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Soil health and global sustainability: translating science into practice[☆]

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Abstract

Interest in the quality and health of soil has been stimulated by recent awareness that soil is vital to both production of food and fiber and global ecosystems function. Soil health, or quality, can be broadly defined as the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Soil quality and health change over time due to natural events or human impacts. They are enhanced by management and land-use decisions that weigh the multiple functions of soil and are impaired by decisions which focus only on single functions, such as crop productivity. Criteria for indicators of soil quality and health relate mainly to their utility in defining ecosystem processes and in integrating physical, chemical, and biological properties; their sensitivity to management and climatic variations; and their accessibility and utility to agricultural specialists, producers, conservationists, and policy makers. Although soils have an inherent quality as related to their physical, chemical, and biological properties within the constraints set by climate and ecosystems, the ultimate determinant of soil quality and health is the land manager. As such, the assessment of soil quality or health, and direction of change with time, is the primary indicator of sustainable management. Scientists can make a significant contribution to sustainable land management by translating scientific knowledge and information on soil function into practical tools and approaches by which land managers can assess the sustainability of their management practices. The first steps, however, in our communal journey towards sustainable land management must be the identification of our final destination (sustainability goals), the strategies or course by which we will get there, and the indicators (benchmarks) that we are proceeding in the right direction. We too often rush to raise the sails of our 'technological' ship to catch the wind, before knowing from where it comes or in properly defining our destination, charting our course, and setting the rudder of our ship. Examples are given of approaches for assessing soil quality and health to define the sustainability of land management practices and to 'translate our science into practice'. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Interest in evaluating the quality and health of our soil resources has been stimulated by increasing awareness that soil is a critically important component of the earth's biosphere, functioning not only in the production of food and fiber but also in ecosystems function and the maintenance of local, regional, and global environmental quality (Glanz, 1995). Soil

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health has been broadly defined as the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (Doran et al., 1996, 1998). Soil health can change over time due to natural events or human impacts. It is enhanced by management and land-use decisions that weigh the multiple functions of soil and is impaired by decisions that focus only on single functions, such as crop productivity. Thus, balance between soil function for productivity, environmental quality, and plant and animal health is required for optimal soil health. Criteria for indicators of soil quality and health relate mainly to their utility in defining ecosystem processes and integrating physical, chemical, and biological properties; their sensitivity to management and climatic variations; and their accessibility and utility to agricultural specialists, producers, conservationists, and policy makers. Although soils have an inherent quality as related to their physical, chemical, and biological properties within the constraints set by climate and ecosystems, the ultimate determinant of soil quality and health is the land manager. As such, the assessment of soil quality or health, and direction of change with time, is a primary indicator of sustainable management.

1.1. Soil — an essential link in the cycle of life

The sun is the basis for most life on earth. It provides radiant energy for heating the biosphere and for the photosynthetic conversion of carbon dioxide (CO_2) and water by green plants into food sources and oxygen for consumption by animals and other organisms (Fig. 1). Most living organisms utilize oxygen to metabolize these food sources, capture their energy, and recycle heat, CO_2 , and water to the environment to begin this cycle of 'life' again. Decomposition processes, as mediated by organisms in soil, play a predominant role in completing this cycle of life, in recycling of building block nutrients to plants and C as CO_2 to the atmosphere. Thus, the thin layer of soil covering the surface of the earth is a major interface between agriculture and the environment and represents the difference between survival and extinction for most land-based life (Doran et al., 1996). The quality and health of soil determine agricultural

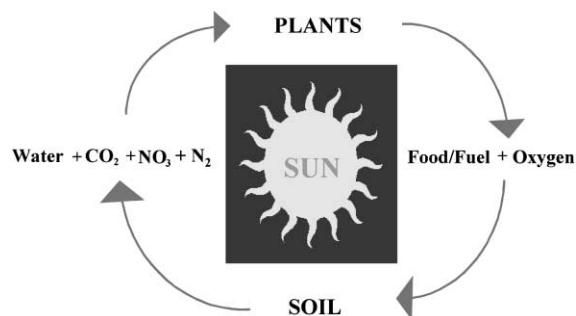


Fig. 1. Simplified version of the "equation of life" illustrating the central role of soil in catalyzing the cycling of C, nutrients, and energy in the ecosphere and interfacing with the environment to optimize the conditions for plant and animal health.

sustainability (Acton and Gregorich, 1995; Papendick and Parr, 1992) and environmental quality (Pierzynski et al., 1994) which jointly determine plant, animal, and human health (Haberern, 1992).

1.2. Threats to global sustainability

Dramatic change has recently occurred in our thinking about agricultural development, our use of natural resources, and stability of the global environment. Even economically undeveloped countries are increasingly more aware and concerned about ecosystem health, the quality of the environment, and rates of resource consumption (Mermut and Eswaran, 1997). Increasing human populations, decreasing resources, social instability, and environmental degradation threaten the natural processes that sustain the global ecosphere and life on earth (Costanza et al., 1992; Postel, 1994). With little new agricultural land to develop, meeting the food needs of future populations will require a doubling of crop yields. However, under current food production practices this will greatly increase inputs into agricultural production systems, thereby vastly increasing opportunity for environmental pollution and degradation and depletion of natural and non-renewable resources (Power, 1996). To sustain agriculture and the world for future generations, we must act now to develop production systems which rely less on non-renewable petrochemical based resources; rely more on renewable resources from the sun for our food, fiber, and energy needs; and achieve the ecological intensification

needed to meet the increased future food demand (Cassman, 1999).

Global climate change, depletion of the protective ozone layer, serious declines in species biodiversity, and degradation and loss of productive agricultural land are among the most pressing concerns associated with our technological search for a higher standard of living for an ever-growing human population. Past management of agriculture and other ecosystems to meet the needs of increasing populations has taxed the resiliency of soil and natural processes to maintain global balances of energy and matter. The quality of many soils in the Americas and elsewhere has declined significantly since grasslands and forests were converted to arable agriculture and cultivation was initiated. In particular, mechanical cultivation and the continuous production of row crops has resulted in physical soil loss and displacement through erosion, large decreases in soil organic matter content, and a concomitant release of organic C as CO₂ to the atmosphere (Houghton et al., 1983). Within the last decade, inventories of soil productive capacity indicate human-induced degradation on nearly 40% of the earth's arable land as a result of soil erosion, atmospheric pollution, extensive soil cultivation, over-grazing, land clearing, salinization, and desertification (Oldeman, 1994). Indeed, degradation and loss of productive agricultural land is one of our most pressing ecological concerns, rivaled only by human caused environmental problems like global climate change, depletion of the protective ozone layer, and serious declines in biodiversity (Lal, 1998). Further, the projected doubling of the human population in the next century threatens accelerated degradation of soils and other natural resources (Power, 1996; Ruttan, 1999). Thus, to preserve agriculture for future generations, we must develop production systems that conserve and enhance soil quality and health. Developing the blueprints for sustainable development, however, will require interaction between society, science, and religious leaders to establish the necessary balance between meeting basic human needs, maintaining environmental stewardship, and achieving intergenerational equity (Bhagat, 1990; Sagan, 1992).

The objectives of this paper are two-fold: (1) to illustrate the intimate linkage between soil health and global sustainability and the critical role of the soil as a major interface with the environment, and (2) to

propose indicators of soil quality and health which are useful tools to land managers in assessing the short- and long-term sustainability of their management practices.

2. Soil quality: indicator of sustainable management

Developing sustainable agricultural management systems is complicated by the need to consider their utility to humans, their efficiency of resource use, and their ability to maintain a balance with the environment that is favorable both to humans and most other species (Harwood, 1990). More simply stated by Tom Franzen, a midwestern farmer in the USA, "a sustainable agriculture — sustains the people and preserves the land". We are challenged to develop management systems that balance the needs and priorities for production of food and fiber with those for a safe and clean environment. Assessment of soil quality or health is invaluable in determining the sustainability of land management systems (Karlen et al., 1997). Soil quality is conceptualized as the major linkage between the strategies of conservation management practices and achievement of the major goals of sustainable agriculture (Acton and Gregorich, 1995; Parr et al., 1992). In short, the assessment of soil quality or health, and direction of change with time, is the primary indicator of sustainable land management.

Although soil's contribution to plant productivity is widely recognized, soil condition also impacts water and air quality. The quality of surface and sub-surface water has been jeopardized in many parts of the world by intensive land management practices and the consequent imbalance of C, N, and water cycling in soil. Agriculture is considered the most widespread contributor to non-point source water pollution in the USA (National Research Council, 1993). The major water contaminant in North America and Europe is nitrate nitrogen, the principal sources of which are conversion of unmanaged land to intensive agriculture, animal manures, atmospheric deposition, and commercial fertilizers. Human alterations of the nitrogen cycle have almost doubled the rate of nitrogen input to terrestrial ecosystems over the past 30 years resulting in large increases in the transfer of

nitrogen from land to the atmosphere and to rivers, estuaries, and coastal oceans (Matson et al., 1997; Socolow, 1999; Vitousek et al., 1997). Soil management practices such as tillage, cropping patterns, and pesticide and fertilizer use influence water quality. In addition, these management practices can influence atmospheric quality through changes in the soil's capacity to produce or consume important atmospheric gases such as carbon dioxide, nitrous oxide, and methane (Mosier, 1998; Rolston et al., 1993). The present threat of global climate change and ozone depletion, through elevated levels of greenhouse gases and altered hydrological cycles, necessitates a better understanding of the influence of land management on soil processes (Bengtsson, 1998).

Scientists make a significant contribution to sustainable land management by translating scientific knowledge and information on soil function into practical tools and approaches by which land managers can assess the sustainability of their management practices (Bouma, 1997; Dumanski et al., 1992). Specifically, assessment of soil quality/health is needed to identify problem production areas, make realistic estimates of food production, monitor changes in sustainability and environmental quality as related to agricultural management, and to assist government agencies in formulating and evaluating sustainable agricultural

and land-use policies (Granatstein and Bezdicsek, 1992). Use of one given approach for assessing or indexing soil quality is fraught with complexity and precludes its practical or meaningful use by land managers or policy makers (Harris et al., 1996). However, the use of simple indicators of soil quality and health which have meaning to farmers and other land managers will likely be the most fruitful means of linking science with practice in assessing the sustainability of management practices (Romig et al., 1995, 1996).

3. Defining strategies for sustainability

In defining sustainable agricultural management practices, Doran et al. (1994) stressed the importance of holistic management approaches that optimize the multiple functions of soil, conserve soil resources, and support strategies for promoting soil quality and health. They initially proposed use of a basic set of indicators to assess soil quality and health in various agricultural management systems. However, while many of these key indicators are extremely useful to specialists (i.e. researchers, consultants, extension staff, and conservationists) many of them are beyond the expertise of the producer to measure (Hamblin, 1991). Also, the measurement of soil quality and

Table 1

Strategies for sustainable agricultural management and proposed indicators of crop performance and soil and environmental health (modified from Doran et al., 1996)

Sustainability strategy	Indicators for producers
Conserve soil organic matter through maintaining soil C & N levels by reducing tillage, recycling plant and animal manures, and/or increasing plant diversity where C inputs \geq C outputs	Direction/change in organic matter levels with time (visual or remote sensing by color or chemical analysis); specific OM potential for climate, soil, and vegetation; soil water storage
Minimize soil erosion through conservation tillage and increased protective cover (residue, stable aggregates, cover crops, green fallow)	Visual (gullies, rills, dust, etc.) Surface soil properties (topsoil depth, organic matter content/texture, water infiltration, runoff, ponding, % cover)
Balance production & environment through conservation and integrated management systems (optimizing tillage, residue, water, and chemical use) and by synchronizing available N and P levels with crop needs during year	Crop characteristics (visual or remote sensing of yield, color, nutrient status, plant vigor, and rooting characteristics) Soil physical condition/compaction Soil and water nitrate levels Amount & toxicity of pesticides used
Better use of renewable resources through relying less on fossil fuels and petrochemicals and more on renewable resources and biodiversity (crop rotations, legumes, manures, IPM, etc.)	Input/output ratios of costs & energy Leaching losses/soil acidification Crop characteristics (as listed above) Soil and water nitrate levels

health does nothing to improve the sustainability of the system under which the soil is managed. In response to this dilemma, Doran et al. (1996) and Doran and Safley (1997) presented strategies for ensuring sustainable management which included generic indicators of soil quality and health which are measurable by and accessible to producers within the time constraints imposed by their normally hectic and unpredictable schedules, as given in Table 1. Note that soil organic matter serves as a primary indicator of soil quality and health for both scientists and farmers (Romig et al., 1995).

Strategies for sustainable management, such as those shown in Table 1, maximize the benefits of natural cycles, reduce dependence on non-renewable resources, and help producers identify long-term goals for sustainability that also meet short-term needs for production. However, successful development and implementation of standards for assessment of soil health and sustainability can only be accomplished in partnership with agricultural producers, who are the primary stewards of the land. Economic survival and viability are the primary goals of land managers, and while most appreciate the need for environmental conservation, the simple fact remains that “it’s hard to be green when you’re in the red” (Ann Hamblin, Ballarat, Australia, April 1996).

4. Translating science into practice

Soil and land management practices are primary determinants of soil quality and health. Consequently, indicators of soil quality and health must not only identify the condition of the soil resource but also define the economic and environmental sustainability of land management practices. The theme of an international conference in Australia, “Soil Quality is in the Hands of the Land Manager,” highlights the critical importance of the land manager in determining soil quality (MacEwan and Carter, 1996). A cotton grower at this conference shared his frustration with the direction soil quality indicators were taking — “I need help from scientists more with tools for management than with indicators of soil quality”. Economic viability and survival are the primary goals of managers of the land, even though most recognize the need for environmental conservation.

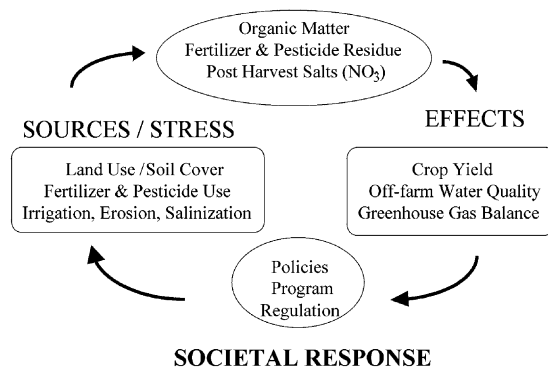


Fig. 2. The politics of soil health. The assessment of soil condition/quality is needed to monitor changes in sustainability and environmental quality as related to agriculture management and to assist governmental agencies in formulating realistic agricultural and land-use policies (Doran and Gregorich, 2002).

Scientists contribute to sustainable land management by translating scientific knowledge on soil function into practical tools with which land managers can assess the effectiveness of their management practices. As illustrated in Fig. 2, assessment of soil condition/quality is needed to identify problem production areas, monitor changes in water and air quality as related to agricultural management, and to assist in formulation and evaluation of realistic agricultural and land-use policies. As mentioned earlier, use of a given approach for assessing or indexing soil quality is fraught with complexity and precludes its practical or meaningful use by land managers or policy makers. However, the use of simple indicators of soil quality and health which have meaning to farmers and other land managers will likely be the most fruitful means of linking science with practice in assessing the sustainability of management practices (Harris et al., 1996; Romig et al., 1996). For example, Gajda et al. (2001) have demonstrated the utility of simplified procedures for assessing soil quality, such as particulate and total soil organic matter by weight loss-on-ignition, in assessing the sustainability of conventional and alternative management systems in the US Central Great Plains.

In an article entitled ‘The greening of the green revolution’ Tilman (1998) concludes that the uncertainties of sustaining a high-intensity agriculture have renewed the search for practices that can

Table 2

Proposed indicators for a simplified approach for assessing the sustainability of agricultural systems at the farm level (after Gomez et al., 1996)

Farmer & society needs, <i>acceptable</i>	Resource & environmental conservation, <i>adequate/acceptable</i>
Yields relative to locale, climate, and soil type	Soil organic matter change with time, relative to local potential
Profits relative net returns & degree of subsidization	Soil depth of topsoil and rooting relative to local potential
Risk/stability economic shortfall in 1 of 5 years	Soil protective cover (%) effective continuous or stratified
Input/output ratio of energy (renewable and non-renewable) and US\$ costs	Leachable salts (NO ₃) at planting and post harvest as indexed by soil electrical conductivity

provide sustainable yields with fewer environmental costs. Since the beginning of agriculture, farmers had countered declines in fertility due to agriculture by manuring fields and alternating crops that increase fertility (such as N fixing legumes) with other crops. In a 15-year research trial in eastern Pennsylvania, Drinkwater et al. (1998) demonstrated that organic management systems, employing animal manure and legumes for N supply were equally as profitable as higher input conventional systems. The organic management systems tended to be more environmentally benign with lower leaching losses of N and higher levels of organic C and N stockpiled in soil. The organic management practices enhanced soil health and supported the major strategies for agricultural sustainability of conserving soil organic matter, minimizing erosion, balancing production with environmental needs, and making better use of renewable resources. Research has clearly demonstrated that initial yield reductions with organic management are more than offset by environmental benefits of soil organic matter buildup and synchronization of N availability with crop needs during the growing season. Research is needed to help agricultural managers assess the sustainability of agricultural management using indicators of soil quality and health to which they have access.

Although much remains to be done, useful models exist for translating soil science into practice. For example, Gomez et al. (1996) provide a unique framework for determining the sustainability of hill country agriculture in the Philippines. It employs indicators that consider both the satisfaction of farmer needs (i.e. productivity, profitability, stability, and viability) and those needed for conservation of soil and water resources. On a given farm, indicators were deemed to be at a sustainable level if they exceeded a

designated threshold level. Specifically, the threshold values for sustainability were identified relative to the average local conditions for crop yield, profit, risk of crop failure, soil depth, percent soil cover, and soil organic matter content. This conceptual framework for assessment of sustainability could be expanded to include other needs of society and environmental conservation as illustrated in Table 2. In particular, adding a category for balancing input and output of energy and monetary costs would better assess the short- and long-term sustainability of management and the value of greater reliance on renewable resources and less dependence on fossil fuels and petrochemicals in enhancing economic, ecological, and environmental resources. Also, expanding the list of resource conservation variables to include leachable salts (especially NO₃), measured as soil electrical conductivity at time of fertilization and after harvest, would permit land managers to better quantify the impact of agricultural practices on air and water quality (Doran, 1997; Doran et al., 1998). Soil electrical conductivity can also be used to conduct an ‘audit of small molecules’ released to the environment, to verify if agricultural management systems enhance sustainability by minimizing system entropy (Addiscott, 1995).

5. Conclusions

The multifaceted and changing nature of sustainability is difficult to define but is aptly captured by a farmer’s simple definition of sustainable agriculture as, “An agriculture that sustains the people and preserves the land.” Modern agriculture has developed into a high technology and high inputs industry that has met the increasing needs of an ever-growing human population. However, this “industrial” system of

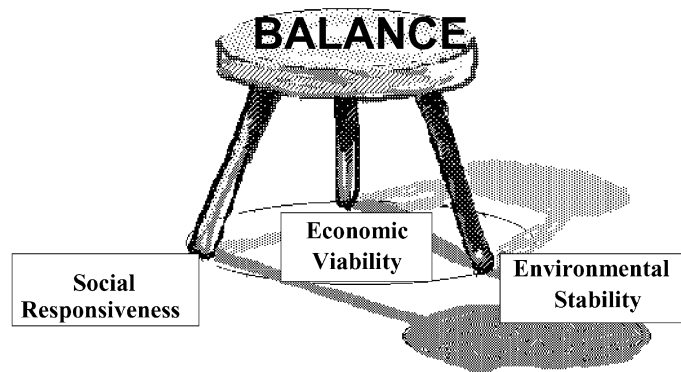


Fig. 3. Agricultural sustainability as analogous to a three-legged stool, the major components (legs) of which must be in balance to achieve long-term sustainability.

agriculture increasingly results in reduced net economic returns to farmers, taxes the resilience of soil, stresses our natural non-renewable resources, and increases the potential for environmental pollution. Continuous monoculture cropping systems and excessive cultivation for seedbed preparation and pest control have led to unacceptable erosion loss of our limited topsoil. Agricultural input alternatives that reduce reliance on non-renewable fossil fuels and petrochemicals, ensure productivity, and maintain the quality of our air, water, and soil resources are badly needed. Soil health and quality indicators, and the changes in those indicators, can be a major link between the strategies of conservation management practices and achievement of the major goals of sustainable agriculture. Confirmation of the effectiveness of systems for residue management, organic matter formation, nitrogen and carbon cycling, soil structure maintenance, and biological control of pests and diseases will assist in discovering system approaches that are both profitable and environmentally friendly. The challenge ahead is to make better use of the diversity and resiliency of the biological community in soil to maintain a quality ecosystem, thus fostering sustainability. One of the greatest challenges for researchers is in “Translating science into practice” through identifying indicators of system performance that are useful to farmers and land managers in assessing the economic, ecological/environmental, and social components of sustainability (Fig. 3). Strategies will then need to be fine tuned using such practices as crop rotation for

greater crop diversity and tighter cycling of nutrients, reduction of soil disturbance to maintain soil organic matter and reduce erosion, and development of systems which make greater use of renewable biological resources. Crop rotation, legume companion crops, and animal manuring practices can reduce reliance on non-renewable fossil fuels and petrochemicals. Ultimately the indicators of soil health and strategies for sustainable management must be linked to the development of management systems that foster reduction in the inputs of non-renewable resources, maintain acceptable levels of productivity, and minimize impact on the environment.

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