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Soil Quality: Relationships and Strategies for Sustainable Dryland Farming Systems

J.F. Parr[1] and R.I. Papendick[2]
[1]International Nature Farming Research Center, Atami, Japan and Bellingham, Washington, U.S.A.
[2]Agricultural Research Service, U. S. Department of Agriculture, Pullman, Washington, U.S.A.

Abstract: The extended concept of soil quality which encompasses the attributes of environmental quality, food safety and quality, and human and animal health, in addition to soil productivity, has been widely accepted in the U.S.A. and abroad. In due course, the indicators of soil quality will need to be properly quantified and weighted according to site-specific conditions. Nevertheless, many scientists now tend to characterize the effects of soil degradative processes and soil conservation practices in terms of the time/rate of change in soil quality. It follows then that soil quality is the linkage or linchpin that bridges the strategies of alternative agriculture and the goals of sustainable agriculture. Thus, soil quality is the real "key" to a more sustainable agriculture. The concept of soil quality and these relationships should provide farmers, researchers, environmentalists, administrators and society as a whole with a better understanding of the challenges ahead, i.e., a) how to increase the productivity of arable/irrigated croplands while maintaining their sustainability and, b) how to increase the agricultural productivity of marginal/drylands without adversely affecting their potential sustainability. These are monumental tasks with problems that will not be resolved by the usual "standardized" research agenda. Rather, it will require new perspectives, innovative thinking, careful planning, and proper organization of both information and people. A vital requisite will be the involvement of scientists, extension agents and farmers working as a team to conduct the necessary research and development, technology transfer, on-farm testing, practical applications and adaptations that will meet these challenges.

Key words: Soil quality, sustainability, drylands, rainfed.

Approximately 40% of the world's land area is comprised of arid and semi-arid regions that are inhabited by more than 700 million people who follow mainly agrarian and pastoral pursuits. Some 60% of these drylands are found in developing countries throughout the Near East, Africa, and Asia. It is noteworthy that farmers in these regions produce most of the world's food grains in dryland or rainfed farming systems including cereals, pulses and oilseed crops. Nevertheless, crop yields under these conditions are very low compared with those obtained in humid and subhumid regions (Parr *et al.*, 1990).

The soils in these dryland regions are frequently described as too "fragile" and "marginal" for sustained crop production because of serious limitations in their characteristics including coarse-texture (i.e., sandy), inherently low fertility, excessive salinity, low organic matter content, shallow soil depth, low water-holding capacity and high susceptibility to wind and water erosion. Indeed, by most taxonomic standards many of these soils would not be classified as arable, i.e., tillable. However, the fact is that these soils are farmed because of an urgent need to produce food for expanding populations and, in so doing, have undergone progressive degradation resulting in soil erosion, nutrient depletion and subsequent loss of soil productivity. The severity of soil degradation can often be attributed to a lack of proper and skilled management practices (Papendick and Parr, 1997). In addition to soil quality limitations exacerbated by degradative processes, climatic factors are particularly difficult to deal with. Rainfall patterns are often erratic and unpredictable throughout the dryland regions, and crops can suffer from moisture deficits and drought even during normal rainfall periods.

The projected food and feed deficits that have been forecast for some countries will have to come from increased yields on established croplands, i.e., both irrigated and dryland, since little new arable land is available for development. For example, in India at the beginning of this decade some 45% of the total crop production came from the drylands. It was estimated then that by the year 2000 this would have to increase to 60% if India is to provide adequate food and fiber for a projected population of one billion people at that time (Indo-U.S. Subcommission Report, 1987; Singh, 1989). The same situation exists in the Near East, Sub-Saharan Africa and in the U.S. drylands of the Great Plains and Pacific Northwest. Throughout these regions there is an urgent need to develop productive, profitable and sustainable dryland farming systems. This can only be done by assigning a high priority for research to improve soil, water and crop management practices for dryland agriculture. Such research has become increasingly important in recent years because of the increased economic costs and environmental impacts associated with irrigated agriculture, the true sustainability of which has been seriously questioned (Steiner *et al.*, 1988; Singh, 1989; Stewart *et al.*, 1990).

This paper discusses the attributes of soil quality and how they relate to the concept of a sustainable agriculture. It also discusses some strategies that are relevant to the development of sustainable dryland farming systems.

Soil Quality: Concept and Definition

The various ways in which soil chemical, physical and biological properties interact will ultimately determine a soil's potential fitness or capability for sustained production of healthy and nutritious crops. The integration of factors that make a soil productive has often been referred to as soil quality. For several decades, the Soil Science Society of America (SSSA, 1984) has defined soil quality as:

> "the inherent attributes of soils which are inferred from soil characteristics

or indirect observations (e.g., compactibility, erodibility, and fertility)''.

This definition has largely and traditionally equated soil quality with soil productivity. Yet, to many of us this definition seemed to be vague and incomplete.

In many countries, including the U.S.A., soils of the dryland regions are being extensively, even irreparably, damaged through such degradative processes as wind and water erosion and salinization, largely resulting from improper farming practices. With soil degradation, there is a concomitant decline in soil quality, i.e., the soil's capacity to produce healthy and nutritious crops, resist erosion, and reduce the impact of environmental stresses on plants. Many decades of research have shown that the best means of improving and restoring soil quality and productivity is by proper and regular additions of organic materials mainly through crop rotations, cover crops, crop residues, animal manures and composts. The adoption of reduced tillage or no-till farming methods helps to prevent the rapid biological decomposition and chemical oxidation of these materials and extends their beneficial effects on soil tilth and fertility over a longer period of time (Papendick and Parr, 1997).

Until recently, there was no scientifically acceptable method or procedure for quantifying and measuring the attributes of soil quality so that the effects of management practices could be evaluated on a field, watershed or regional scale. Many argued that if properly characterized, soil quality should serve as a measure or indicator of the soil's capacity to: (a) produce optimum levels of safe and nutritious plant and animal products, (b) enhance human and animal health, (c) overcome soil degradative processes, and (d) maintain or enhance environmental quality. Consequently, in July 1991, the Rodale Institute Research Center sponsored a workshop on ''Assessment and Monitoring of Soil Quality'' at Emmaus, Pennsylvania. Scientists attending were asked to discuss the concepts and relationships of soil quality, soil health, and sustainable agriculture (Papendick and Parr, 1992; Parr *et al*., 1992). The workshop concluded that:

- Soil quality is the key to a sustainable agriculture.
- Soil quality is directly related to soil degradation. Indeed, soil degradation from various processes can be defined as the time/rate of decline in soil quality.
- Maintenance and regeneration of soil quality are highly dependent on proper and regular additions of organic amendments and on an array of beneficial microorganisms and macroorganisms that it supports.

Soil quality attributes include soil productivity, environmental quality, food safety and quality, and human and animal health.

Based on these conclusions, in 1995 a select committee of the Soil Science Society of America approved a conceptual definition of soil quality (SSSA, 1995) as follows:

> ''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''.

Thus, the official SSSA definition now encompasses the attributes of soil productivity, environmental quality, and human health as major functions of soil quality.

Sustainable Agriculture: Concept and Definition

Sustainable agriculture is increasingly viewed as a long-term goal that seeks to overcome problems and constraints that confront the economic viability, environmental soundness, and social acceptance of agricultural production systems both in the U.S.A. and worldwide. While there are many definitions of sustainable agriculture, most of them encompass the same elements of productivity, profitability, conservation, health, safety, and the environment, differing only in the degree of emphasis. Furthermore, ''sustainable'' implies a time dimension and the capacity of a farming system to evolve and endure indefinitely (Lockeretz, 1988). The Agricultural Research Service (U.S. Department of Agriculture) has defined sustainable agriculture as:

> ''Agriculture that for the foreseeable future will be productive, competitive, profitable, conserve natural resources, protect the environment, enhance public health, and promote food safety and quality''.

The U.S. Congress (1990) offered a similar but more specific definition of sustainable agriculture as ''an integrated system of plant and animal production practices having site-specific application that will, over the long-run:

- satisfy human food and fiber needs,
- enhance environmental quality and the natural resource base,
- make efficient use of nonrenewable resources,
- utilize natural biological cycles and controls,
- improve the economic viability of farming systems,
- enhance the quality of life for farmers and society as a whole''

The driving force behind the sustainable agriculture movement in the U.S.A., and other countries as well, is to minimize the adverse effects of soil degradation that often result from intensive row-crop and monoculture production practices. Thus, according to the National Research Council (NRC, 1989), the ultimate goal of sustainable agriculture is to develop farming systems that are productive and profitable, conserve the natural resource base (i.e., soil and water), protect the environment, and enhance health and safety.

Finally it needs to be understood that sustainable agriculture has three principal components which must be reasonably compatible and in balance before a farming system can be judged as truly sustainable. First, the farming system must be economically sustainable, i.e., the farmer must make a profit; second, it must be environmentally sustainable, i.e., no adverse environmental impacts; and third, the system must have no harmful effects on people or society as a whole from agricultural development, production or marketing.

Table 1. A comparison of alternative and conventional agricultural practices according to the U.S. National Research Council (NRC, 1989)

Alternative Agriculture	Conventional Agriculture
Crop rotations	Monocultures
Reduced tillage/no-till	Intensive tillage
Integrated pest management	Chemical pesticide usage
Nitrogen fixing legumes	Chemical fertilizer usage
Organic recycling	Little organic recycling
Skilled management	Management deficiencies

Alternative Agriculture: Concept and Definition

The term "alternative agriculture" is often used to refer to various alternative production and management practices that many feel are essential to the development of long-term sustainable farming systems. The term really encompasses a number of other terms and definitions that refer to a spectrum of low-chemical, resource-conserving, energy-conserving, and resource-efficient farming methods, for example, "biological", "ecological", "natural" and "regenerative".

According to the National Research Council (NRC, 1989), alternative agricultural practices provide the best means of achieving a more sustainable agriculture, and thus, defined alternative agriculture as:

> "A system of food and fiber production that applies management skills and information to reduce input costs, improve efficiency, and maintain production levels through alternative practices and principles".

Table 1 lists the practices that are emphasized by alternative agriculture compared with those which are generally applied under conventional agriculture. Perhaps the single most important component for a successful transition to a sustainable agriculture is skilled management.

Soil Quality: The Linkage Between Alternative Agriculture and Sustainable Agriculture

It was mentioned earlier that soil quality is now considered by many in a broader context than just soil productivity, i.e., that the concept should include the attributes of food safety and quality, human and animal health, and environmental quality. It follows then, that the best means of improving and maintaining soil quality are alternative agricultural practices such as crop rotations, recycling of crop residues and animal manures, reduced input of chemical fertilizers and pesticides, and increased use of cover crops and green manure crops, including nitrogen-fixing legumes. All of these help to maintain a high level of soil organic matter that enhances soil tilth, fertility, and productivity while protecting the soil from erosion and nutrient runoff. Effective implementation of these alternative agricultural practices, using a holistic or systems approach, requires skilled management and innovativeness by the farmer (Parr and Colacicco, 1987; Hornick and Parr, 1987; Reganold *et al.*, 1990; Parr and Hornick, 1992).

A conceptual diagram of how the attributes of soil quality provide the essential

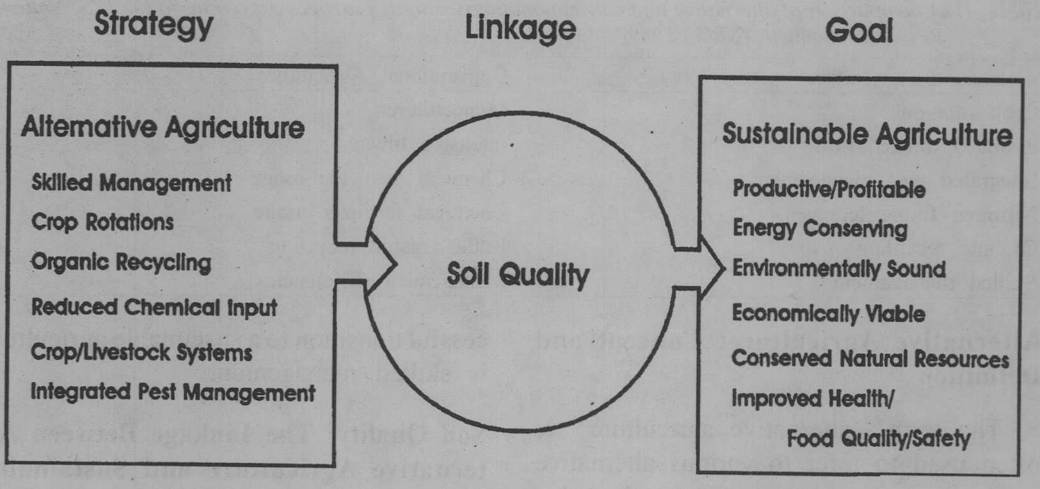

Fig. 1. A conceptual diagram that illustrates how the attributes of soil quality provide a link between the strategy of alternative agriculture and the ultimate goals of sustainable agriculture (Parr et al., 1992).

linkage between the strategies of alternative agriculture and the ultimate goals of sustainable agriculture is shown in Fig. 1. Soil quality occupies a pivotal position in this concept and, indeed, is the real ''key'' to agricultural sustainability (Papendick and Parr, 1992; Parr *et al*., 1992).

Strategies for Sustainability: Relevance to the Drylands of India

Malthus revisited

In a recent paper Swaminathan (1996) reminds us that the 200th anniversary of the published essay of Thomas Malthus will occur next year. It was in 1798 when Malthus predicted that mankind would eventually be unable to balance population growth with his food production capability, culminating in widespread famine, starvation and death. Swaminathan (1996) points out that despite the technological progress made by many developing countries during the last three decades, largely due to the Green Revolution, there is growing concern that the Malthusian prediction could come true for some countries in the early 21st century. Such concern in India today relates to three pressing issues:

- Green Revolution technologies are now associated with environmental pollution by fertilizers and pesticides, and genetic vulnerability of crop cultivars.
- India's increasing population has caused a steady decline in the per capita availability of land and water. This has made higher productivity per unit of land and water imperative but not likely due to problems of Green Revolution technologies.
- Food insecurity that currently exists among one-third of the Indian population, and which, according to Dr. Swaminathan, is largely the result of inadequate purchasing power and not a lack of food in the marketplace.

Integrated Intensive Farming Systems for Small Farmers

To dispel these concerns and to achieve sustainable food security in India, Swaminathan (1996) proposes the development of Integrated Intensive Farming Systems (IIFS) which, he believes, will foster an "Evergreen Revolution" in agriculture. To fulfill the promise of IIFS, he cites seven important areas where appropriate technology and more efficient (and effective) farm management practices are needed:

- Soil health care
- Water harvesting and management
- Integrated nutrient and pest management
- Energy conservation and management
- Post-harvest technology and management
- Integrated crop/livestock systems
- Information management and network systems.

Interestingly, in mobilizing these resources to achieve a more sustainable agriculture and food security, Swaminathan (1996) does not call for additional research. He does, however, urge a better organization and dissemination of information, and appropriate application of existing technologies at the household, farm and village levels.

The Indo-U.S. Dryland/Sustainable Agricultural Research Project (1990-1997)

Producing food for rapidly increasing populations in countries such as India involves two distinct tasks: (a) increasing the productivity of arable lands, mainly irrigated croplands and, (b) developing the agricultural potential of marginal lands, mainly drylands, for sustained but lower productivity. Agricultural research in India for many decades has focused primarily on the improvement of irrigated farming systems while the needs of dryland/rainfed agriculture were largely neglected. During the 1980's there was increasing concern that crop production in the Indian drylands would have to increase substantially if the country was to meet its food grain production goals by the year 2000 (Indo-U.S. Subcommission Report, 1987). Consequently, the Far Eastern Regional Research Office (FERRO) of the U.S. Department of Agriculture, and the Indian Council of Agricultural Research (ICAR) agreed to develop a cooperative research project that would address the critical agricultural and technological needs of the Indian drylands. The project goals were to conduct research for improving agricultural productivity and long-term sustainability of the dryland/rainfed areas, while protecting the natural resource base and the environment. The consensus of the joint planning committee was that the following five sub-projects were of the highest priority for funding and implementation which began in 1990:

- Improving fertilizer use efficiency in conjunction with residue management and reduced tillage in dryland crops and cropping systems.
- Enhancing germplasm for drought tolerance and reclamation of wastelands.
- Integrating soil conservation practices for watershed management.

- Developing models to simulate field water balance and water use-crop yield relations to optimize production in arid and semi-arid regions.

- Improving mechanization of dryland agriculture.

The research approach that has been emphasized in the conduct of each sub-project is to improve soil quality through the proper management of soil, water and nutrients. Indeed, each sub-project comprises important elements and attributes of soil quality which is the real key to sustainable agriculture because it integrates the effects of soil degradative processes (such as erosion) with the effects of soil conservation practices (such as organic recycling). During the course of these sub-projects a wealth of information has been generated on (a) validation and testing of soil/water/crop models to identify best management practices, (b) improved soil productivity through nutrient/residue/reduced tillage/crop rotation interactions, (c) improved water conservation and erosion control practices, (d) managing water stress effects on crop growth, (e) improved germplasm selections for drought tolerance and wasteland reclamation, and (f) improved planting/fertilizing/harvesting methods from modification of existing implements. Although these research results mainly target low rainfall conditions, many of the concepts and principles would also apply to higher rainfall areas, as well as irrigated lands, for improving the productivity and the economic and environmental sustainability of farming systems.

Future Actions And Initiatives for the Indo-U.S. Dryland Sustainable Agriculture Research Project

While the Indo-U.S. Dryland Research Project has been largely successful in developing new and improved methods, technologies and practices for adoption by farmers, there is more to be done. There is an urgent need to integrate the research results across the projects so that the information can be used in developing whole farm management strategies for the most effective and efficient production and conservation systems. This integration approach is essentially the same as that recommended by Swaminathan (1996) for the Integrated Intensive Farming System (IIFS) as a means of achieving sustainable food security for a hunger-free India. Among the tasks which remain to be done under the auspices of the Indo-U.S. Dryland Agricultural Research Project are the following.

Technology transfer and on-farm testing

The research results need to be integrated across the projects (i.e., disciplines) and developed into management packages complete with recommended practices, strategies and decision-making perspectives. Once this is done, the management packages can be transferred to the farmers and extension agents for on-farm testing. Results of the testing trials would be sent back to the research group for possible revision and/or modification of the management package.

On-farm research trials

If the management packages that are developed from the integration of sub-project results are deficient or ineffective due to site-specific conditions, or other differences, it may be necessary to conduct on-farm research trials. These should include active participation by the farmer, researcher and extension agent. Trials may evaluate the effect of timeliness and precision of various management practices (e.g., tillage, crop sequencing, organic recycling and fertilizer applications) on site-specific conditions, crop yield/quality, and profitability.

Reducing the complexity of on-farm trials

In conjunction with on-farm trials it may be necessary to develop new experimental designs to simplify the establishment of field/farm trials and data collection. In collaboration with statisticians, agronomists, pest management specialists, and soil scientists, innovative experimental designs should be evaluated to reduce the complexity of conducting on-farm trials. New and appropriate methods and techniques for conducting simplified on-farm research trials should be incorporated into extension bulletins and distributed accordingly.

Upgrading management skills and training

On-farm testing of technological packages and/or conducting on-farm research trials will require the development of educational materials (i.e., extension bulletins, videos, etc.), training workshops, and technical assistance for both farmers and farm workers, including (and especially) women. It is important that concepts, methods and techniques be understood and that the upgrading of management skills for conducting on-farm tests and research trials be based on the latest and most appropriate scientific knowledge.

Assessing and monitoring soil quality

All of the sub-projects and the integration of research results into management packages and practices can ultimately influence soil quality. Improving soil quality depends largely on proper and regular applications of organic materials to the soil. It follows then that probably the best and most reliable indicator of soil quality at any one time is the soil organic matter content and whether it is changing in response to management inputs. Soil quality is the key to a more sustainable agriculture, since soil degradation is considered to be the time/rate of decrease in soil quality. Thus, regular monitoring of the soil organic matter content through soil testing should give the farmer a good indication of whether he is gaining or losing sustainability. Farmers should also be aware that intensive, conventional tillage accelerates the biological and chemical oxidation of soil organic matter. Consequently, it may be necessary to adopt reduced tillage methods before any significant increase is observed in the soil organic matter content.

Summary and Conclusions

Most of the world's rainfed/dryland regions are comprised of soils that are considered to be marginal and fragile, and often not arable, because of serious limitations due to steep slopes, coarse texture, low fertility, excessive salinity, poor drainage, and inadequate soil organic matter. Yet, these soils are farmed and grazed by the people who inhabit these regions to sustain not only their food production needs, but where they collectively produce most of the world's food grains. Despite this, crop yields in the dryland regions are very low, often at the subsistence level, and soil degradative processes (e.g., wind and water erosion, and nutrient depletion) are rampant because of poor soil management practices, resulting in a progressive decline in productivity.

There is a growing awareness in many countries, such as India, that increased amounts of food grains must be produced in the drylands in the immediate future if they are to keep pace with the food production needs of their expanding populations. The situation has become rather critical because of increasing costs and environmental impacts of irrigated, chemical-intensive, Green Revolution-type agriculture.

There is a strong consensus that improving soil quality is the real key to sustainable agriculture and is particularly appropriate if we are to enhance the sustainability of dryland farming systems. The attributes of soil quality, i.e., productivity, environmental quality, food safety and quality, and human and animal health, all depend upon proper and regular additions of organic materials to ensure soil health, water quality and air quality. Soil quality is also the linkage between alternative agricultural practices and the ultimate goal of sustainable agriculture.

Research to develop more cost-effective, environmentally-sound, and resource-conserving management practices for dryland farming systems should be an ongoing commitment by national governments. However, in most cases we have already generated considerable knowledge and information from dryland research programmes and the time has come to organize, integrate, package and disseminate this information to the farm level for testing and evaluation.

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