Strategies and Perspectives for Soil Quality and Sustainability

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Abstract
Soil science is in transition from a paradigm that was driven by a short-term goal of maximum crop yield to one driven by the need to assure the long-term soil functions necessary for healthy ecosystems. During this transition, soil structure, which determines the habitat for soil biological processes, is being emphasized over chemical processes. Concerns for soil quality are changing from pollutants in soils to the buffering function of soil, to the advantages of soil variability, to concepts such as the degrees of freedom in uses of soils, and to an antidegradation policy for soils. Compartmentalized thinking about soils, based on the present divisions of soil science, is giving way to planning based on integrating concepts of soil functions. Organization of soil science research and teaching are reflected in the changes in the comprehension of, and planning for, sustained use of soils.

Introduction

The discipline of soil science has been a secondary player in developing concepts and in conducting experimental studies on soil quality. This is now changing as soil science goes through a transition from concerns about measuring inputs required for maximum crop production to a paradigm that focuses on soil processes necessary for healthy ecosystems. Soil has, in the past, been considered almost as an inert medium to which inputs of energy were added to maximize an economical crop yield; research was on the annual effects of these inputs. The subsidies provided by society for different energy inputs made this a very productive system in the short run. However, questions about soil quality, the resulting quality of crops growing in the soils, and the relation of food quality to human health require that we take a broader view of the functioning of soils. This paper will explore some of the past perspectives in soil science and then examine how these perspectives might change in the future.

Soil Quality and Sustainability

Sustainability has been a question of keeping the soil in place. The emphasis in soil conservation has been on physical structures to control erosion; recently, soil management technologies have become a larger component. Sustainability also requires maintaining those processes necessary for soil to perform its functions in an ecosystem (Table 1). Sustainability is not necessarily an equilibrium, but it is a continuing adjustment to changing environmental conditions (Castle, 1993).

Table 1. Elements of Sustainability for Soil Quality.

Keeping soil in place
erosion control
Keeping soil processes functioning
habitat provided by soil structure
biological activity
biochemical cycles

The fundamental characteristics necessary to maintain soil quality include habitat and biological processes (Table 2). The property most difficult to specify is soil structure, the system of stable, interconnected pores that allows the biological processes to occur. This is the concept of soil tilth. The system provides water, air and nutrients in solution. Different niches within the soil provide these requirements in different proportions to suit the needs of different organisms.

Table 2. Soil Properties Fundamental for Soil Quality.

Structure
Soil surfaces and interfaces
Buffering against rapid change

Interfaces present unique environments because they combine two or more habitat characteristics. The solid surface of soil particles is the site for adsorption of organic and inorganic constituents, as well as a place for microbial cells to adhere. Some adsorption forces are due to electrical charges, others are less specific. Beyond the surface is an aqueous environment that contains soluble nutrients and energy sources. At the liquid/air interface, oxygen is available and an easy exchange of carbon dioxide and other gases is possible.

The third important soil property that defines habitat is the buffering action against rapid changes in temperature, water content, pH, or nutrient content. At the soil surface the variation in temperature and water content can be large. At 10 cm or more below the surface, decreases in water content below the plant wilting point are small, and microorganisms are able to adjust; the daily temperature variation is also small. Changes in concentration of the soil solution are relatively slow unless large amounts of soluble materials are added to the soil. The relative stability in the habitat is important for optimum growth and metabolism of microorganisms.

The examination of fundamental soil properties leads to the identification of soil quality parameters required for sustainability (Table 3). The biological habitat includes the habitat for microorganisms that are responsible for many soil processes, and the habitat for root growth, development and function. Root proliferation is required to take advantage of the nutrients released in soil cycles. This involves a pore size distribution with a sufficient number of large pores, and an intermediate soil strength that allows roots to expand by moving soil particles but also provides anchorage for the shoots.

Table 3. Soil Quality Parameters for Sustainability.

Quality of biological habitat
root growth
organisms responsible for decomposition and recycling
Soil interaction with water
erosion
water quantity
water quality
Ability to neutralize contaminants

The second major parameter for sustainability relates to the interaction of soil with water. Water erosion is one aspect; soil must remain in place in order to be sustainable. The quantity of water available is determined by interactions at the surface. Low infiltration results in greater runoff and less water entering the soil. The interaction of soil with water provides soluble components and sediment, which are the important parts of water quality.

A third soil quality parameter is the ability to neutralize contaminants added to soils. For example, the neutralization may be through decomposition of an added organic molecule, through precipitation of added soluble inorganic ions, or through reduction/oxidation reactions that decrease the toxicity of the contaminant.

Changing Paradigms in Soil Science

We now need to look at how soil science has viewed soil sustainability. In looking to the future, it is instructive to understand what has happened in the past. What we find is not a linear progression but rather periods of time in which particular paradigms were generally recognized. These paradigms reflected general attitudes about natural resources and their management. Winter (1989) has pointed out that the beginning of this century was a period in which the main concerns were access to resources and application of technology to provide economic returns from resource use. This was followed by a period in which waste or pollutants were recognized, but were considered a necessary part of most activities; the concern was largely in cleaning up the environment or in disposing of the pollutants after their production. We are now entering a new era where production processes are being modified to produce less waste and fewer undesirable external effects. Rather than cleaning up after the production of goods and services, processes will be designed that do not produce wastes. This is the essence of sustainable development.

Equivalent changes are found in soil science thinking. We are leaving a period of concern with the economics of inputs for crop production and entering a period of concern for the biological processes that occur in soils and that provide alternatives to high energy inputs. In this transition, we realize that we do not know very much about the biological system, and this has led us to an examination of the discipline of soil science. We realize we do not have the answers because the questions have not been asked. Different questions have been asked at different times in the history of the discipline (Warkentin, 1992).

Before 1850, some ideas for soil management came from scientific studies, but more of them came from practitioners (Table 4). Practitioners, many of them gentleman farmers, would meet regularly to exchange information. Papers were presented on modifications that they had made on equipment, tillage, crop rotations, and rejuvenation of worn-out soils.

Table 4. Changing Ideas in Soil Science.

Before1850	General and holistic knowledge developed by practitioners
1850 - 1910	Experimental soil science from laboratory and field
1910 - 1940	Soils and landscapes
1940 - 1980	Soils as inputs to crop production
1980	Soils mediating global processes

The holistic view of soils and soil management gave way to detailed studies of soil characteristics. The publication in 1840 of von Liebigs' book on mineral nutrition of plants was a turning point in the study of soils. Questions were asked about specific soil characteristics, and either water or fertilizer requirements for different crops. Modern agricultural experiment stations with field and laboratory research facilities were developed after 1850. By 1910 many of the basic physical and chemical soil properties had been elucidated from analytical experiments and described in specialized journals. Biological studies of soils came later in this period, but they were not strongly developed.

The first half of the 1900s saw the return of a broader view of soils. Soil mapping and classification were developed during this time as were soil conservation and erosion control methods. Suitability of different soils and different climates for different crops was a common theme during the early part of the century.

After the 1940s, large research resources were applied to single factor studies. Good information was obtained on the inputs that could be added to soils for maximum annual crop production. Soil processes and functions were of secondary interest. This period ended with the realization of the importance of soils in ecosystems. Questions were asked about the role of soils in the global carbon balance and why small amounts of pesticides that were strongly adsorbed onto soil particles were being detected in groundwater. These questions made it necessary to look much more closely at the pore size distribution and flaxes of materials in soils as well as the biogeochemical cycling in soils. The emphasis became focused on processes rather than on the static properties of soils.

An example of this change is how diversity is considered. Soil variability was considered as a nuisance during the period of emphasis on crop production. Field experiments were replicated to take out the natural variability effect. Statistical procedures were developed based on the assumptions that variability was random, and that soil characteristics were normally distributed about a population mean. Now diversity is considered a strength of natural soils; the niche habitats created by diversity are seen to have specific roles in the soil processes.

Perspectives on Soil Quality

Today we are struggling to achieve a better understanding of soil quality. The older definitions were based on crop production parameters and concentrated on those characteristics that could not be changed readily such as soil depth and water holding capacity. These characteristics rated a soil for potential crop production. New perspectives require that soil quality parameters measure habitats and include biological processes.

Table 5, adapted from Warkentin and Fletcher (1977), summarizes our changing concepts of soil quality. We are leaving the period where the central concept was suitability for crop production or suitability of soils to withstand loads from engineering structures. The criteria for quality was required energy inputs; a soil of higher quality required fewer energy inputs of fertilizer, irrigation water, or tillage. Also, we are leaving the period where soil quality was inversely related to soil pollution. A soil contaminated by oil spills, heavy metals or salt accumulation could not meet the desired uses and hence had a lower quality: the criterion of quality was the cleanup cost. For relatively small volumes of contaminated soil, such as from oil spills or near hazardous waste sites, the approach was to remove the soil to a landfill or dump. The new approach is to encourage soil processes of decomposition by creating the habitat requirements for microorganisms that degrade the petroleum components.

Table 5. Changing Concepts of Soil Quality.

Quality Concerns	Criteria for Quality
Suitability for crops, or for bearing loads	Energy inputs required
Contamination	Cleanup costs
Quality of crops	Human and animal health
Functions of soil in ecosystems	Range of uses, degrees of freedom for uses
Intrinsic value of soil	Irreplaceability and uniqueness

Soil quality that is defined by quality of crops which determines human and animal health is not a new concept, but it is gaining recognition as we think more broadly about connections to nutrition. We are now trying to define a concept of soil quality that is based on soil function in an ecosystem. The criteria could be the range of functions or the degrees of freedom for uses of the soil. These functions are limited by soil structures that determine habitat such as surfaces, and pore size distribution; by mineral and organic components that determine the nutrients available for release during decomposition; and by environmental factors such as temperature and water.

There are also continuing ideas about intrinsic value of soils where the criteria could be irreplaceability and uniqueness. The ideas have been developed by Leopold (1966) and in writings in the social sciences that examine the ethical dimensions of land use. Some are found in land classification systems that recognize the uniqueness of soils.

Strategies for the Future

The strategies for maintaining soil quality, Table 6, revolve around the central question of how the natural processes in soils are enhanced. Soil degradation studies are recognized as an important part of soil science. Some soils have been stressed beyond the limit of quick recovery. Stress in soils is not easily recognized because of the strong buffering activity. Changes are incremental and small, and they are difficult to detect until large changes have occurred, e.g., sheet erosion. Natural biological processes have adapted to recurring drought cycles, but they may not be able to recover from the additional stresses of soil management systems that accelerate organic matter decomposition. A sustainable system has evolved for regular flooding and drying of soils in paddy rice production, but the inter-actions of upland cropping systems with irregular flooding events are not understood. The degradation stress from heavy machinery on wet soils is difficult to overcome. Soil management systems based on specific water conditions in soils show weaknesses under either wetter or dryer conditions.

Table 6. Strategies for Enhancing Soil Quality.

Understanding and avoiding soil degradation
Managing soil diversity
Land ethics and World Soils Charter
Soil science teaching and research

A second strategy is to learn to manage diversity. This is a shift from energy to knowledge as the main input in soil management. How can we benefit from variability rather than trying to avoid it? Managing variability on a landscape scale leads to the present ideas of farming by landscape position. The conditions for crop growth on a slope are very different at the crest, the mid slope and the toe slope positions. Water, soil chemicals, and soil particles have all moved to create very different environments that need to be managed, differently. On a microscale, we can manage tillage for aerobic and anaerobic niches; we can manage root zones by distances between crop rows. Devising management systems requires more detailed knowledge of soil processes on several scales.

The ideas about land ethics need to be developed into specific soil management guidelines. Should we have an antidegradation policy for soils similar to the antidegradation policy for quality of special water bodies? If so, we must be able to measure soil quality parameters to assure that they do not decrease. These ideas are being developed in activities such as the World Soils Charter which is promoted by the International Society of Soil Science. Soil Protection Acts are being considered in various countries and in some states in the USA. These activities have grown from soil conservation efforts during the past 50 years, but now they include more aspects of soil quality than protection from erosion.

As an academic soil scientist, I am interested in how the changes now taking place benefit from, and in turn drive, changing ideas in the discipline of soil science. Soil physics, soil biology, soil mineralogy, etc., are separate units in professional societies, in research institutes and at the universities, and they are often studied separately. The current need, of course, is to combine these areas. Exciting ideas are coming from studies combining soil physics and soil biology in order to determine habitat and processes for microorganisms. It would, therefore, appear to be useful to organize the discipline of soil science into more functional groups.

I have recently suggested (Warkentin, 1994) four such divisions (Table 7) which are similar to four models for soil science that were suggested by Stone (1975). Scientists with competence in one or more of these areas can work together effectively in crop production, waste management or water quality.

Table 7. Suggested Functional Divisions in the Discipline of Soil Science.

Soil processes - combined bio-, geo-, chemical, physical cycles
Soil surface interaction with water
Soil reactions in the rhizosphere
Soils as natural bodies

And in all this let us not forget the poet's view, that ability to capture in a few words the ideas that motivate people. A fragment from a poem by Sheila Weaver (1987) reads: “ . . . I am soil/ look at ME/ smell me, touch me, feel me/ walk on me with your bare feet/ sing and dance on me/ observe me closely/ . . .as a living, changing, vital link/ in a vast ancient web/ intricate and delicate/ of which YOU too are part. . . I am soil/ nurture me/ plant in me/ shelter me with trees/ rescue me where/ I am thin and worn/ BUT ABOVE ALL/ teach your children. . . to know me/ and to value me."

The plea for this broader perspective on soils can be summarized in a quote from von Humboldt (1850), "In order to comprehend nature in all its vast sublimity, it would be necessary to present it under a two-fold aspect, first objectively, as an actual phenomenon, and next subjectively, as it is reflected in the feelings of mankind."

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