ISN 81983

Soil quality: Attributes and relationship to alternative and sustainable agriculture

J.F. Parr, R.I. Papendick, S.B. Hornick, and R.E. Meyer

Abstract. *Different chemical, physical, and biological properties of a soil interact in complex ways that determine its potential fitness or capacity to produce healthy and nutritious crops. The integration of these properties and the resulting level of productivity often is referred to as "soil quality." Soil quality can be defined as an inherent attribute of a soil that is inferred from its specific characteristics and observations (e.g., compactability, erodibility, and fertility). The term also refers to the soil's structural integrity, which imparts resistance to erosion, and to the loss of plant nutrients and organic matter. Soil quality often is related to soil degradation, which can be defined as the time rate of change in soil quality.*

Soil quality should not be limited to soil productivity, but should encompass environmental quality, human and animal health, and food safety and quality. There is inadequate reliable information on how changes in soil quality directly affect food quality, or indirectly affect human and animal health. In characterizing soil quality, biological properties have received less emphasis than chemical and physical properties, because their effects are difficult to measure, predict, or quantify. Improved soil quality often is indicated by increased infiltration, aeration, macropores, aggregate size, aggregate stability, and soil organic matter, and by decreased bulk density, soil resistance, erosion, and nutrient runoff. These are useful, but future research should seek to identify and quantify reliable and meaningful biological/ecological indicators of soil quality, such as total species diversity or genetic diversity of beneficial soil microorganisms, insects, and animals.

Because these biological/ecological indexes of soil quality are dynamic, they will require effective monitoring and assessment programs to develop appropriate databases for research and technology transfer. We need to know how such indexes are affected by management inputs, whether they can serve as early warning indicators of soil degradation, and how they relate to the sustainability of agricultural systems.

Keywords: global change, soil erosion, soil degradation

Introduction

The 1980s became the "decade of awareness" that the productivity of agricultural soils worldwide was in general decline. Food grain production per capita decreased significantly in some parts of sub-Saharan Africa, the Near East, and Asia during that decade. Although some of this decline was due to increased population growth and periodic drought, much of it occurred because of poor management and exploitive farming practices, and with them the degradation of agricultural lands by wind and water erosion, nutrient depletion, and the loss of soil productivity (Food and Agriculture Organization, 1986; Parr et al., 1990; Dregne, 1992). In the United States, soil erosion by wind and water, and the associated loss of soil productivity and damage to soil quality, continue to be our most serious agricultural and environmental problems (Larson et al., 1990).

Erosion causes the world's topsoil to be lost at an estimated 0.7% per year (Brown and Wolf, 1984). This is cause for concern because intensive, high yielding crop production requires mineral nutrients in this layer that may not be easily replaced by fertilizers alone. Where the topsoil has been entirely removed, or where it has been severely eroded, crop yields are from 20 to 65% lower than on non-eroded soils (Langdale et al., 1979; Massee, 1990). Less than 12% of the earth's total land surface is currently cultivated, and little additional arable land is available (Smith and Paul, 1990).

Agricultural productivity depends largely on the topsoil, the uppermost layer, which is about 15 to 20 cm deep for most soils. Topsoil serves many functions. It provides a rooting zone for plants, supplies a balanced mix of plant nutrients, and retains, stores and releases moisture for plant use. It also enhances seed germination and root penetration, and supports a complex community of beneficial microorganisms that decompose organic wastes, recycle plant nutrients, and protect plants from pests. All these functions are essential for maintaining the tilth, fertility and productivity of agricultural soils; soils with these capabilities are considered by many to be "healthy soils."

Recently, Haberern (1992) introduced the idea of a "Soil Health Index" to characterize a soil's capability for sustainable production of healthy and nutritious crops. He likened this to a "report card" that

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Reprint from the American Journal of Alternative Agriculture.
Volume 7, Numbers 1 and 2, 1992, published by the
Institute for Alternative Agriculture.

would document the gains and losses in soil quality as they are affected by management practices. The purposes of this paper are: to explore the components of soil quality; to discuss how they relate to alternative and sustainable agriculture; and to consider how soil quality might be quantified to indicate the status of soil health and provide an early warning of soil degradation and the need for remedial measures.

An Emerging Crisis

A crisis has emerged, especially during the past decade, in which we must make decisions concerning the state of the world's soil resource base. There is a strong consensus that we no longer can tolerate extensive soil degradation and loss of productivity (Brown and Wolf, 1984; Oldeman et al., 1990). Gibbons and Wilson (1984) concluded that because of poor management and exploitive agricultural practices, many U.S. farmers do "treat their soils like dirt."

The collapse of early civilizations in the Near East and North Africa have been attributed mainly to the degradation of agricultural soils by excessive erosion, siltation, and salinization (Lowdermilk 1953). Even today, soil degradation is the single most destructive force diminishing the world's soil resource base. Because of this, some countries have already experienced increased food costs and acute food shortages; however, too few people have related this to the loss of soil quality. Action is needed to sensitize governments in both developed and developing countries to the grim consequences of soil degradation, and to encourage national and regional programs that will conserve and enhance soil quality on a global scale. Brown and Wolf (1984) concluded that the soil erosion crisis must be viewed in a global context because the production, distribution, and consumption of food is part of the global economy. They emphasized that if the loss of topsoil continues, it will lead to acute economic destabilization worldwide.

Some would argue that agricultural soils should be regarded as similar to the world's oil reserves. Both are valuable natural resources that are being depleted at alarming rates, but they should be conserved and used much more efficiently. Until now, there has been far greater worldwide awareness and concern about the rate of oil depletion than about the rate and significance of soil degradation and loss of productivity. This situation could change as we address such issues as increased population growth, global warming, food production deficits, environmental pollution, and quality of human life in the years ahead.

The Concept of Soil Quality

Various physical, chemical, and biological properties interact in complex ways that determine a soil's potential fitness for sustained production of healthy and nutritious crops. The integration of growth-enhancing factors that make a soil productive has often been referred to as "soil quality." The Soil Science Society of America (1984) defines soil quality as an inherent attribute of a soil that is inferred from soil characteristics or indirect observations (e.g., compactability, erodibility, and fertility). Thus, soil quality has traditionally focused on, and has been equated with, soil productivity. More recently, the concept of soil quality has been broadened to include attributes of food safety and quality, human and animal health, and environmental quality, as shown in Figure 1. Soil quality therefore might be defined this way: The capability of a soil to produce safe and nutritious crops in a sustained manner over the long-term, and to enhance human and animal health, without impairing the natural resource base or harming the environment.

The soil serves as an environmental filter for removing undesirable solid and gaseous constituents from air and water. Almost all recycling of organic materials, and the retention and release of water and nutrients for plants and soil organisms, occurs in the soil and is enhanced by a biologically-active and healthy soil. Although not well understood, soil quality may also play a major role in plant health and in the nutritional quality of the food that is produced. Thus, if properly characterized, soil quality should serve as an indicator of change in both the soil's ability to produce optimum levels of safe and nutritious food, and its structural and biological integrity, which in turn is related to the status of certain degradative processes and to environmental and biological plant stresses.

Some people believe that good quality soils are essential for producing healthy and nutritious crops that in turn can en-

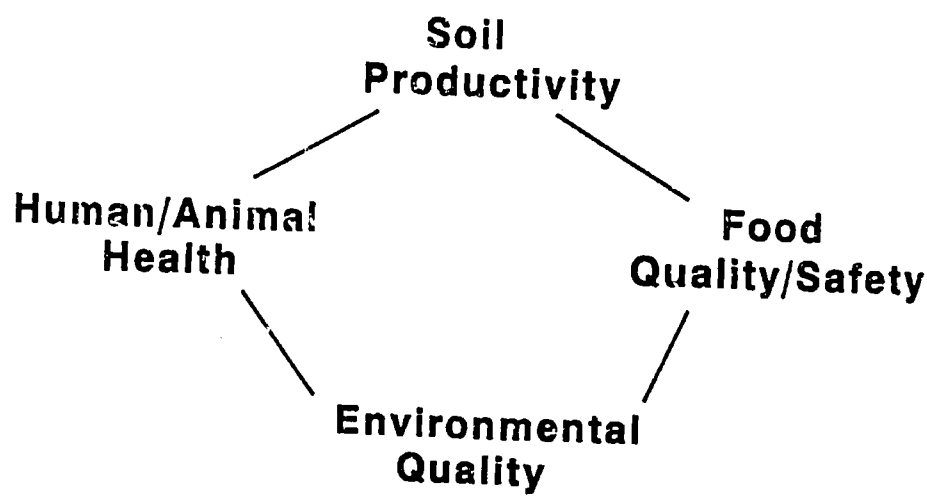

Figure 1. Attributes of soil quality.

hance human and animal health. Figure 1 suggests such a linkage, but research is needed to verify this relationship.

Soil quality can decline from many causes: not just wind and water erosion, but also such degradative processes as nutrient losses from runoff and leaching, depletion of soil organic matter, crusting, compaction and desertification; it also can occur through the accumulation of toxic substances from excessive use of chemical fertilizers and pesticides, and atmospheric deposition or improper waste disposal (Sampson, 1981; Hornick and Parr, 1987). The maintenance or restoration of soil quality is highly dependent on organic matter and an array of beneficial macroorganisms and microorganisms that it supports. Proper and regular addition of organic amendments such as animal manures and crop residues can effectively offset many of these degradative processes. It also is the best way to develop a biologically active soil that requires less energy for producing crops, increases the resistance of plants to pests and diseases, and enhances the decomposition of toxic substances such as residual pesticides (Allison, 1973).

Indicators of Soil Quality

Efforts to characterize soil quality have focused primarily on soil chemical and physical properties because relatively simple and standardized methods of measurement are available. Soil biological properties have been neglected largely because of the difficulty in quantifying and predicting soil biological behavior, so that no single reliable index of soil quality has been developed.

Improved soil quality is generally indicated by increases in infiltration, macropores, aggregate size and stability, soil organic matter and aeration, and by decreased soil resistance to tillage and root penetration, and decreased runoff and erosion (Granatstein, 1990). More attention should be given to soil biological properties because their relationships with soil chemical and physical properties, plant health, and food quality are obviously important, but poorly understood. Plant health and nutritional quality may prove to be useful and reliable indicators of soil quality (Hornick, 1992).

Soil microorganisms and invertebrates play a vital role in decomposition of organic matter and nutrient cycling, and could be important indicators of soil quality. The various species, numbers, and functions of these organisms often are sensitive to environmental stresses and changes in soil properties associated with tillage and cropping practices. Changes in biodiversity of soil organisms (microorganisms, insects, and earth worms) may provide indications of soil degradation or rehabilitation (Stork and Eggleton, 1992; Visser and Parkinson, 1992).

Besides these properties, other potential indicators of soil quality should be considered, including crop yield (grain or biomass production), plant vigor, rooting patterns, and surface and groundwater quality. In certain situations, the latter may be very important since water quality can profoundly affect soil chemical, physical and biological properties.

Although some indicators of soil quality may be sensitive to change, others may be more subtle. The overlying question is whether we can measure and quantify these indicators and develop them into a Soil Quality Index that can be used reliably to monitor and predict the effects of farming systems and management practices on soil productivity, environmental quality, food safety and quality, and human and animal health. Moreover, can these indexes provide an early indication of soil degradation and the need for remedial measures, and characterize changes in soil properties that would reflect the extent of rehabilitation or regeneration of degraded soils?

The ultimate goal is to develop a mathematical relationship or model that could quantify the various attributes of soil quality, and from it derive one or more indexes for simulation and prediction.

Such a relationship could take the following form:

$$\text{Soil Quality Index} = f(SP, P, E, H, ER, BD, FQ, MI)$$

where

SP = Soil Properties
P = Potential Productivity
E = Environmental Factors
H = Health (Human/Animal)
ER = Erodibility
BD = Biological Diversity
FQ = Food Quality/Safety
MI = Management Inputs

We would have to determine the interaction of these indicators, and the relative weight of each. Much valuable information is already available from research on benchmark soils and from long-term tillage and fertility trials.

We can also speculate on how soil quality indices might be used, including the following:

1. Assess the impact of management practices on soil degradation and soil conservation.
2. Assess the accrued benefits on highly erodible lands under the Conservation Reserve Program that was authorized by the 1985 Farm Bill.
3. Provide a basis for conservation compliance.
4. Establish the loan value and price of land.
5. Establish a more realistic base for tax assessment and tax credit.
6. Assess the impact of management practices on human and animal health.
7. Assess the impact of management practices on food safety and quality.
8. Assess the impact of management practices on water quality.
9. Provide information for simulating and predicting environmental change.
10. Provide an improved basis for land capability classification.

Monitoring and Assessing Global Soil Quality

There is an urgent need to develop the institutional capability for continuously monitoring and assessing the status or quality of the world's soil resources (Sanders, 1992). This should be linked with other efforts in the arena of global change, and include the development of databases and multinational programs on environmental issues such as air and water quality, soil biological diversity, and global warming. The soil is a highly interactive

component of regional and global processes that can significantly influence the behavior and response of agroecosystems.

An example is the issue of carbon dioxide buildup in the atmosphere and warming of the earth's environment. The soil can be either a net source or a net sink for carbon. The loss of carbon from surface soil layers from cultivation of arable lands was estimated at 30% over a 20- to 50-year interval (Schlesinger, 1986). The net release of carbon from agricultural clearing operations during the past decade was estimated at 15% of the annual emission from the burning of fossil fuels (Houghton et al., 1983; Schlesinger, 1984). However, Kern and Johnson (1991) have estimated that increasing the adoption of conservation tillage in the U.S. from 27 to 76% of planted cropland could change agricultural land from a net source of atmospheric carbon to a net carbon sink. Thus, soil quality and land use should be given high priority in observational and monitoring programs on global change.

A program on monitoring and assessing soil quality on a global scale would accomplish the following important objectives:

1. Create a global awareness and concern for the world's limited and fragile soil resource base and its relationship to environmental parameters that affect agroecosystems.
2. Stimulate local and regional concern about the widespread degradation of agricultural soils that is occurring from mismanagement and improper land use, and the threat this poses to the sustainability of agriculture and the quality of human life.
3. Enhance the quantification of soil quality indexes that are essential for identifying problem areas and for reliably estimating world food prospects.
4. Provide information that is needed to develop reliable models that can simulate and predict global environmental change.
5. Provide information to governments that is essential for drafting realistic agricultural policies and for allocating limited resources for programs to conserve, protect, and improve the soil resource base.

Current Initiatives to Expand our Knowledge of Soil Degradation and Soil Quality

We have only limited quantitative data on the rate and extent of soil degradation and its effects on soil quality and loss of productivity. Nevertheless, some countries and organizations have recognized the need for this information and have begun compiling national, regional, or global databases on soil degradation and soil quality. We briefly discuss some examples:

The United States: Several definitive studies have shown how erosion is related to loss of soil productivity (Papendick et al., 1985; Pierce et al., 1983). Many states have developed or are now developing guidelines and standards for certifying organically grown foods. One criterion sometimes used requires the producer to provide evidence that soil quality is being improved, or that it is being maintained at a high level.

Efforts are underway in some countries using computer models such as the U.S. Erosion Productivity Impact Calculator (EPIC) and the Productivity Index (PI) to evaluate the long-term productivity and economic impacts of soil erosion (Pierce et al., 1983). In some cases, computer-based expert systems are being developed to advise practitioners on remedies for soil degradation. So far, however, no program or procedure can track changes in soil quality on a global scale.

France: The Government of France established an observation network for soil quality in 1985 (Gomey and Juste, 1986). Priority was given to soil contamination by heavy metals, but other factors also are being monitored, including physical and chemical properties, plant products, biological properties, and physical degradation other than erosion.

African Soil Science Society: At their inaugural conference in 1988 in Kampala, Uganda, the African Soil Science Society Organizing Committee drafted a resolution calling attention to the problem of rampant soil degradation throughout the continent as the principal cause of declining food production and increasing poverty. The committee urged scientists to develop improved management practices that would halt soil degradation, restore productivity, and conserve the soil resource base for future generations.

International Federation of Organic Agriculture Movements: The alarming rate of soil degradation in Africa and the need to implement remedial and regenerative measures was also emphasized at the Seventh IFOAM Conference held in 1989 at Ouagadougou, Burkina Faso. This was the first time that IFOAM held its conference in a developing country. It brought U.S. and European scientists face-to-face with the monumental problem of restoring and improving the productivity of severely degraded agricultural lands and the overriding question of how this would be accomplished with such limited resources (Reganold and Parr, 1988).

Canada: In 1990, Agriculture Canada initiated a National Soil Quality Evaluation Program, with the objective of developing nationally acceptable criteria and standards of soil quality, and a periodic assessment of the status of soil quality and soil degradation. The program will identify and monitor the processes that cause changes in soil quality, and develop procedures and systems for predicting these changes. It also will provide a means for measuring changes in soil quality over time, to ensure that appropriate and effective land management practices are implemented. More than 20 benchmark sites have been established across Canada to monitor changes in soil properties under different farm management systems. The overall goal of the program is to develop the capability of evaluating the effect of changes in soil quality indicators on the productivity and sustainability of farming systems in Canada and elsewhere (M.A. Arshad, Agriculture Canada, personal communication).

United Nations: The United Nations Environment Programme (UNEP) and the International Soil Reference and Information Center (ISRIC) in Wageningen, The Netherlands, completed publication of a world map on human-induced soil degradation (Oldeman et al., 1990). More than 2,000 mapping units provide information on the type of degradation process (e.g., water erosion, wind erosion, and chemical or physical deterioration), and the soil's

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status expressed as a combination of the degree of soil degradation and fraction of the mapping unit affected.

Relationship of Soil Quality to Alternative Agriculture and Sustainable Agriculture

The National Research Council (1989) defined alternative agriculture as a system of food and fiber production that applies management skills and information to reduce costs, improve efficiency, and maintain production levels through such practices and principles as:

- Crop rotations instead of monoculture
- Integrated crop/livestock systems
- Nitrogen fixing legumes
- Integrated pest management
- Conservation tillage
- Integrated nutrient management
- Recycling of on-farm wastes as soil conditioners and biofertilizers.

A U.S. House of Representatives Report (1988) considered low-input or alternative agricultural practices as promising strategies for preventing groundwater pollution and lowering farmers' production costs. The report implied that these goals could be achieved by reducing, or largely excluding, the use of chemical fertilizers and pesticides.

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. and worldwide. Although there are many definitions of sustainable agriculture, most of them encompass the same elements: productivity, profitability, conservation, health, safety, and the environment. They differ mainly in emphasis.

The U.S. Congress (1990), in drafting the Food, Agriculture, Conservation, and Trade Act of 1990, P.L. 101-624 (better known as the 1990 Farm Bill), defined sustainable agriculture as an integrated system of plant and animal production practices, having site-specific application, that over the long-term will do the following:

- Satisfy human food and fiber needs
- Enhance environmental quality and the natural resource base
- Make efficient use of nonrenewable resources
- Use natural biological cycles and controls
- Improve the economic viability of farming systems
- Enhance the quality of life for farmers and society as a whole.

As mentioned earlier, soil quality is now considered in a broader context to include attributes of food safety and quality, human and animal health, and environmental quality. It follows that the best means to improve or maintain 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. 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.

A conceptual diagram of how the attributes of soil quality link the strategy of alternative agriculture to the ultimate goal of sustainable agriculture is shown in Figure 2. Soil quality occupies a pivotal position in this concept, and many would agree that soil quality is the "key" to agricultural sustainability.

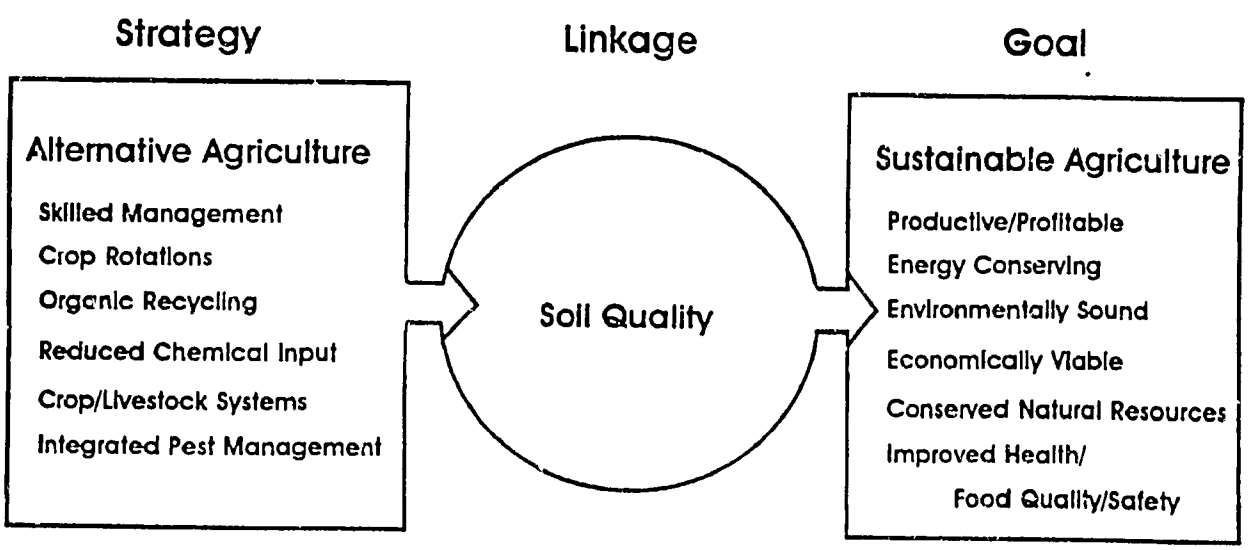

Figure 2. A conceptual diagram that illustrates how the attributes of soil quality provide a link between the strategy of alternative agriculture and ultimate goal of sustainable agriculture.

Research Needs and Priorities

There is a strong consensus that establishing a global network for monitoring, assessing, improving, and restoring the quality of degraded soils is a logical and appropriate goal. Research is needed to quantify the indicators or attributes of soil quality into indexes that can accurately and reliably characterize the relative state of soil quality as affected by management practices and environmental stresses. The best indicators of soil quality probably will differ according to agroecological zones, agroclimatic factors, and farming systems. For example, soil quality indicators would be different for paddy rice and for crops grown in well-drained soils.

Before a global network is developed, baseline information is needed. For example, literature surveys should be conducted to gain perspectives on monitoring requirements and the potential effects of changes in land use on soil quality. These surveys should include estimates of how much soil degradation costs farmers and society, and how various indicators of soil quality could be integrated to provide higher order indexes or attributes. From such information, maps could be produced to focus attention on the severity of degradation and conservation priorities. A logical first step may be to compile national and regional databases that could be linked into a global network.

We also need to improve our monitoring and assessment capabilities. For example, remote sensing and geographic information systems (GIS) could greatly enhance our ability to monitor changes in soil quality on a landscape basis. Existing land classification systems such as the Land Capability Classification System (Reganold, 1986) and the Storie Index Rating Scheme (Storie, 1976), need to be evaluated and possibly modified to provide accurate and meaningful characterizations of how land use affects soil quality.

Questions inevitably will arise regarding the feasibility of an effective global network for monitoring soil quality. Moreover, what is the best way of organizing and implementing such a program? What institutions or agencies should be involved? How should the program be managed? How is the information to be processed and used? And who is going to pay for it? Hopefully, most of these questions will be answered as linkages develop between institutions, projects, and soil quality researchers. Workshops, seminars, conferences, and task forces also will provide strong incentives to develop such a network.

In their paper on international networking of agricultural research, Plucknett and Smith (1984) discussed the essential elements on which successful networks are based. Perhaps most important, the problem should be defined clearly and a realistic research agenda developed. Then, the problem must be widely shared; strong self-interest by scientists and governments must be reflected; participants must be willing to commit personnel, facilities, and other resources; outside funding from interested donors must be available to operate the network for a reasonable time; participants must have the necessary training and expertise to make meaningful contributions; finally, it is essential to have strong and effective leadership. If any of these elements is missing, the prospects for a successful network are diminished. We should keep these principles firmly in mind as we pursue our goal of a global network for monitoring and assessing soil quality.

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