Ecological Sustainability in Agricultural Systems: Definition and Measurement

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SUMMARY. "Sustainable agriculture" has emerged as the most agreed-upon term to synthesize a variety of concepts and perspectives associated with agricultural practices that differ from those of conventional production. Definitions of sustainable agriculture contain three equally important components: environmental quality and ecological soundness, plant and animal productivity, and socioeconomic viability. The Agroecosystem component of the Environmental Monitoring and Assessment Program is developing a systems-level approach to the long-term monitoring of agroecosystem sustainability. Measurements will be made for a suite of indicators at sites selected from a probability sampling frame. Associations between indicator values over time will be used to assess agroecosystem condition and status on a regional and/or national scale. One or more measures of sustainability will be developed by organizing indicators and assessment endpoints into a framework based upon the three components of sustainable agriculture.

INTRODUCTION

Conventional agriculture in the United States includes capital-intensive monocultures; continuous cropping; a substantial reliance on manufactured

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inputs such as fertilizer, pesticides, and machinery; as well as an extensive dependence on credit and government subsidies. Perceived as businesses, farms are often operated with a priority of maximizing short-term profits. Although not quantified, the ecological cost of developing and maintaining U.S. agricultural systems has been high. For example, one-third of the topsoil on U.S. agricultural land has been lost over the last 200 years (Edwards 1990). In addition, soils have become compacted and lost fertility; groundwater has been depleted and polluted from pesticides and fertilizers; wildlife habitats have been lost or damaged due to chemical runoff; and forests, range, and wetlands have been converted to croplands. Frequent use of some pesticides has resulted in the development of resistant strains of pests and pathogens, which has led to the need for more or different pesticides and has increased costs (Edwards 1990). Most of these high-input systems, sooner or later, will probably fail because they are neither economically nor environmentally sustainable over the long term (Parr et al. 1990).

Interest in sustainable agriculture has increased during the last decade. This interest has been fostered by increasing consumer concern for food free of pesticide residues, farmers' concern for their own health and that of others, and the concern of the public and policymakers about the degradation of the natural environment through various conventional agricultural practices in the United States. The term "sustainable agriculture" has been used in many different ways both in scientific papers and in popular news, and its meaning has become obscure (Lockeretz 1988). This result may be partly due to the multitude of components that comprise sustainable agriculture. The purpose of this paper is to identify common themes in the many definitions of sustainable agriculture, place the themes in an ecological context, and discuss measurable indicators and assessment endpoints that have potential for use in monitoring the sustainability of agroecosystems.

DEFINITION OF SUSTAINABLE AGRICULTURE

Evolution of the Term

The science and practice of sustainable agriculture is as old as the origins of agriculture, although the contemporary use of the term evolved more recently (Altieri 1987). Pioneers of "sustainable agriculture" were Franklin King, Lord Northbourne, and Lady Eve Balfour. In 1911, King published *Farmers of Forty Centuries: Permanent Agriculture in China, Korea and Japan*. His book documents how farmers in parts of East Asia worked fields for 4,000 years without depleting the fertility of their soil (Reganold et al.

1990). He compared the low-input and sustainable approach of oriental agriculture with what he perceived as the reckless and wasteful methods used by U.S. farmers (Stenholm and Waggoner 1990). King conveyed the idea that agriculture could not be sustained over the long-term in economic, biological, or cultural terms unless it was "rooted firmly in frugality and recycling of fertilizer elements and organic materials" (Stenholm and Waggoner 1990). Lord Northbourne was the first to use the term "organic farming" in his book *Look to the Land*, published in 1940. His vision of the farm was "a sustainable, ecologically stable, self-containing unit, biologically complete and balanced–a dynamic living organic whole" (Scofield 1986). The phrase "sustainable agriculture" was not used until the late 1970s, when it was coined by Lady Eve Balfour (Rodale 1990). Dick and Sharon Thompson (Boone, Iowa) began conducting on-farm research on "organic farming" in the 1960s, and research centers, including Rodale Research Center (Emmaus, PA), The Land Institute (Salina, KS) and Washington University (St. Louis, MO), emerged in the 1970s (Bidwell 1986). The terms "lower input agriculture" and "low-input/sustainable agriculture" (LISA) were coined in the 1980s by Clive Edwards and Dennis Oldenstadt, respectively (Madden 1989).

"Sustainable agriculture" has emerged as the most agreed-upon term to synthesize a variety of concepts and perspectives associated with agricultural practices that differ from those associated with conventional production agriculture. "Low input" or resource-efficient agriculture focuses on the resource dynamics of the agroecosystem. Other perspectives emphasize the social and ecological aspects (e.g., agroecology) (Altieri 1987), a specific set of practices (e.g., organic farming) (Lockeretz 1988), or management concepts combined with an ecological/social overview (e.g., biodynamics and permaculture) (Hauptli et al. 1990).

The definition of sustainable agriculture adopted by the American Society of Agronomy is "one that, over the long-term, enhances environmental quality and the resource base on which agriculture depends, provides for basic human food and fiber needs, is economically viable, and enhances the quality of life for farmers and society as a whole" (Schaller 1990). This definition is similar to one proposed by Altieri (1987) in which "sustainability refers to the ability of an agroecosystem to maintain production through time, in the face of long-term ecological constraints and socioeconomic pressures." Both of these definitions correspond to the relationship of agriculture to indigenous cultures; agriculture was developed to "even out environmental and economic risk and maintain the productive base of agriculture over time" (Altieri 1987).

Three common themes occur in definitions of sustainable agriculture:

plant and animal productivity, environmental quality and ecological soundness, and socioeconomic viability. All three aspects must coincide before sustainable agriculture is possible. A system must be ecologically sustainable or it cannot persist over the long run, and thus cannot be productive and profitable. Likewise, a system must be productive and profitable over the long run, or it cannot be sustained economically (Altieri 1987; Ikerd 1990)–no matter how ecologically sound it is (Stenholm and Waggoner 1990).

Method, Myth or Philosophy?

Sustainable agriculture is an approach or a philosophy (Luna and House 1990; Schaller 1990) that integrates land stewardship with agriculture. Land stewardship is the philosophy that land is managed with respect for use by future generations. Since factors that determine sustainable agriculture are measured on a time scale of decades or generations, future generations may be best able to evaluate whether or not their predecessors practiced sustainable agriculture. However, a predictive mechanism for determining sustainability of agroecosystems would be helpful *now*.

A perplexing attribute of sustainable agriculture is that there is no precise, set formula that applies to all situations. Sustainable agriculture is not simply a list of methods (Luna and House 1990; Schaller 1990) or crop production with reduced use of agricultural chemicals (Stenholm and Waggoner 1990). Sustainable agriculture is applied uniquely to each site and is a management-intensive, resource-conserving process that considers both long- and short-term economics (Stenholm and Waggoner 1990). Although sustainable agricultural practices must be tailored to specific regions, soil types, topography, and climate (Lockeretz 1988), ten general attributes (1-9 from Lockeretz 1988; 10 from Hauptli et al. 1990) may be associated with the concept of sustainable agriculture. These include: (1) crop varieties and livestock selected for suitability to a farm's soil and climate, as well as for resistance to pests and pathogens; (2) livestock housed and grazed at low densities; (3) farm-generated resources preferred over purchased materials since the former are generally renewable; locally available off-farm inputs preferred over those from distant regions because the former require less energy in transport; (4) diversity of crop species desired for stability and achieved by rotations, intercropping, and relay cropping practices; (5) rotation of crops, enhancing utilization of nutrient reserves in lower soil strata by including deep-rooted crops, and aiding in control of weeds and pests; (6) cover crops and mulching used to reduce erosion and to conserve moisture by protecting the soil surface; (7) soils managed to increase their ability to hold nutrients and to release them at an appropriate time for crop utilization; (8) soluble inorganic fertilizers applied at a level that a crop can use efficiently, and only to the extent that nutrient deficits cannot be met by livestock manures and legumes; (9) synthetic pesticides used to enhance control of weeds, insect pests, and pathogens, but only as a last resort when there is a clear threat to the crop; and (10) biocides, when employed, targeted to specific organisms and meeting the criteria of low mammalian toxicity, limited persistence, and low environmental mobility.

Sustainable agriculture requires increased knowledge about and management of ecological processes. In conventional U.S. agricultural practices, ecological processes viewed as necessary for sustainability may be disrupted or altered by large inputs of agricultural chemicals. For example, use of insecticides may increase weed populations by removing natural enemies of weeds; application of fungicides may act on nontarget soil fungi that provide a natural control of nematode population levels; and use of insecticides and fungicides may reduce earthworm populations, thus lowering soil fertility and water infiltration rates (Luna and House 1990).

Conservation of resources is essential to permit long-term use of agricultural lands. Conservation of resources should not be confused with *preservation* of resources. Conservation implies the wise "use" of resources and assumes an understanding of the difference between renewable and nonrenewable resources (Schaller 1990). Ecological resources must be recycled–not depleted–or agriculture cannot persist.

MONITORING AGROECOSYSTEM SUSTAINABILITY

Ecosystem Perspective

Agricultural systems are "ecosystems." By definition, an ecosystem is a unit composed of associated communities of organisms and their physical/chemical environment. By intention, people represent one of the communities in agroecosystems and are *not* external to ecosystem functions. People play a governing role in regulating agroecosystem processes, some that lead toward and others that impede sustainability in agroecosystems. People are responsible for the selection of crop varieties and livestock breeds, and they impart techniques, social organizations, values, and knowledge to the function of agroecosystems. Ecosystem-level concepts require "systems-level" thinking and research; systems are inherently complex, with a multitude of interactions. A "systems" approach to studying and measuring agroecosystem structure and function is interdisciplinary and includes biological, chemical, physical, and social scientists. Ecosystem-level concepts are the *core* of sustainable agriculture–both in definition and measurement!

A major challenge in monitoring agroecosystem sustainability is to have indicators that identify system function or dysfunction at scales ranging below and above individual ecosystems (i.e., populations to global systems) (Gliessman 1990). At all scales, the three components of sustainable agriculture (environmental quality, plant and animal productivity, socioeconomic viability) are confounded with at least four important ecological processes: nutrient cycling, hydrology, population dynamics, and energy flow. Below are some examples of quantifiable attributes of the three components of sustainable agriculture in relationship to ecosystem structure and function.

Environmental quality and ecological soundness in agroecosystems can be monitored by measuring selected indicators of nutrient cycling, hydrology, and resource conservation. Persistence of life requires recycling of nutrients between living organisms and the physical environment. Several measures are used to assess and monitor cycling of nitrogen within agroecosystems. Measures of nitrogen inputs to an agroecosystem include the amount of nitrogen in rainfall, and the timing and rate of application of chemical fertilizers, animal manure, or sewage sludge. Two factors that affect the conversion of nitrogen to useable forms by plants include (1) the use of legumes in crop rotations and (2) populations of microfauna that graze on microbial decomposers (i.e., bacterial-feeding nematodes) (Freckman 1988). In agroecosystems, nutrients are removed from their cycles as harvested products (King 1990) or are exported from the field through leaching, denitrification, volatilization and erosion. Nutrients must be replaced in order for agricultural production to continue at an economically viable level. Measures to determine nitrogen removal include erosion, depletion of organic matter, and chemical exports from the field.

Availability of water (without toxic levels of contaminants) at appropriate times and locations is essential to the sustainability of an agroecosystem. Of course, water is essential for the physiological functioning of biological organisms. Water flow affects nutrient inputs and losses through leaching and erosion. Factors that regulate water cycling include inputs such as precipitation, run-on and irrigation, and outputs such as runoff, infiltration, and mechanical drainage (e.g., subsurface tiles). These factors can be measured, as can the quality of ground and surface water (e.g., salinity, presence of agricultural chemicals, and other contaminants).

Ecological soundness includes maintaining the physical, chemical, and biological integrity of soils. In sustainable agriculture, it is important to maintain a certain level of crop production along with diversity and well-being of soil-inhabiting organisms (Hauptli et al. 1990). Ecological integrity of soils can be achieved by balancing degradative processes such as soil erosion, nutrient runoff, and organic matter depletion with the beneficial effects of crop rotation, conservation tillage, and recycling of animal manures and crop residues. The challenge is to achieve a balance between the degradative and beneficial processes (Parr et al. 1990) so that the three basic attributes of sustainability are realized. A useful index of soil quality should integrate physical, chemical, and biological parameters that quantify the relationship between degradative and beneficial processes.

Nematode community patterns could provide an indication of the biological health of soils. Omnivorous and predaceous nematodes provide "connectedness" to the detritus foodweb (Coleman et al. 1983) and lengthen food-chains, respectively; their presence and/or abundance reflect agroecosystem stability (Wasilewska 1979). Bactivorous nematodes are important regulators of decomposition because they feed on microbial decomposers (Freckman 1988). Abundant populations of plant-parasitic nematodes may limit crop productivity by consuming primary production (Wasilewska 1979).

Population dynamics of organisms are important in maintaining a sustainable balance between populations, their respective food sources, and space requirements. Population dynamics of crops are regulated by factors including hydrology, soil structure and fertility, climate, fertilizers, crop diversity, and other organisms. Population dynamics of insects, pathogens, and weeds are regulated by predator-prey interactions, competition, mutualism, and human activities including cultural, chemical and biological control practices. Toxic agricultural chemicals and metal contaminants may influence human population dynamics. Measures that could be used to monitor regulation of biological populations include applications of herbicides, pesticides, and fertilizers; populations of insects (both beneficial insects and pests); employment of cultural control strategies, including selection of crop varieties and livestock breeds; and management practices that influence biological diversity.

Biological complexity and diversity, which are essential components of sustainable agriculture, require the maintenance of a wide range of plant types and habitats on the farm (Hauptli et al. 1990). Increased diversity of species within an agroecosystem (e.g., polycultures, hedgerows) may decrease risks of production failure by providing alternate crops and by promoting natural predators of pests (Hendrix et al. 1990). The establishment and maintenance of complexity and diversity require a sophisticated understanding of population dynamics to manipulate relationships among hosts, pests, and predators in the agroecosystem. This manipulation, in turn, serves to minimize major disruptions that require other kinds of intervention (e.g., pesticide applications for pest management) (Hauptli et al. 1990). Indicators of biodiversity include (1) employment of management strategies such as strip-cropping, crop rotation, trap crops, inter-cropping and multilines; (2) indices of diversity and fragmentation of agricultural landscapes; and (3) the quality of wildlife habitats.

Productivity is a measure of energy flow, the foundation of an ecosystem. A productivity index can be developed to reflect the energy efficiency of production by differentiating renewable and nonrenewable sources of energy. This requires conversion of all ecologically important inputs and outputs to a common currency. Ecologically important inputs include solar radiation, human labor, work of machines, fertilizers and herbicides, seed, hay, irrigation water, pollutants, and pesticides. Ecologically important outputs include plant and animal products (grain, vegetables, meat, milk, etc.), chemical exports, and sediment loss (Olson and Breckenridge 1992). A variety of currencies exist for comparing inputs and outputs. A common currency may take the form of net primary productivity, net caloric output per caloric input, protein output per unit caloric input, or standardized dollar values.

Socioeconomic indicators may reflect the quality of life and profitability for farmers, farm workers, and rural communities. Farm-level indicators include the operator's age, farm size, whether a farm is managed by the owner or a hired manager, and level of indebtedness. Field-level indicators include land tenure, fuel costs in cultivation, pesticides and fertilizers, and person-days of hired, custom, or family labor. The challenge is to select indicators that reflect the well-being of people and the environment.

Environmental Monitoring and Assessment Program

The Agroecosystem component of the Environmental Monitoring and Assessment Program (EMAP) is developing a systems-level approach to monitor the "sustainability" of agroecosystems on a long-term, regional and/or national scale. The Agroecosystem Resource Group (ARG) is one of seven ecosystem resource components of the larger EMAP, established as an initiative of the U.S. Environmental Protection Agency (EPA) in 1988 (Kutz and Linthurst 1990). The ARG program is a cooperative program between EPA, the U.S. Department of Agriculture (USDA) (Heck et al. 1991), and North Carolina State University. One objective of the program is to provide current estimates of the condition of U.S. agroecosystem resources as a baseline against which future changes could be compared with statistical confidence. Through time, measurements for a suite of indicators and assessment endpoints will be taken from area segments selected from a probability sampling frame in collaboration with the USDA's National Agricultural Statistics Service (NASS). Indicators are being selected based on (1) the availability of techniques for obtaining measurements; (2) suitability of indicator for use in a single sampling period; and (3) interpretability of data (Meyer et al. 1992). Selected indicators and assessment endpoints are organized to reach the program's ultimate goal of developing an overall index of agroecosystem health or sustainability.

The ARG program has adopted the following definition of a healthy agroecosystem: "one that balances crop and livestock productivity with the maintenance of air, soil and water integrity and assures the diversity of wildlife and vegetation in the noncrop habitats" (Heck et al. 1991). This definition resembles definitions of sustainable agriculture.

The ARG is developing a number of indicators that address the three principle components of a sustainable agroecosystem: plant and animal productivity, environmental and ecological soundness, and socioeconomic viability. The initial pilot program being developed by the ARG will include indicators associated with the following assessment endpoints: crop productivity, soil quality, chemical use and export, water quality, and land use. Additional indicators are being developed to address assessment endpoints of animal production, quality of wildlife habitat, and socioeconomic viability. More specifically, ecological soundness and environmental quality will be measured by indicators of (1) soil integrity including soil structure, water and nutrient-holding capacity, vulnerability to erosion, extent of acidification, salinization and contamination, and nematode community patterns; (2) chemical export from fields; (3) irrigation water availability, quality, and runoff; (4) wildlife habitat quality; and (5) land use patterns. The efficiency of production will be measured by an aggregation of input indicators such as farm labor, mechanical power and machinery, agricultural chemicals, and seed purchases; and output indicators including crop production available for human or livestock consumption. Specific methods for monitoring socioeconomic viability are being developed and will include factors such as operator age, land tenure of individual fields, and management practices. Some indicators and assessment endpoints can be included under more than one component of sustainability.

The ARG program is in a developmental phase and welcomes innovative ideas for monitoring and assessing the ecological condition of agroecosystems. The program is designed as a vehicle for monitoring agroecosystem health. The program's monitoring efforts need support from fundamental, systems-level research of agroecosystem structure and function to help identify, evaluate, and interpret indicators that consistently measure aspects of sustainability.

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