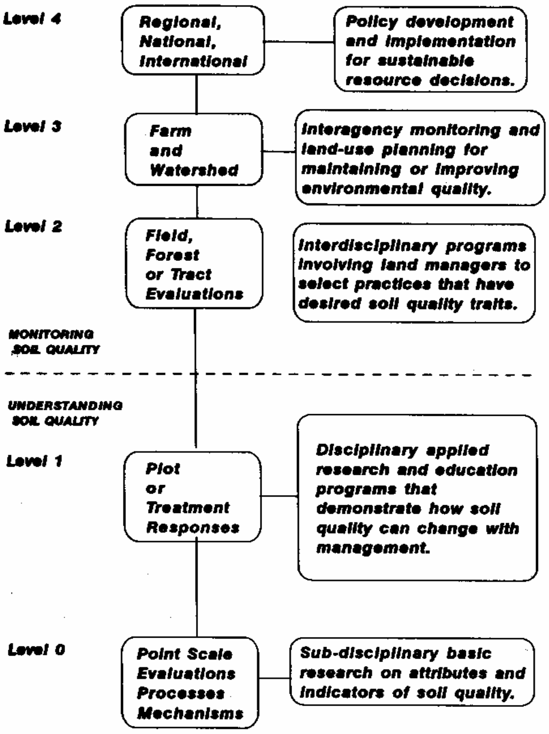

Fig. 1. Multiple scales for soil quality evaluation.

tion, aggregate stability, saturated hydraulic conductivity, particle bonding, or retention mechanisms. Chemical properties important for a soil used for waste renovation might include exchange capacity, pH, C content, and adsorption capacity. Biological indicators of soil quality for the function of sustaining plant growth might include parameters such as microbial biomass and/or respiration, mycorrhizal associations, nematode communities, enzymes, or fatty-acid profiles.

Depending on the function for which an assessment is being made, trade-offs among the nearly infinite list of parameters can be made. The consistent part of the framework is that, regardless of the property or process being evaluated, it must (i) somehow influence the function for which the assessment is being made, (ii) be measurable against some definable standard, and (iii) be sensitive enough to detect differences at the point scale in time and space. At the point scale, soil quality can be described through traditional disciplinary lines of investigation and integrated into an overall assessment of soil quality for a very specific set of conditions. This may be useful for establishing "full-potential" values for a specific soil, but it may be more realistic to develop the full-potential values for groups of soils. At the point scale, however, transferability of information will be restricted to sites having similar biological, chemical, and physical conditions.

Table 1. Selected indicators of soil quality and some processes they impact.

Measurement	Process affected
Organic matter	Nutrient cycling, pesticide and water retention, soil structure
Infiltration	Runoff and leaching potential, plant water use efficiency, erosion potential
Aggregation	Soil structure, erosion resistance, crop emergence, infiltration
pH	Nutrient availability, pesticide absorption and mobility
Microbial biomass	Biological activity, nutrient cycling, capacity to degrade pesticides
Forms of N	Availability to crops, leaching potential, mineralization and immobilization rates
Bulk density	Plant root penetration, water- and air-filled pore space, biological activity
Topsoil depth	Rooting volume for crop production, water and nutrient availability
Conductivity or salinity	Water infiltration, crop growth, soil structure
Available nutrients	Capacity to support crop growth, environmental hazard

"Plot-scale" evaluations of soil quality would probably also be conducted with a disciplinary focus, although cross-disciplinary interaction may be more useful for identifying soil function within larger systems. Critical soil functions could be defined with respect to issues like tillage response, plant productivity, or capacity for biosolid application. Appropriate physical, chemical, and biological parameters would need to be selected, measured, and interpreted, using somewhat less precise but more generalizable information that might be extrapolated from several different point scale evaluations. The plot scale is also where adjustments of full-potential values would have to be made with regard to soil function for different land uses and with regard to a particular soil in a specific environment. For example, nutrient cycling and supply requirements are much different for intensive corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production than for semiarid grazing lands, forest ecosystems, or urban land uses.

During the past 4 yr, the plot scale is where most of the experience in attempting to evaluate soil quality has been obtained. Karlen et al. (1994a,b) assessed the long-term effects of three tillage practices and three crop residue management strategies on 23 potential soil quality indicators. The data were interpreted or "scored" based on published data or expert opinion, and a simple index was used to evaluate soil quality based on four critical soil functions: (i) accommodating water entry; (ii) retaining and supplying water to plants; (iii) resisting degradation; and (iv) supporting plant growth. Each measurement was assigned to one or more of these functions based on general relationships between measurements and processes (Table 1). This assessment showed that use of no-tillage or applying supplemental crop residues in the non-glaciated Major Land Resource Area (MLRA) 105 could improve soil quality compared with more intensive tillage practices or removal of crop residues. Differences in soil quality were documented by rainfall simulation studies that showed less soil loss from no-till than plowed treatments (Karlen et al., 1994b). Corn yield, which averaged 13.0, 12.0, and 11.7 Mg ha^{-1} in 1994 for the previous double-residue, normal-residue, and residue-removal treatments, respectively, showed that effects of the management practices were still evident 4 yr after tillage and crop residue management treatments were terminated.

Rangeland soil quality was evaluated by Manley et al. (1995), who found that after 11 yr of grazing, soils had higher amounts of C and N in the surface 30 cm than in native rangeland where livestock were excluded. The results indicated that grazing mixed-grass prairie did not detrimentally affect soil organic C and N levels and suggested that soil quality was actually improved because of greater opportunities for plant residue incorporation on grazed lands and for less loss through oxidation.

Soil quality assessments were also used to evaluate the effects of alternative cropping systems that were designed to compare the use of animal manure, legumes, and green-manure crops, with "conventional" practices that used inorganic fertilizers and pesticides to support crop production (Doran and Werner, 1990). This eastern USA study showed little difference in chemical and physical indicators of soil quality such as soil organic C, electrical conductivity, pH, or bulk density. Soil respiration, faunal populations, and infiltration rates indicated higher biological activity with organic management systems than with conventional practices (Werner and Dindal, 1990). The magnitude and importance of microbial biomass N, potentially mineralizable N, and soil NO_3–N varied temporally and with management practice (Table 2). The organic system with a winter cover crop had higher levels of microbial biomass and potentially mineralizable N, but lower levels of NO_3–N in early spring (10 April). With regard to the soil functioning to protect the environment by decreasing the potential for NO_3–N leaching, this was interpreted to indicate an improved soil quality. However, the trade-off was that the higher residue cover and lower potential N leaching losses during the non-growing season resulted in lower available N, which was a potential limitation with regard to the soil functioning for corn production.

Table 2. Effects of alternative cropping practices on selected soil quality indicators measured for the surface 30 cm of a Comly silt loam (Typic Fragiudalf) with <5% slope (after Doran et al., 1987; Doran and Werner, 1990; Werner and Dindal, 1990).

		Organic-based crop rotation		
Indicator	Sampling time	Animal manure	Legume cover crop	Conventional fertilizer and pesticides
Organic C, Mg ha^{-1}	April	59	70	61
Conductivity, dS m^{-1}	May	0.15	0.11	0.13
pH (0.01 M $CaCl_2$)	June	5.8	5.9	6.3
Respiration, kg C ha^{-1} d^{-1}	June (lab)	38	35	28
Infiltration, cm min^{-1}	June (lab)	3.8	3.8	2.4
Earthworms, kg ha^{-1}	1 June	10	20	0
	1 July	120	70	60
	28 July	440	70	60
Collembola, 1000 m^{-2}	1 June	4.0	10.0	1.5
	1 July	10.5	12.5	6.5
Biomass N, kg ha^{-1}	10 April	83	121	92
	15 May	52	113	56
	12 June	74	75	64
Mineralizable N, kg ha^{-1}	10 April	1010	1260	990
	15 May	1010	1260	950
	12 June	1000	1180	990
NO_3–N, kg ha^{-1}	10 April	52	9	42
	15 May	91	39	56
	12 June	113	142	83

These examples illustrate the interdependence among soil quality indicators, and the goals established for problems being addressed. Quantifying the critical relationships, relating them to alternative management strategies, and defining tradeoffs among all factors are examples of how soil quality assessments could be used. Although soil quality cannot be measured directly, it serves as an umbrella concept for examining and integrating relationships and functions among various biological, chemical, and physical parameters that are measured and important for sustainable agricultural and environmental systems.

Field-, farm-, and watershed-scale evaluations of soil quality (Fig. 1) require a transition from an experimental mode that contributes to an "understanding" of soil quality to more interdisciplinary "monitoring" approaches. This transition requires an interdisciplinary approach and is where the application of existing information and identification of applied knowledge gaps accelerates. Soil quality assessments at this scale are more likely to involve actual land managers and decision makers working in cooperation with research and education professionals. This level of investigation will more likely assess soil quality using criteria similar to that given by the National Research Council (1994) for evaluating rangeland health (Table 3).

The need for regional, national, and international assessments of soil quality has also been identified (Granatstein and Bezdicek, 1992; Sanders, 1992). At this level, however, soil quality assessments are often incorporated into overall land quality or sustainable land use issues (Blum and Santelises, 1994). The indicators still reflect physical, chemical, and biological processes, but assessments must be made using very broad and generalized perspectives (Fig. 1). This level of assessment, however, is where policy decisions are made, and thus provides a tremendous challenge for research and education professionals.

Table 3. Potential soil quality indicators and criteria for evaluating rangeland health (adapted from National Research Council, 1994).

Phase	Criteria	Indicators
Soil stability and watershed function	Soil movement by wind and water	A horizon present Rills and gullies Pedastaling of plants Scour or sheet erosion Sedimentation or dunes
Distribution of nutrients and energy	Spatial distribution of nutrients and energy	Plant distribution Litter distribution and incorporation Rooting depth Photosynthetic period
Recovery mechanism	Plant demographics	Age class distribution Plant vigor Germination and presence of microsites

Research and Education Needs

To further our understanding and evaluation capabilities with regard to soil quality, research and education are needed to identify appropriate parameters and protocols for combining measurements into meaningful index values at various scales. Efforts to develop a systems approach are needed to integrate the basic knowledge of soil science into solutions for natural resource problems. A systems approach is important for soil quality assessments because numerous interactions and trade-offs must be considered when trying to meet diverse societal goals such as enhancing water quality, sustaining productivity, ensuring food quality, increasing biodiversity, and improving recreational opportunities. Innovative landscape or agroecosystem approaches as described by Peterson et al. (1993) are needed to facilitate basic research, and if used within management projects can be effective for education and technology transfer among researchers, land managers, and decision makers.

Quantitative baseline information related to various soil functions must be obtained and made readily available through public databases. Since research and demonstration projects cannot be conducted at every possible site, simulation models will be needed to predict and verify whether a soil is being aggraded or degraded. This application, however, requires care to ensure that predictions are not extended beyond the precision of original or baseline data (Thomas, 1991b). These soil quality research needs provide further evidence that long-term research is the only way to obtain the information necessary to evaluate the sustainablity of agriculture (Jenkinson, 1991) or any other land use practice.

SUMMARY AND CONCLUSIONS

The concept of soil quality is emotional and evolving, and has high public visibility. This essay was written to share the perspectives of a 14-member SSSA committee. It is not a final statement on behalf of the SSSA, but is intended to provide a focal point for further discussion.

Addressing soil quality will require soil scientists to use their knowledge to identify the critical functions that soils preform within and across ecosystems. New methods to measure how well different soils and similar soils with different initial conditions function will be required. Stimulated by the National Research Council report entitled *Soil and Water Quality: An Agenda for Agriculture*, the soil quality concept provides members of the SSSA an opportunity to openly discuss the complex problems brought to us by our rural, urban, and suburban clientele. We suggest that SSSA members should examine the concept, enter into active dialogue to address many of the questions raised, and determine how it might impact their research, education, and outreach activities.

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