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Sustainability and Resource Assessment: A Case Study of Soil Resources in the United States

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A Case Study of Soil Resources in the United States

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ABSTRACT

Assessment of environmental condition is critical to wise management and policy decisions. However, for some concerns such as sustainability, it is difficult to assess environmental condition because it involves disparate social objectives and an understanding of complex ecological systems. Here, a general framework is proposed to examine sustainability of environmental resources in objective, measurable ways. By using soil quality as an example, sustainability research is taken beyond theory and into application.

Sustainability depends on the quality of resource endowment. Endowment of a natural resource can be modeled as an index of quality to assess the degree of sustainable management. This index, consisting of the most important identifying characteristics of the resource, is placed into a dynamic model of production to determine how resource use affects three different versions of sustainability. The economic, social, and environmental impacts are identified for each sustainability requirement, and the long-term path of resource quality is evaluated.

Soil quality was chosen as a natural resource because its importance is immediately obvious and because there is a wealth of data compared to other resources. Three general soil types—stable, neutral, and susceptible—were selected. The index of soil quality was used in a corn production setting to address three questions: (1) What are the impacts of different definitions of sustainability on the economy and the environment? (2) Do U.S. soil conservation policies address sustainability objectives? (3) How do substitution, reversibility, and uncertainty affect optimal soil use?

Results show that impacts, as well as the ability to meet sustainability goals, are highly dependent on soil type and on how sustainability is defined. In some cases, soil can be managed the same under any definition, but, in other cases, different sustainability concepts are at odds. In general, the deeper and better the soil, the more obvious and consistent was the approach to sustainability. Lower quality soil types require more complex approaches.

The results of this study can be used to help determine which soils need to be protected, identify tradeoffs between conservation and nitrate leaching as erosion occurs, show how risk and uncertainty affect soil conservation decisions, and provide other information helpful to policy makers dealing with soil management. Additionally, the methods used here can be useful to evaluate other, more complex natural resources such as forest health.

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1. INTRODUCTION

Society's ability to produce goods depends on the availability and quality of inputs. Inputs may be natural, and either renewable or nonrenewable. They may also be unnatural, or reproducible human made inputs, such as labor, technology, and physical capital. For a long time these delineations were unimportant. The rise of the popular sustainability movement has, however, given impetus to questions of where inputs come from and which resources are affected. Disregard for sustainability may reduce long-term economic productivity and encourage environmental and ecological losses. Sustainability of the production process requires that inputs from natural resources be given equal consideration to outputs or consumption because resources provide more services to society than simply producing goods.

Assessing natural resource sustainability is not easy. Ecosystems are complex compared to the broad terms used to express societal goals, such as "clean water" and "sustainable" environment. Consequently, policy makers need complex information about ecosystems expressed in simple terms. *Ecosystem assessment* is the process of interpreting and evaluating scientific data and information for the purpose of answering policy-relevant questions about ecological resources. Addressing policy concerns involves more than integration and aggregation of facts. Ecosystem assessment must help assign significance or value to the information collected through appraisal and judgment. It is desirable to keep value judgments to a minimum and to make such judgments as objective and transparent as possible. However, the intrusion of values is unavoidable when condensing information about a complex system into a simple measure.

1.1 PURPOSE

Sustainability suffers a similar predicament to many worthy causes. A majority want to achieve it, but few can agree upon the means. Inputs are closely tied to each other and therefore society's use of its natural resource endowment may have profound impacts on its future. Sustainability advocates offer three general convictions. One group asserts that the flows from

natural capital should be transformed into human capital to maintain sustainability. Another contends that perpetuating a constant stock of natural capital is the only way to achieve sustainability. A third group specifies no formula for sustainability, asserting only that the end result should provide equity across generations.

The dilemma is not trivial. Society has a fixed endowment of natural resources and the consequences of miscalculating appropriate resource management could be severe.
If management is too conservative, production in some sectors of the economy may needlessly degenerate, and social welfare (standard of living) for future generations could decrease.
If management overly exploits natural resources, basic environmental functions may go unfulfilled, leaving irreversible damages for future generations.

1.2 OBJECTIVES

The objective of this study is to evaluate the sustainability of a production process that uses both renewable and nonrenewable inputs. Sustainability will be examined by testing for the existence of substitutability, reversibility and uncertainty criteria for three different definitions of sustainability. This study is applied to soil quality for producing crops. And, although it is applied to agriculture, it offers some general procedures that may be applied to other areas of production (such as forests), where the loss of nonrenewable resources is of great concern.

To explore sustainability in an agricultural production setting, sustainability literature and economic theory are coupled with an empirical model of production. The objective may be met by addressing the following three questions: (1) What are the impacts of different definitions of sustainability on the economy and the environment? (2) Do U.S. soil conservation policies address sustainability objectives? (3) How do substitution, reversibility, and uncertainty affect optimal soil management?

2. WHAT IS SUSTAINABILITY?

2.1 DEFINITION

Sustainability has been defined by many people in an almost equal number of ways (Pezzey, 1992; Gold, 1994). In effect, it is much easier to agree to be sustainable than it is to define or achieve it (Helmers and Hoag, 1993; Schuh and Archibald, 1993). Definitions range from a precise sustain-me approach that focuses on one concern only, such as the health of rural economies (DowElanco, 1994) or environmental conservation (U.S. Department of Agriculture, 1980), to an all-inclusive definition that addresses many considerations. However, a review of the economic and development literature shows that most definitions are centered around economic, environmental and social welfare objectives (Cernea, 1993; Munasinghe, 1993; Rees, 1993).

It is difficult to get people to agree about what is sustainable when objectives are valued so differently. Although there are many interpretations, the three well known definitions we have adopted for this study are (1) sustainability as constant consumption, (2) sustainability as a constant stock of natural resources, and (3) sustainability as intergenerational equity.

2.1.1 Constant Consumption

Hartwick (1977, 1978) and Solow (1974a, 1974b) defined sustainability as the ability of society to maintain a constant stock of consumption (or productivity). This definition, referred to as *weak sustainability*, addresses economic concerns. Under weak sustainability, natural capital (natural resources) and manmade capital (physical capital) may substitute for each other in the production process. Researchers (Dixit et al., 1980; Hartwick, 1977, 1978; Page, 1977; Solow, 1974a, 1991) have proven theoretically that total production and per capita consumption may be maintained as long as profits from the use of natural resources are invested into physical capital. Weak sustainability does not require any particular endowment of capital or final goods to be passed on to future generations. Instead, it requires only that a general capacity to reproduce be maintained.

2.1.2 Constant Stock of Natural Resources

A second and seemingly contradictory definition focuses on the means of sustainability by placing great importance on the form in which productive capacity is transferred across generations. Pearce and Atkinson (1993, 1995), among others (Beckerman, 1992; Boulding, 1973; Daly, 1995; Jansson et al., 1994), contend that natural and manmade capital complement each other in the production process. In this relationship, known as *strong sustainability*, natural capital that is not easily reproducible is the limiting factor of production and, therefore, must be preserved for production to be sustainable.

Those who support strong sustainability defend their position by invoking three arguments. First, uncertainty of the consequences of natural resource depletion should lead decision makers to adopt a conservative position with regard to resource use. As Pearce and Warford (1996) note, this is comparable to the notion of safe minimum standards for plant and animal species advocated by Bishop (1978) and discussed by Lesser and Zerbe (1993). Second, natural resource depletion is permanent and any permanent change should be approached very slowly and carefully. Third, not only do natural resources provide inputs for production, they also perform multiple functions in the environment. Resources should be preserved to ensure fulfillment of these other functions.

2.1.3 Intergenerational Equity

A third and more general definition, created by the World Commission on the Environment and Development, contends that sustainability is a process "…of change in which the exploitation of resources, the direction of investment, the orientation of technological development and institutional change are made consistent with future as well as present needs" (World Commission on Environment and Development, 1987, p. 13). In other words, sustainability requires that the needs of the present are met without compromising the ability of future generations to meet their needs.

This definition differs from the previous two in that it imposes neither substitutability nor complementary relationships on natural and human inputs but requires some undefined measure of intergenerational equity to be fulfilled. This allows researchers the opportunity to test different criteria for their contribution to sustainability.

Support for both consumption and preservation of resources is reflected in governmental policies and legislation. Over the course of six decades, the U.S. Department of Agriculture has promoted both soil conservation (set asides) and maximum production (plant fence row to fence row) policies. Similarly, logging has been restricted in some areas of the country and expanded in other areas. These examples suggest that society benefits from both the consumption and the preservation of its natural resources. But how much should be preserved? How much may be consumed? Comparing the impacts of different resource management levels can help determine where the optimal level of resource protection lies and what a genuine notion of sustainability may be.

2.2 THREE COMMON THEMES

When resources are placed in a production setting, three criteria can be used to evaluate the impacts of each definition of sustainability on resource management: substitutability, reversibility, and uncertainty. The values placed on these criteria by society and by individuals can determine the allocation of resources.

2.2.1 Substitutability

Substitutability refers to the change in the use of one input as the price or the availability of another input changes. Ease of substitution is extremely relevant when one or more inputs to production are becoming scarce, since sustainability will depend on how easily and effectively other resources can substitute for the scarce input.

Substitution among inputs can be broken into three general cases: perfect substitution, imperfect substitution, and complements. Inputs are *perfect substitutes* when there is one input that can completely replace another. For example, if the current supply of coal was depleted, other fuels or hydroelectric power could be used in its place to maintain energy production. Inputs are *imperfect substitutes* when one input can partially replace a scarce input; however, some minimum amount of the scarce input is needed to maintain production. A high percentage of the human workforce may be replaced with machines, but one human will always be needed to make sure the machinery is operating properly. Inputs are *complements* when they can only be

used in some fixed proportion to produce a given level of output. Water is produced when two parts of hydrogen mix with one part of oxygen. Water will not form when any other ratio of hydrogen to oxygen is combined.

Theory addresses the substitutability of inputs on two general levels: factor interdependence and technical interdependence. *Factor interdependence* measures how the change in the price of one input will affect the demand for another input as output is held constant. *Technical interdependence* measures how the change of the price in one input will affect the demand for another as both prices and output are allowed to change. The differences, though subtle, are important. Under factor substitution, in order to maintain output at a given level, as the use of one input goes up the use of its substitute goes down. Because output is free to change under technical substitution, both inputs are free to move either up or down. Under factor complementarity, for output to remain constant, the level of both inputs applied must remain the same. Yet under technical complementarity, inputs are free to change, provided they both move in the same direction. Factor and technical interdependence examples are illustrated below.

Substitution/complementarity relationships are mapped on a single quadrant graph (Figure 2-1) with the scarce/unique input on one axis and a potential substitute on the other axis. An isoquant measures the various combinations of the two inputs which produce some constant level of output. The optimal input mix is found where the isoquant is tangent to a line representing the current price ratio (PR_1) of the two inputs. In all three panels in Figure 2-1, the optimal input mix rests at point M.

The ease of substitution is defined by the curvature of the isoquant. The flatter the isoquant, the greater the substitution possibilities. Once the isoquant forms a 90° angle, it is no longer possible to substitute away one input for another and maintain the given level of output. Suppose the ratio of prices changes from PR_1 to PR_{2a}. In order to find the new optimal input mix that produces the same level of output, a parallel shift is made from the new price ratio line to another (from PR_{2a} to PR_{2b}) so that the parallel line is tangent to the isoquant. The new point of tangency (N) represents the new optimal input mix. In Panel 1, the flat isoquant line suggests that even if all coal is depleted, energy production will be maintained with hydroelectric power. In Panel 2, the slight curve in the isoquant suggests that machinery is an imperfect substitute

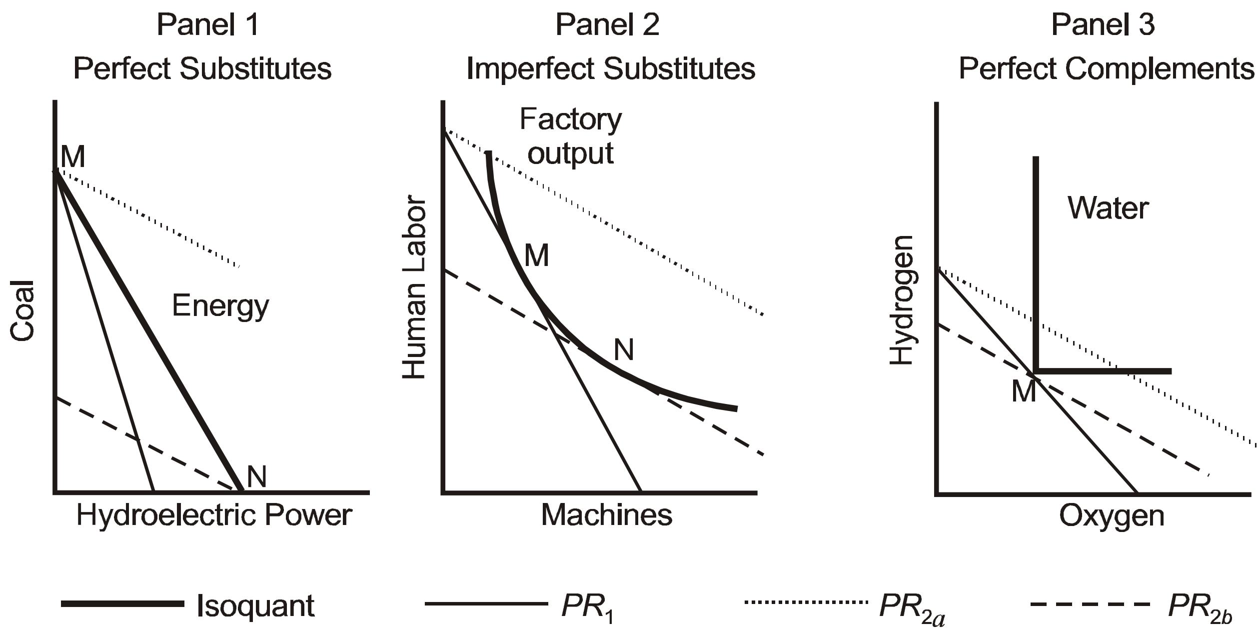

Figure 2-1. Partial substitution/complementary relationships.

for human labor—some degree of human labor will be necessary to maintain production. The kink in the isoquant in Panel 3 illustrates that there is no other mix of hydrogen and oxygen that can produce the given amount of water as effectively.

Any two inputs that are perfect factor substitutes will be perfect technical substitutes. Any two inputs that are perfect factor complements will be perfect technical complements. However, as illustrated in Figure 2-2, imperfect factor complements can become either technical substitutes or technical complements.

Assume that an automobile factory has the option to use both human labor and machinery to produce cars. In the first panel of Figure 2-2, as the ratio of human wages to machinery prices changes from PR_1 to PR_{2b}, more automobiles can be produced by increasing the use of machinery and decreasing the use of human labor (from Y_0 to Y_1). These inputs, which are factor substitutes, are also technical substitutes. However, in other types of production (perhaps another factory that uses both human and mechanical inputs), changes in output levels can only be made by some fixed ratio of change in the level of inputs used. In this case, two inputs that were factor substitutes are technical compliments.

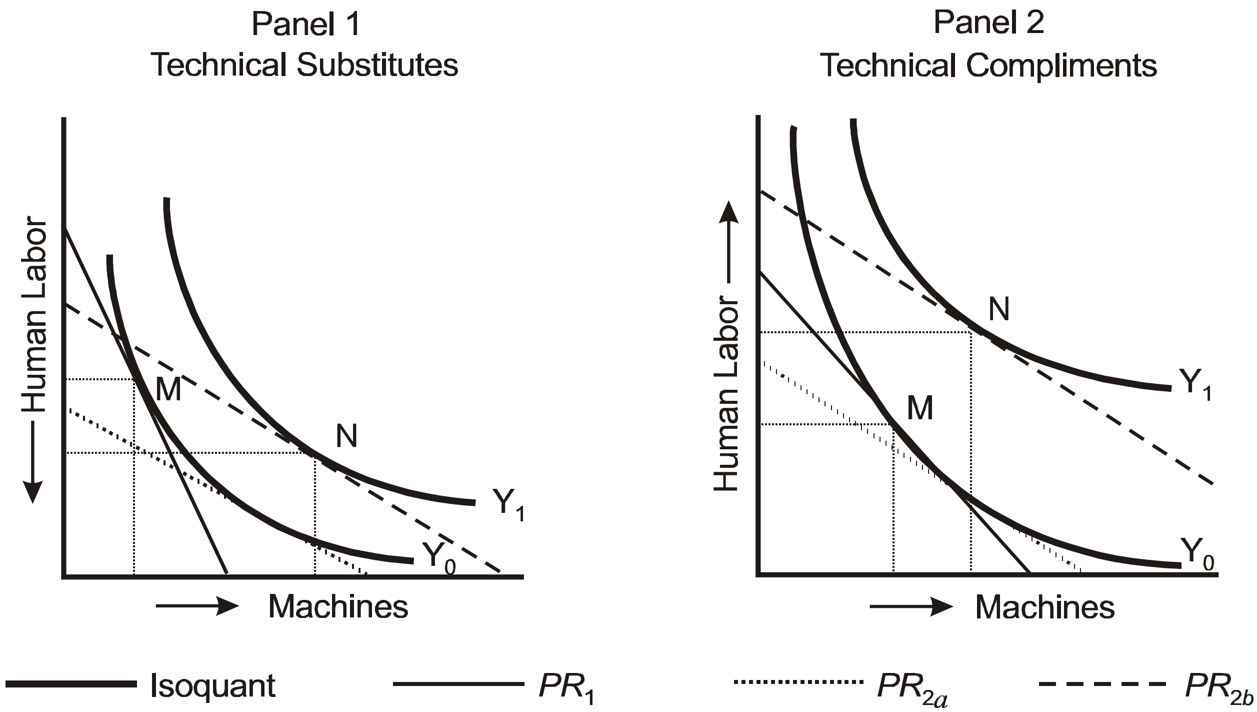

Figure 2-2. Degrees of technical interdependence.

2.2.2 Reversibility and Uncertainty

Reversibility and uncertainty are best explained together. Reversibility pertains to the ability of production to revert back to a former input mix once it has chosen others. Uncertainty refers to any unforeseen circumstances (both positive and negative) that may either follow as a consequence of, or impact production. Uncertainty arises with respect to all prices, input supply, output supply, profits, and environmental impacts.

As production depletes a natural resource it becomes more dependent on other inputs. If use of these replacement inputs later leads to unforeseen consequences, the producer may not be able to readjust because it is costly, difficult and time consuming, or even impossible. The ability to reverse input mixes becomes extremely important for two reasons, especially when circumstances resulting from uncertainty are negative. First, in many cases these impacts do not limit themselves to the particular production process but may affect other sectors of the economy or the environment. Second, these impacts may be irreversible. The three scenarios that follow illustrate degrees of reversibility and possible consequences.

Scenario 1

Reversibility: Easy
Consequences: Minimal

A manufacturer may use plantation trees or synthetics to produce office paper. If the stock of mature plantation trees is depleted, production can be maintained with synthetic substitutes. If the price of synthetics increases greatly in the future, the manufacturer can harvest the newest crop of mature trees, and manage the plantation so that it provides a continuous supply of wood for the future. It may take time, however, and be difficult to acquire an equilibrium of trees, creating serious income or cook flow problems.

Scenario 2

Reversibility: Difficult
Consequences: Moderate to Serious

A land manager controls a parcel that is 50% dry land and 50% wetlands. The wetlands are drained in order to have 100% dry land for agricultural production. Later the land manager finds that the wetlands helped control water flow (important for production) and provided habitat for rare birds. Part or all of the natural wetlands may be restored, but it may take time, effort and expense. Water flow and species habitat may be hampered until the wetland is restored.

Scenario 3

Reversibility: Impossible
Consequences: Severe

A tea maker uses exotic and domestic tea leaves to produce a flavorful tea. The exotic leaf is necessary to production because it alone can produce the special taste. Other manufactures use this leaf in other production processes and native insects depend on the leaf as a vital food source. As the exotic leaf is consumed, production remains relatively unaffected. When the plant becomes more scarce, however, production drops until it reaches zero as the leaf is completely depleted. Multiple production processes have been slowed or halted, and two natural resources (the exotic leaf and the insect species) have been lost forever.

The process of irreversibility is illustrated in Figure 2-3. Again, the isoquant represents all the various combinations of two inputs which can be used to generate the same specified level of

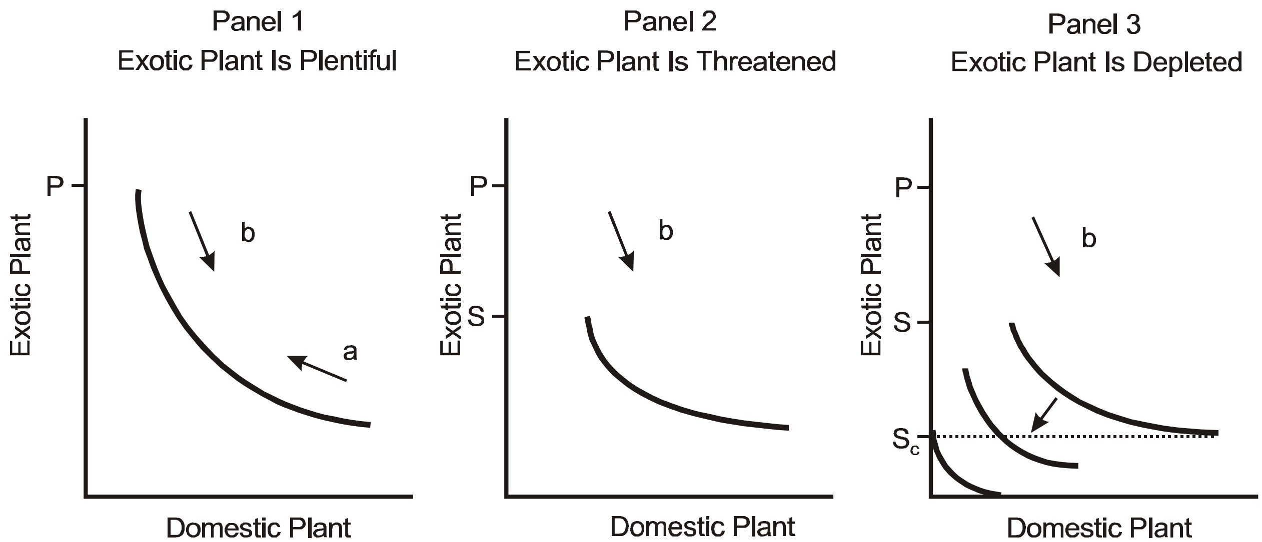

Figure 2-3. Illustrating irreversibility.

output. Let this particular level correspond to the demand for the product in the market. Returning to the tea leaves example, when the exotic plant is plentiful (P), the tea manufacturer has the option to (a) move away from domestic leaves and use more exotic, or (b) move away from the exotic and use more domestic, in response to availability and price of the two types of leaves. However, as supplies of the exotic plant become scarce (S), the manufacturer will be forced to move the input mix further down the curve in the (b) direction. Graphically, the isoquant has been truncated, as shown in Panel II. Although in theory the isoquant still looks the same, the loss of the exotic plant has reduced the manufacturer's real set of possible input combinations to exclude the upper portion of the isoquant. At some point, as the supply of the exotic plant falls below its critical level (S_c), the plant can no longer reproduce itself. Output levels will drop with the loss of the plant, since there simply is not enough input to produce the desired output. Ultimately, the plant is extinct and production no longer possible.

When input mixes dependent on substitutes for natural resources lead to unforeseen negative consequences, it is likely that the magnitude of the negative impact will be much larger for society than it will be for the individual producer. Profits for a tea maker may decline, if the quality of tea is reduced by the loss of the exotic plant. However, two natural resources—a plant and an insect species—have been completely destroyed. Reversing societal decisions can be

slow or impossible (it might take a lawsuit to restrict the harvesting of the exotic plants— during this time the plants could become extinct). Therefore, it is also likely that the risk that society attaches to depleting a natural resource will be higher than that for an individual. Individuals will be more likely to deplete a natural resource than society, and thus, when left to individuals, it is likely that the resulting level of natural resource conservation will be suboptimal from society's point of view.

Appropriate Input Substitution for Scarce Resources

Rule 1: A scarce input may be partially (completely) depleted when an imperfect (perfect) substitute exists that imposes little or no negative externality (i.e., negative economic, environmental or social impacts).

Consequence: Output may be maintained or increased, as shown in the cases of energy and automobile production.

Rule 2: Resource conservation may be needed if an input's contribution is unique to a production, ecological or valuation process and not easily substitutable.

Consequence: If the resource is regenerative, production can be maintained at a level that requires the use of a resource that is less than or equal to its regenerative rate. If the resource is finite, then production levels must decrease in order to preserve the resource.

2.3 ASSESSING SUSTAINABILITY

There are many ways to consider whether the actions of society are sustainable. Here, the following question is asked: How should society manage a unique resource stock to provide both economic and environmental services? To begin to answer this question, the following points should be considered.

- Society is endowed with a stock of a natural resource.
- This resource provides economic and environmental services.
- If the economic services of the resource are stressed, will it crash or can an equilibrium be found where some environmental services are maintained?
- What is the relationship between the stock of the resource and the economic and environmental services it provides?

- What is a sustainable path for the economic and environmental services?

  Case 1: The resource quality crashes and both the economic and environmental values are lost.

  Case 2: All environmental values are preserved and no economic value gained.

  Case 3: A sustainable combination of both economic and environmental services is found based on the value of each.

3. A CASE STUDY OF SOIL CONSERVATION IN THE UNITED STATES

3.1 BACKGROUND

Although many studies have discussed an assessment of the environment based on sustainability criteria, few have been able to model real natural resources. Consequently, these studies usually are unable to provide empirical conclusions that support theories about substitution, reversibility and uncertainty. This study conducts a detailed empirical analysis of one of the most impacted ecosystems in the country, soil on American farms. Soil management is a reasonable place to start when examining environmental assessment. One reason is that soil is the most studied environmental stock in the world. Examined first for its part in promoting crop production (Hilgard, 1892; Karlen et al., 1997; Olsen, 1943; Walker and Young, 1986), data and analyses now also exist to explain the role of soil in food quality and safety and ecosystem management (Johnson et al., 1992; Kennedy and Papendick, 1995; National Research Council, 1993; Parr et al., 1992; Warkentin, 1995). Results from these studies illustrate other reasons why environmental assessment may begin with the soil.

- Soil has an important impact on the environment. For example, according to the National Research Council, erosion from agriculture is responsible for over half of all surface water pollution (National Research Council, 1993). Soil is now recognized for its positive impact on many functions of the ecosystem, such as nutrient recycling, rainfall partitioning and buffering. However, when it leaves the farm, soil is also responsible for negative impacts that affect water quality, air quality and wildlife habitat.
- For over a half century, the U.S. Government and farmers have spent billions of dollars for soil conservation on croplands in an effort to reduce soil erosion and reduce impacts on wildlife and water (U.S. Department of Agriculture, 1994).
- Because soil quality is related food production, it can significantly impact human life.

There are two further reasons which make soil an appropriate area of focus. First, recent research in soil science has produced a list of measurable soil characteristics that can be used to describe the quality (stock) of a particular soil (Bowman et al., 1989; Doran et al., 1996; Kiniry

et al., 1983; Larson and Pierce, 1994; Pierce et al., 1983). This creates some general consensus about the assessment endpoint of soil quality. Second, data for soil are more abundant in the U.S. than data for any other natural resource. There are extensive national homogenous databases (Soils-5, National Resource Inventories) with soil variables for polygons as small as a few acres. In addition, a team at the USDA Blacklands Research Center in Temple, Texas, supports the most extensive soil management database available to date. Together, these data can be used in simulation models to examine the impacts of the multiple objectives of sustainability on resource assessment. Policies or management that maintains soils, and those that maintain other objectives such as economic returns, can be compared. Using biophysical models of soil productivity, potential impacts can be observed before they actually happen.

The existing soils, sociology, development, ecology and economic literature was surveyed for two purposes. The first was to determine what, if any, related work has been undertaken. This included a review of the many notions of sustainability and the criteria used to judge sustainability. The second purpose was to gather theories that would help formulate theoretical underpinnings for resource management.

A review of the literature showed that many studies have acknowledged the need for an extensive study of sustainability, but none have yet undertaken an analysis of multiple concepts and criteria of sustainability via an expansive resource data set. Perhaps this is because no single discipline possesses all the theoretical and empirical tools needed to attempt a project of this proportion. By combining sustainability and evaluation criteria from the social and ecologic literature with soil quality, degradation, and regeneration relationships adopted from the agronomy and soil science fields, the following proposal was made: for soil, sustainable resource management will be determined by the availability of soil and substitute inputs subject to the ease of substitution and the risks associated with irreversibility and uncertainty.

This postulation is tested by developing an index of soil quality and applying it in a dynamic model of production.

3.2 CONCEPTUAL FRAMEWORK

3.2.1 Introduction to Soil Quality

Soil is a dynamic, heterogeneous, living system of micro-organisms, organic matter, water, gases and mineral particles. Each system, comprised of surface and subsurface layers, or horizons, is formed from long term interactions of parent materials,[1] weathering and biological processes. The resulting combination is called a soil series, of which there are over 17,000 classified in the United States to date (Natural Resources Conservation Service, 1995).

The particular combination of a soil's many chemical, biological and physical properties determines its ability to function. The definition of soil quality proposed by the Soil Science Society of America encompasses the multiple functions of the soil. "[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" (Karlen et al., 1997, p. 6).

Soils acquired their particular characteristics through years of formation, and may still be modified by natural processes (primarily erosion, yet also temperature and water content) and human activities (mixing or erosion) today. Changes in these soil properties can alter the soil's ability to function and, therefore, could have implications for sustainability.

3.2.2 Soil Quality Assessment

Assessing soil quality is often compared to assessing human health (Larson and Pierce, 1991; Doran and Parkin, 1994; Acton and Gregorich, 1995). During a medical exam, key indicators such as temperature, heart rate, blood pressure, height and weight are measured that together make a general account of health. If these measurements are within accepted levels, the individual is assumed to be functioning normally. If these measurements are outside of an acceptable range, further tests can be conducted to determine the cause for the irregularity and perhaps prescribe a healing treatment. Similarly, if there exists a set of basic measurable soil indicators, there would be a means of assessing soil health. If the indicators are within an

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[1]Parent material is defined as the "unconsolidated and more or less chemically weathered mineral material from which soils may be synthesized," (Buckman and Brady, 1960). These materials develop from igneous, sedimentary and metamorphic rocks.

acceptable range, the soil can be presumed to possess the capacity to carry out its functions. If these indicators are outside of the acceptable range, a careful look at other chemical, physical, and biological soil properties may help identify the cause of the abnormality.

The assessment endpoint (quality) may vary substantially for different purposes. Using the health analogy, someone well enough to walk may not be well enough to run a marathon. Consequently, any measure of soil quality must consider the intended use. For soil, producing native grasses may be easier to sustain than monocultural cropping. Therefore, using a series of indices to describe soil quality, each with its own purpose, is recommended. Here, the focus is on two such indices, the quality of soil for producing crops, and nitrate leaching. No specific index is developed for nitrate leaching, but rather the impact of quality for yield on leaching is investigated to determine consistency between the two objectives.

3.2.3 An Index of Soil Quality

Recently, many researchers have recommended so called "complete" sets of soil quality indicators.[2] However, a model developed by Pierce et al. (1983) seems to be the best starting point here. The Pierce model is simple to understand, and not only does it specify both a set of soil quality indicators and a standard to measure them against, but it can also be used to predict the changes in soil quality (and possibly production) brought on by resource degradation. In this model, soil productivity (*PI*) was calculated as

$$PI = \sum_{i=1}^{r} (SAWC_i * SBD_i * SPH_i * WF_i), \tag{3-1}$$

where *SAWC* is the sufficiency of available water capacity, *SBD* is the sufficiency of bulk density, *SPH* is the sufficiency of pH, *WF* is a weighting factor associated with each i^{th} horizon, and *r* is the number of 10-centimeter horizons in the rooting depth.

In the Pierce et al. (1983) study, soil quality was calculated for three different soils types: (1) stable soil (soil quality does not change much with erosion), (2) neutral soil, and (3) susceptible soil (soil quality may change greatly with erosion). The researchers forecasted potential impacts of erosion on soil quality and production for each soil type. The analysis

[2]See National Research Council (1993), Doran et al. (1994) and Karlen et al. (1997) for more details.

revealed four important insights about the relationship between erosion and soil productivity and the relationship between soil productivity and production.

(1) Erosion can change the levels of available water capacity, bulk density and pH in the soil and thus change the productivity of a soil.

(2) Susceptible soils will experience greater changes in soil quality than stable soils under conditions of erosion.

(3) A positive (negative) change in soil productivity will likely have a positive (negative) effect on agricultural production.

(4) The directional change in soil productivity depends on the relative quality of subsoils as compared to the quality of the surface soils.[3]

3.2.4 Soil Quality in a Production Setting

In agricultural production, yield is a function of weather conditions, added inputs and soil quality. Added inputs include variables of production that the farmer can control, such as tillage level and use of fertilizers and chemicals. In addition to these inputs, there is an endowment of soil quality. Soil quality is a unique input in the production process because (1) unlike added inputs, the farmer has no control over the initial endowment, and (2) as illustrated in Figure 3-1, soil quality can contribute to the effectiveness of the added inputs and thereby have implications for production levels and the mix of inputs a farmer will use in production.

Assuming that a farmer chooses an optimal mix of two added inputs, fertilizer and water, a maximum yield can be attained ($Y_{f,w}$) as in Figure 3-1. Including soil quality (sq) in the production of the crop can have a positive impact on the plant growth. The amount of impact depends on how much soil quality affects how water and fertilizer contribute to plant growth. If soil quality acts independently of both water and fertilizer, productivity of those inputs does not change. If their productivity levels do not change, the farmer will continue to use those inputs in the same way, regardless of what happens to soil quality. For example, if soil quality

[3]From this insight, it is evident that soil is a very unusual resource. Erosion can remove some of the soil base and negatively impact soil quality. But in some cases, by partially depleting the soil resource base, soil quality may improve and therefore better perform its multiple functions in its ecosystem. See Popp (1997) for further discussion of this particular case.

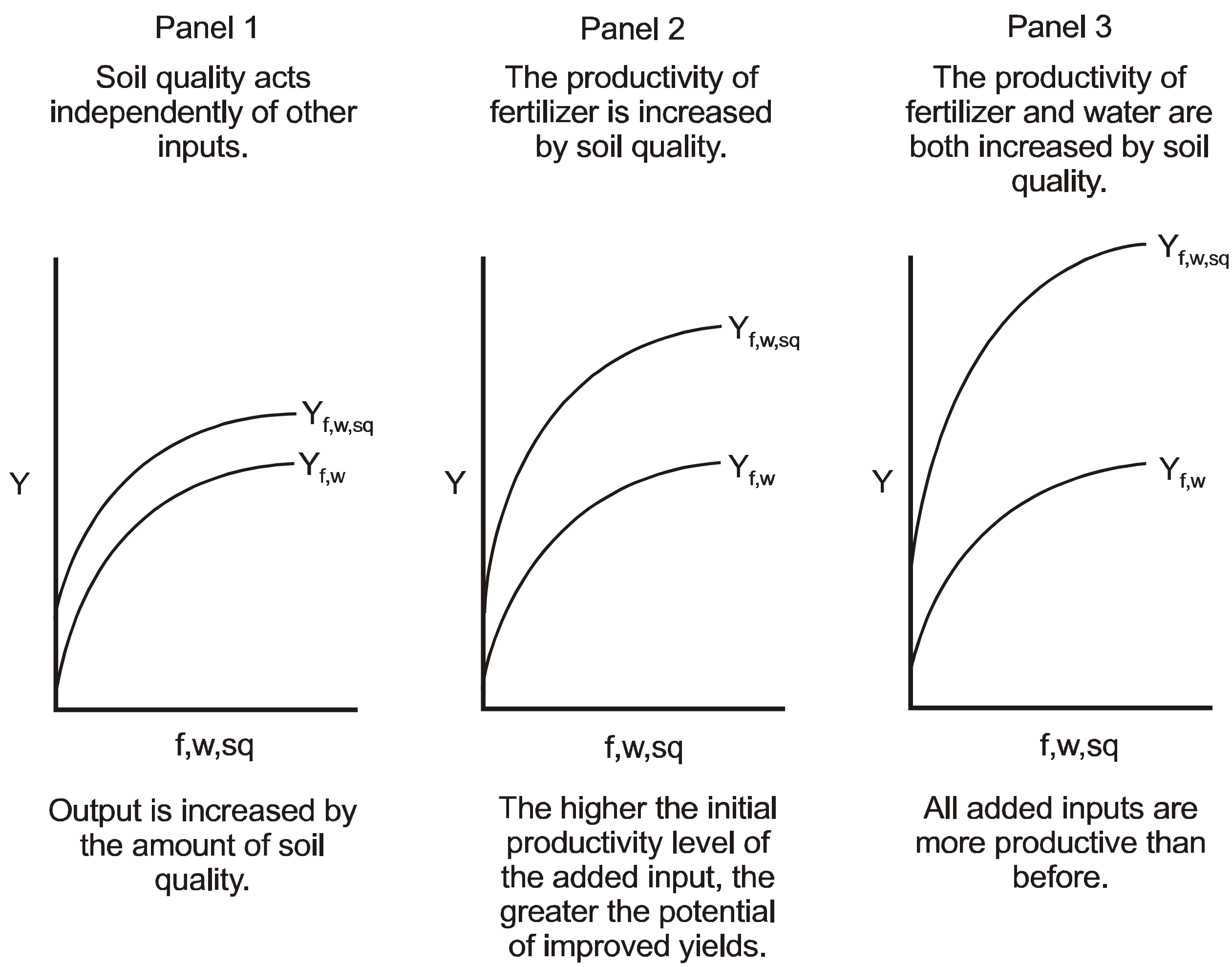

Figure 3-1. Impacts of soil quality on production.

adds 50 units of productivity to the production process, output will be 50 units more for every level of fertilizer and water used.

Sometimes soil quality and other inputs, such as water and fertilizer, are dependent on each other (complements or imperfect substitutes). For example, a reduction in soil quality due to erosion might make fertilizer less productive. If fertilizer is less productive than before, a farmer might have to reduce fertilizer and, consequently, the output, as soil quality is diminished.
An example of how productivity increases for fertilizer as soil quality is improved (or diminishes as soil quality is reduced) is shown in the second panel of Figure 3-1. Productivity gains are

greater at higher levels of fertilizer input due to the multiplicative impacts of soil quality and fertilizer working together.

Soil quality could affect all added inputs in the production process. As shown in the third panel of Figure 3-1, output will increase the most for this example, because both water and fertilizer are more productive. The substitutability of soil quality for other inputs, therefore, greatly impacts the importance of protecting a given endowment of soil. Given that soil quality improves output, farmers would rather have some endowment of soil quality than none at all. And, to the extent soil quality improves the productivity of other inputs, farmers would rather have higher levels of soil quality than lower levels.

3.2.5 Soil Quality Degradation—Natural Influences

All natural resources change over time through the normal operations of the natural environment.[4] Eutrophication (the aging process of a lake) provides a good example. When a lake is newly formed, there is little plant life. But as time goes on, plant life multiplies and the water slowly disappears until the lake no longer exists. Tourists may walk around the lake on paved trails to observe plant life in its natural habitat. Just looking at the lake has no impact on the eutrophication process. Eutrophication depends only on the resource quality, which in this case is the characteristics of the lake and the living organisms within it.

Similarly, all soils are subject to a natural rate of change caused by erosion. Erosion removes soil from the surface and eventually exposes the subsurface layers. Soil quality degradation will depend, in part, on how much change erosion can cause (i.e., where potential change is determined by the quality of the topsoil compared to the quality of the lower horizons[5]). This will depend on the quality of the surface horizon when compared to the lower horizon, on the ability of natural processes to offset erosion, and on the influence of human activities that accelerate slow erosion rates.

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[4]Only cases of deterioration are examined here. Although all soils have a natural rate of regeneration, that rate is slow enough for soil to be considered a nonrenewable resource for the time frame of this research.

[5]Similarly, the erosion rate also will be determined, in part, by the slope of the land. The process remains the same; only the rate will differ.

There are many paths of change soils may take. This study examines three general cases as depicted in Figure 3-2. Soils whose subsurface layers have a similar quality to the top soil are called *stable* soils. As these soils are worn away by erosion, their quality remains relatively unchanged (Panel 1). Some soils have lower layers that are similar but reduced in quality. These are called *neutral* soils because as they are impacted by erosion; the soil degrades for a time but then stabilizes, as shown in Panel 2. Other soils, *susceptible* soils, are very vulnerable to erosion because beneath a thin good quality top layer is a very poor quality soil. With erosion, the quality of the soil declines continuously until it (asymptotically or actually) reaches zero, as shown in Panel 3. Examples of these soil cases are discussed further in Pierce et al. (1983).

3.2.6 Soil Quality Degradation—Human Influences

Humans can influence soil quality degradation by altering the rate of erosion. Some inputs in a production process may increase or decrease erosion rates. As shown in each of the panels of Figure 3-3, the natural path of soil quality is altered up or down. Conventional tillage equipment (such as a moldboard plow) may loosen soils, making it easier for them to be carried away by wind and water. This *soil using* input can have initial positive impacts on production, but will increase the rate of production decline later. Inputs that do not have any impact on soil degradation are considered to be *soil neutral* inputs. A producer may choose to establish conservation practices, such as placing vegetative cover on fallow land, contour plowing, or terracing. These practices may or may not impact current production levels, but will slow the rate of soil degradation.

3.2.7 Managing Soil Quality for Sustainability

As soil quality changes, farmers will attempt to adjust the input mix to maintain economic viability (and meet environmental standards if society requires them). In other words, these firms manage for sustainability. Managers begin by asking, Is the production process sustainable as soil quality declines? The answer depends on the relationship between soil quality and output, as well as the relationship between soil quality and other inputs. The impacts of depreciating natural capital can be complex. Human resources have a technical relationship among themselves and with the natural capital (soil quality). The relationship between any input and

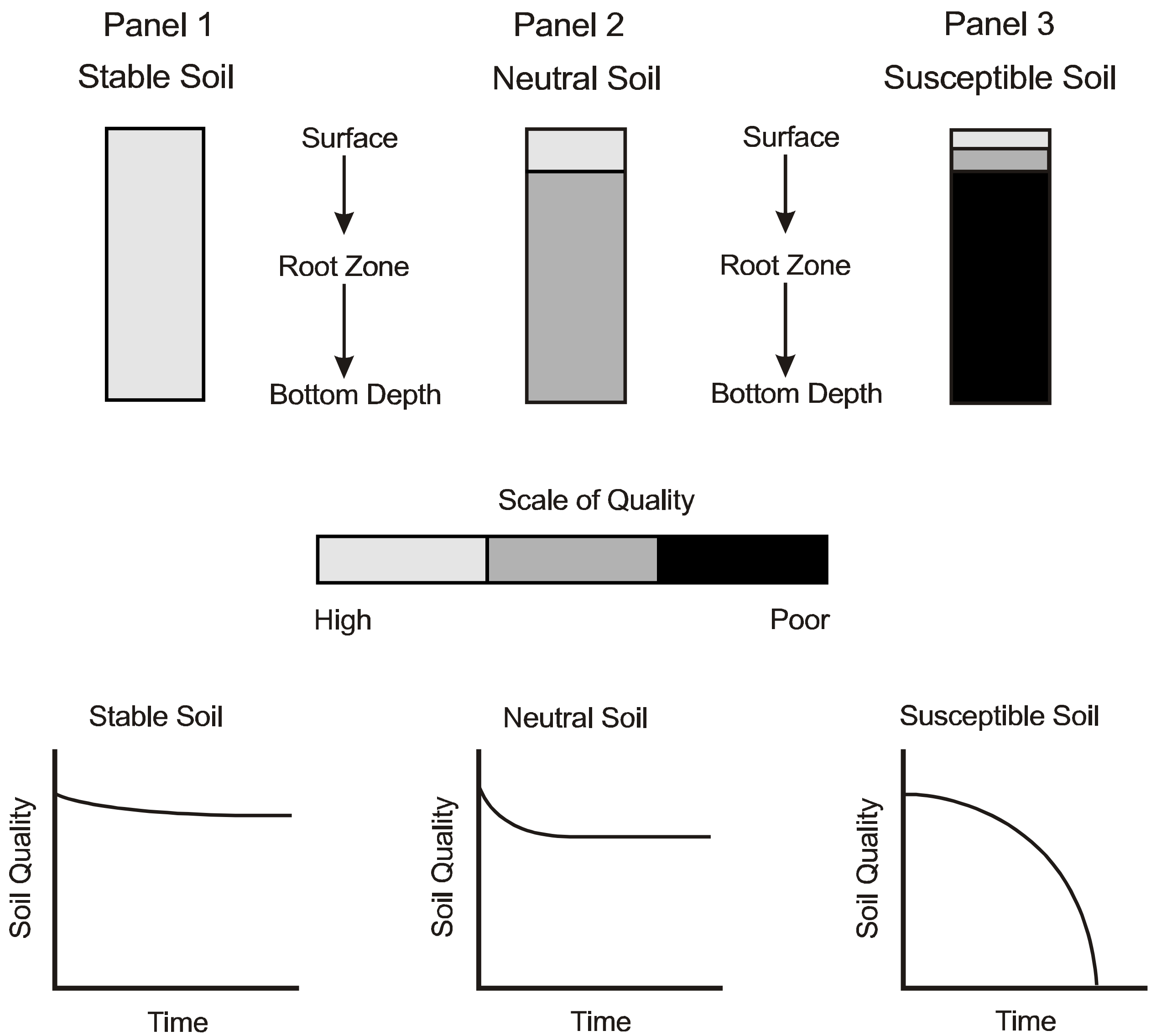

Figure 3-2. Three types of soil and their paths of soil quality deterioration.

soil quality will be independent, substitutable, or complementary. Moreover, this relationship may change as soil quality deteriorates. It is expected that as long as substitutes exist, as soil quality decreases, the use of other inputs will follow one of the paths in Figure 3-4 in an attempt to maintain output levels.

A producer may choose to irreversibly depreciate soil quality in favor of a substitute, as shown in Panel 1. When the input mix changes this dramatically, yields may be maintained for a time. However, unforeseen economic and environmental consequences may ensue. For

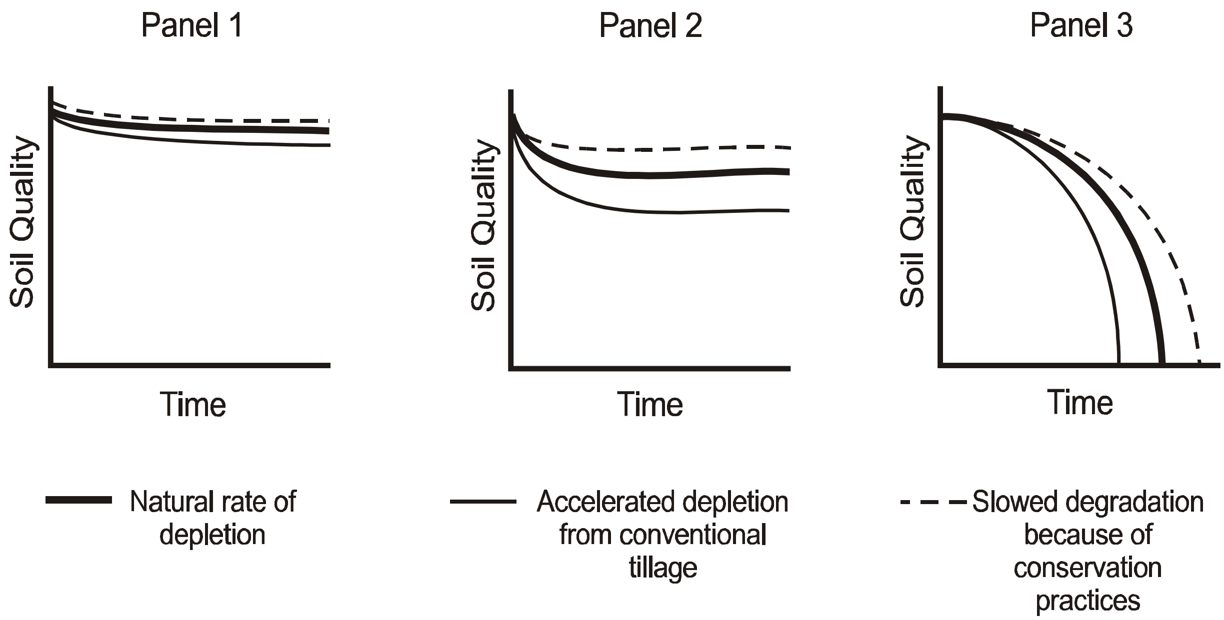

Figure 3-3. The effect of erosion on soil quality.

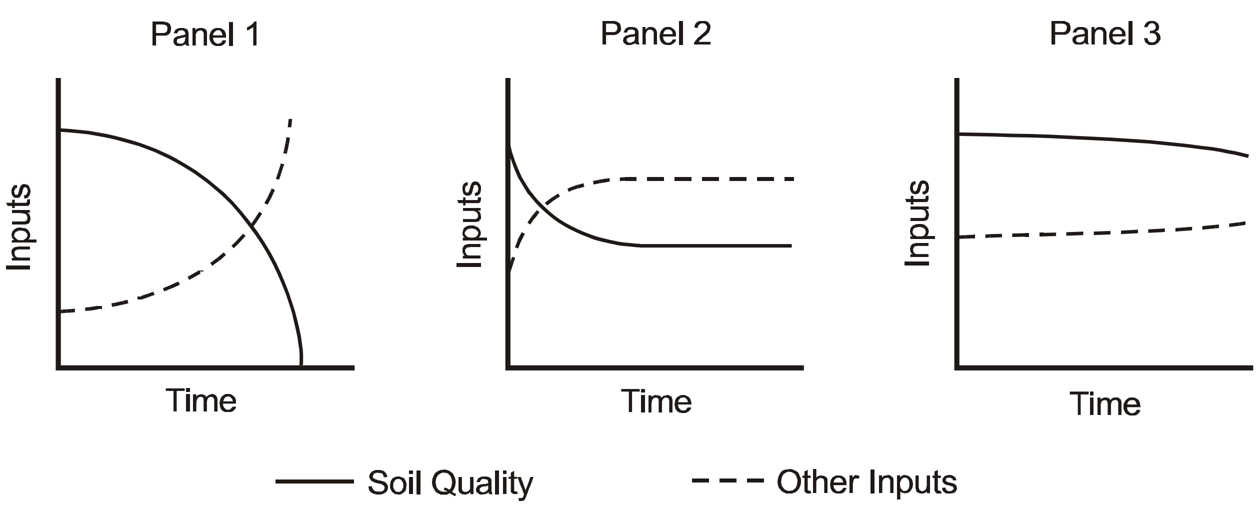

Figure 3-4. Possible trade-off between soil quality and other inputs.

example, the increased use of a compensating input in one sector may cause excess demand in the overall economy, increasing the price of the input, and reducing its affordability in all sectors. Whereas moderate use of a particular input may cause little or no environmental damage, vast

increases in the use of an input in a short period of time may overwhelm the assimilative capacity of the environment and cause long term damage. In either circumstance, a producer may want (or be forced) to change the optimal input mix to include more soil quality and less of one or more other inputs. If soil quality has followed a path of degradation, as in Panels 2 or 3, increasing soil quality may still be possible. However, if soil quality has followed a path of irreversible decline, as in Panel 1, the possibility of altering the input mix to include more soil quality has been eliminated and production may no longer be sustainable.

3.3 A DYNAMIC MODEL OF SUSTAINABILITY IN PRODUCTION

The empirical dimension of this investigation builds upon the works of Clark and Furtan (1983), McConnell (1983), Pierce et al. (1983), Saliba (1985), Segarra and Taylor (1987) and Hoag (1997). Although none of these projects sought to study sustainability directly, their theoretical and empirical innovations have identified many of the key determinants of production and the impacts of changes in soil quality. Along with data for real inputs and the characteristics of soil quality, the models in the above studies provide the basis for a dynamic model of production and soil quality that illustrates the economic, social, and environmental aspects of various definitions of sustainability.

Production of any crop *Y* is a function of soil quality (*SQ*), soil using inputs, and soil neutral inputs. In agricultural production, tillage (*L*) is a soil using input, whereas soil nitrogen (*SN*), nitrogen fertilizer applied (*N*), and sprayed pesticides (*P*) are soil neutral inputs. Accounting for precipitation (*W*) as well, production can be expressed as some function *f*:

$$Y_t \ = \ f(SQ_t, L_t, SN_t, N_t, P_t, W_t)\,. \qquad (3\text{-}2)$$

Soil quality is some function *g* of the characteristics that impact its ability to perform in its environment. Pierce et al. (1983) stated that these characteristics were available water capacity (*AWC*), bulk density (*BD*), and pH (*PH*). Recent studies (Doran et al., 1996; Karlen et al., 1997) have stated that soil organic matter (*SOM*) is also an important indicator of soil quality. Together these four components can be used to create an index of soil quality:

$$SQ_t \; = \; g\,(AWC_t\,, BD_t\,, PH_t\,, SOM_t\,)\,. \tag{3-3}$$

The change in soil quality each year is determined by annual soil loss. Soil loss in any period depends upon both the natural level of soil loss (a function of the previous period's soil quality) and the decisions (*M*) a producer makes each period, which can increase (tillage) or decrease (soil conservation) the rate of soil loss. Therefore, the change in soil quality in each year can be expressed as some fraction h of soil quality and management decisions:

$$SQ_t = h(SQ_{t-1}, M_t). \tag{3-4}$$

Soil nitrogen, in any period, is some function *k* of the soil nitrogen level, nitrogen applied, the level of tillage, what was taken up by the crop (proxied by yield) and what leached out (*LCH*), all from the previous period:

$$SN_t \; = \; k(SN_{t-1}, N_{t-1}, W_{t-1}, L_{t-1}, Y_{t-1}, LCH_{t-1}). \tag{3-5}$$

Leaching, in any period, is some function *m* of soil nitrogen, nitrogen applied, tillage, precipitation, and crop uptake in the same period:

$$LCH_t \; = \; m\,(SN_t\,, N_t\,, W_t\,, Y_t\,)\,. \tag{3-6}$$

Together, Equations 3-2 through 3-6 provide the basis for a producer's dynamic problem that can be used to address economic, environmental, and social aspects of production. Simply stated, the producer's problem is to maximize the discounted profits of production subject to the availability of soil quality and the level of the environmental byproducts of production:

$$\begin{aligned} \max \text{II} \; = \; \sum_{t=0}^{T} (1+r)^{-t}\,[\,P_y\; f\,(SQ_t\,, L_t\,, SN_t\,, P_t\,, W_t\,) \; - \\ u_1 L \; - \; u_2 N \; - \; u_3 P \; - \; u_4 SC], \end{aligned} \tag{3-7}$$

subject to $$SQ_1 = h(SQ_{t-1}, M_t), \tag{3-8}$$

$$SN_t = k(SN_{t-1,} N_{t-1,} L_{t-1,} Y_{t-1,} LCH_{t-1}), \tag{3-9}$$

$$LCH_t = m(SN_t, N_t, L_t, W_t, Y_t) \tag{3-10}$$

where P_y is the price of the output, the u_i are prices for the various management practices, and r is the discount rate.

A producer's management decisions influence the level of crop production in any given year and have economic, environmental, and social consequences. Social considerations are captured by tracing the paths of the economic and environmental impacts, thus allowing the use of this model to examine the various concepts of sustainability and soil quality identified above in a more meaningful way. By imposing the different definitions of sustainability on the model, the conditions described below are expected.

- For each soil type, there is an optimal path of input use that will result in the optimal amount of soil quality depletion, output, profit, and environmental waste.
- When output levels are not allowed to fall on a stable soil, soil depletion may be averted by changing the input mix. As a result, soil quality and profits may remain stable and environmental impacts minimal.
- When output levels are not allowed to fall on a susceptible soil, adjustment of the input mix may not be enough to compensate for the depleted soil quality. As a result, output may not be maintained, profits may fall, and environmental impacts may become worse through the increased use of substitutes for soil quality (i.e., more fertilizers that can run off into water bodies).
- Because stable soils are not easily impacted by erosion, maintaining soil quality on a stable soil may require only slight adjustments to the optimal input mix. Profits, output, input levels, and environmental impacts may remain stable.

- Maintaining soil quality on susceptible soils will likely require large investments in soil conservation capital. Output may be maintained, but profits will decrease unless the revenue from the maintained output exceeds the cost of soil conservation.

These conditions, among others, can be investigated over multiple soils and regions of the country. Empirical results of this investigation are presented in Chapter 4.

4. ANALYSIS AND RESULTS

This analysis is divided into four parts. First, soil series and crop management data are placed into a model to simulate crop growth and other economic and environmental aspects of production. Using some of the soil characteristics produced by the simulation runs, a new index of soil quality is generated. Next, through regression analysis, simplified mathematical representations of a producer's dynamic problem from the simulation output are estimated. Finally, these functions are placed into an optimization framework where the three definitions of sustainability are examined.

4.1 DATA COLLECTION

Nonirrigated corn production on three soils each in Minnesota, Iowa, and Missouri were chosen as the setting to test the impacts of the various definitions of sustainability. The state, crop, and soil selections were based on previous studies using productivity indices (Kiniry et al., 1983; Pierce et al., 1983), and on advice from experts from the Natural Resources Conservation Service (Ceolla, 1997; Tammons, 1997). Three levels of tillage, fertilizer, and pesticide use for corn producers in those states were taken from a national survey of producers (U.S. Department of Agriculture, 1990-1995), the USDA's newest and most extensive data set on soil quality characteristics, and on information from USDA about soil management patterns. This data has been integrated into a simulation model framework (EPIC) by members of the Natural Resource Conservation Service in Temple, Texas, thereby providing a setting that simulates in multiyear periods the economic, environmental, and social impacts of production on soils and for realistic management practices.

4.1.1 EPIC Simulation Model

The Environmental Policy Integrated Climate (formerly Erosion Productivity Impact Calculator), or EPIC, model has been used extensively to evaluate crop productivity, degradation of soil resources, impacts on water quality, responses to different input levels and management

practices, responses to spatial variations in climate and soils, and risks of crop failure (Mitchell et al., 1995). It has also, in part, been designed to track and answer the following questions, all of which are related to the issues of sustainability (Dyke and Heady, 1985).

- To what extent can capital and labor substitute for soil resources altered by erosion?
- What is the additional cost incurred when these substitutions are made?
- When do these substitutions become physically or economically impossible?

Crop production was simulated for 100 years based on the soil and management specifications listed in Table A4-1 (all tables cited in this chapter are located in Appendix 4A). Corn production was simulated for nine tillage/fertilizer management scenarios:

(1) conventional/low,
(2) conventional/medium,
(3) conventional/high,
(4) conservation/low,
(5) conservation/medium,
(6) conservation/high,
(7) no till/low,
(8) no till/medium, and
(9) no till/high.

Starting values for all other variables were set to the EPIC defaults. A total of 81 scenarios, nine tillage/fertilizer scenarios on nine soils, were run for 100-year increments. As a result, 8,100 observations were generated for more than 200 soil, production, weather, economic, and environmental indicator variables. Simulated yields were calibrated against actual reported yields in the three regions to help ensure that the model results were representative of the study area.

4.2 DEVELOPMENT OF A SOIL QUALITY INDEX

Because many studies advocate the importance of soil organic matter for soil quality (Acton and Gregorich, 1995; Bowman et al., 1989; Doran et al., 1996; Karlen et al., 1997; Olsen et al., 1994), the index developed by Pierce et al. (1983) was adapted to include organic matter information. A sufficiency for soil organic matter was created based on the works of Bowman and Petersen (1996) and Pieri (1995). Calculations for the other index components were

consistent with the methods used by Pierce et al. (1983). Soil quality (*SQ*), in any given year, is the summation of the product of a weighting factor (*WF*) and sufficiencies of available water capacity (*SAWC*), bulk density (*SBD*), pH (*SPH*), and organic matter content (*SOMC*) for each i^{th} horizon in the rooting depth:[6]

$$SQ = \sum_{i=1}^{r} (SAWC_i * SBD_i * SPH_i * SOMC_i * WF_i). \tag{4-1}$$

Values for the individual sufficiency equations and weighting factors range from zero to one. When multiplied together, these sufficiencies form an index of soil quality that also ranges from zero to one. The closer the value is to one, the better the soil quality.

Table 4A-2 shows the ranges of soil quality for each soil under three levels of tillage. Fertilizer levels are ignored because fertilizer is a soil neutral input and has no influence on inherent soil quality. Even under conventional tillage, stable soils reach a steady state quality at 0.72. Neutral soils are impacted by erosion and tillage more than stable soils, but eventually their soil quality levels stabilize at about 0.66. The quality of susceptible soils decreased at an increasing rate, even under no till practices, suggesting that susceptible soils may become completely depleted over time.

4.2.1 Soil Quality and Yield

As reported in Table 4A-3, yield fluctuations over the 100 years were considerable. For example, yields as high as 166.7 bushels and as low as 100.4 bushels were recorded on the Iowa stable soil. Moreover, yields on neutral and susceptible soils sometimes were greater than on stable soils. For example, Minnesota's neutral soil produced a high yield of 197.4, whereas the high yield on the stable soil was only 164.7. These fluctuations occur in EPIC-type growth models because of extreme weather events within the simulation period or other modeling factors. On average, over the 100 years, soil quality/yield relationships were as expected for all soil types. That is, the stable soils produced higher yields than neutral soils, and produced much higher yields than the susceptible soils.

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[6]Details about the index formulation can be found in Popp (1997).

These results from the simulation model are consistent with the proposition that soil quality is an important input into agricultural production. The better the soil quality, the greater the yield per unit of input. Also, soils that are more susceptible to erosion (whether natural erosion or erosion induced by human activities) have greater losses in soil quality.

4.3 ECONOMETRIC EVALUATION OF RELATIONSHIPS

Soil quality was placed in a dynamic setting to examine how changes can influence the use of other inputs. This can be a convoluted process; EPIC expresses crop production as a complicated relationship among hundreds of variables. Dynamic sustainability questions are, however, more manageable when the components of the optimization model are expressed as a function of a few key variables. Using fewer variables also provides more degrees of freedom and reduces the possibility of multicollinearity. A brief discussion of the pertinent data manipulation techniques follows.

The EPIC simulation model generates data both across characteristics and over time. Panel data has been used frequently to address questions in classical areas of economics, such as market structure return, investment, and market demand. Rarely has it been employed to examine agricultural and resource issues in economics. Using the fixed effect regression technique on the panel data, the following four equations over nine soils were estimated:

$$Y_t = f(SQ_t, L_t, SN_t, N_t, P_t, W_t) \qquad \text{adj } R^2 = .729 \qquad (4\text{-}2)$$

$$SQ_t = h(SQ_{t-1}, L_{t-1}) \qquad \text{adj } R^2 = .986 \qquad (4\text{-}3)$$

$$SN_t = k(SN_{t-1}, W_{t-1} N_{t-1}, L_{t-1}, Y_{t-1}, LCH_{t-1}) \qquad \text{adj } R^2 = .999 \qquad (4\text{-}4)$$

$$LCH_t = n(SN_t, N_t, W_t, SQ_t, P_t, L_t) \qquad \text{adj } R^2 = .737, \qquad (4\text{-}5)$$

recalling that *Y* is corn yield or output, *SQ* is soil quality, *SN* is soil nitrogen, *N* is added fertilizer, *P* is pesticide, *W* is precipitation, *L* is tillage (the soil conservation component of M, tillage and soil conservation, was added later in the optimization section of the project), *LCH* is leaching, and $_t$ and $_{t-1}$ represent current and previous period values, respectively. Using methods suggested

by Hsiao (1986), Maddala (1993), and Vickner (1997), all equations were tested and corrected for misspecification, homoskedasticity, and serial correlation associated with panel data analysis. Although the set of relevant variables has been reduced from over 200 to only 14, the adjusted R^2 values reveal that these variables have captured between 73% and 100% of the variation in the dependent variable for each equation.

For the fixed effects model, some of the estimated parameters are unique to a particular group. Therefore, even within the regression equation for corn production, there are actually nine estimated equations. The sets of parameters for the four estimated equations for each soil are given in Tables 4A-4 through 4A-7.

The production function (Equation 4-2) was fitted to the transcendental functional form. This form is extremely relevant to the issues of sustainability because it allows the substitution and complementarity relationships among inputs and soil quality to change over the range of input use (time). For example, fertilizer and soil quality may be substitutes at high levels of soil quality. Once soil quality is reduced below a certain level, however, the relationship may become complementary, meaning that further increases in fertilizer use cannot offset the declines in production due to loss of soil quality. This and other scenarios are examined in the dynamic model.

The soil quality function (Equation 4-3) has both quadratic and linear elements. The soil nitrogen function (Equation 4-4) was estimated as a linear function. The leaching function (Equation 4-5) was estimated as a logarithmic function, meaning that as the value of the variables increases, their impact on leaching is still increasing, but at a decreasing rate.

4.4 TESTING THE DEFINITIONS OF SUSTAINABILITY IN AN OPTIMIZATION FRAMEWORK

The optimization portion of the analysis was conducted using the GAMS (General Algebraic Modeling System)/MINOS approach (Brooke et al., 1992). This model solves the producer’s dynamic problem over discrete time. Along with the equations estimated through regression analysis, corn fertilizer, tillage, pesticide, and soil conservation prices and discount rates taken from the USDA (U.S. Department of Agriculture, 1996, 1997) were incorporated into the GAMS framework to create a total of nine optimization problems, one for each soil in each

region. From these baselines, new scenarios were created to meet the conditions for the following objectives:

- *Profit maximization*—Profit may be maximized based on the selection of fertilizer, tillage, pesticide, and soil conservation practices in the production process.
- *Sustainability as constant consumption*—Yield in any year must be at least 90% of the yield recorded in the first year of the baseline scenario.
- *Sustainability as a constant stock of a resource*—Conservation practices must be implemented every year in the 100-year period.
- *Sustainability as intergenerational equity*—Leaching over the 100-year period must be at least 10% less than leaching over the 100-year period in the baseline scenario.
- *Sustainability as intergenerational equity*—Measured by income potential or profitability over the 100-year period.

Baseline scenarios for all nine soils are in Appendix 4A.

Sustainability scenarios were constructed based upon sustainability definitions found in the literature. Based on the soil quality indices created from the soils data generated by EPIC, the initial level of soil quality was set between 0.78 and 0.80, depending on the soil. Discounted profit, and the paths for soil quality degradation and fertilizer, tillage, pesticide,[7] and soil conservation were noted in all relevant runs. Highlights from three sustainability scenarios are summarized in Tables 4A-8 to 4A-10.

4.4.1 Baseline Scenario

In the baseline scenario, producers maximized discounted profits over the 100-year period by choosing an optimal input mix of soil quality, tillage, pesticide, and fertilizer. Soil conservation options were not offered. As no conservation measures were available, the path of soil quality depreciation generated by both natural and human influences over 100 years could be observed.

In this scenario, soil quality on stable soils depreciated from 0.80 in the early years of production but reached a steady state at around 0.72, even with the use of conventional tillage

[7]Pesticide usage was fairly constant under all scenarios and provided few insights. Thus, it has been left out of the tables and most of the discussion.

practices. The optimal mix of soil quality and added inputs generated high annual yields, no less than 134 bushels per acre, and discounted profits of at least $7,100 per acre. In Iowa and Missouri, fertilizer leaching increased as soil quality was degraded. On the Minnesota stable soil, leaching decreased initially and then increased.

Steady states for soil quality and input use were also attained on the neutral soil, but later in the planning period. Soil quality leveled out at roughly 0.66 on all three neutral soils. Discounted profits were at least $6,500 and minimum yield in any year was at least 122 bushels. Conventional tillage was used throughout the planning period on all soils. Although still relatively low, fertilizer leaching was greater than for stable soils. In all three cases, leaching increased as soil quality decreased over time.

None of the susceptible soils reached a steady state. The Iowa susceptible soil had degraded to 0.198 by the end of the planning period and the Minnesota soil quality fell to 0.254. For all soils, fertilizer inputs initially increased as soil quality fell, but then decreased as the relationship between soil quality and fertilizer became complementary. No till replaced conventional tillage as depletion of soil quality intensified. As these input levels fell, production levels also fell about half (on average from 120 bushels to 60 bushels) on all susceptible soils. Although leaching rates on two susceptible soils were up to nearly 11 lbs/year, leaching levels for the Missouri susceptible soil diminished from 1.6 to 0.59 lbs/year as soil quality was degraded.

4.4.2 Profit Maximization Scenario

A soil conservation option was added to the baseline scenario to determine profitability of soil conservation. The option available was dependent on soil type. A mathematical representation of the impact of the respective conservation practice was included in the soil quality equation in GAMS. Details are found in Popp (1997).

Implementing easy and inexpensive conservation measures on all stable soils for the entire 100 years slightly improved soil quality from 0.80 to 0.811 on average. Annual yields increased and discounted profits were slightly greater than in the baseline. The input mix stayed relatively constant throughout the entire planning period. In Iowa and Missouri, soil quality and the added inputs produced a high steady output and high profits with low levels of leaching. In Minnesota, however, an overall increase in soil quality led to high output and profit levels but increased, then decreased leaching.

Conservation measures were somewhat effective in maintaining soil quality on all neutral soils, but because of regional price differences for input, output, and conservation practices, the most profitable level of conservation varied. Consequently, the point in time and the level that soil quality reached a steady state varied among the neutral soils. Given the high cost of conservation practices for neutral soils (such as terracing) compared to other inputs, soil quality was degraded and substituted with slightly more fertilizer for most years in the planning period. As fertilizer costs grew, both conservation tillage and terraces were introduced into the production process. Conservation tillage practices were introduced on all soils late in the production period. Conservation practices were introduced and maintained on the land for 5 years in Minnesota, 10 years in Iowa and 19 years in Missouri. When compared to the baseline scenario, minimum yields were raised about 3 bushels on each neutral soil, profits increased slightly and leaching was reduced about 10%.

None of the susceptible soils reached a steady state of soil quality even when conservation measures were available. Conservation practices for susceptible soils were the most costly of the soil conservation investments. On the Iowa and Missouri soils, conservation practices were not effective enough in maintaining soil quality and yield to justify their expense at any time in the production period. Consequently, for these two soils, the paths of input use and soil quality degradation that provide the best solution to this scenario are the same as those for the baseline scenario. Conservation practices were employed for 5 years on the Minnesota soil. As a result, profits increased about 1% over the baseline scenario and soil quality had fallen to 0.260 at the end of the 100 years, as opposed to 0.254 in the baseline scenario.

4.4.3 Sustainability as Constant Consumption

The first definition of sustainability examined was the ability of society to maintain a constant stock of consumption. The condition required to fulfill this definition of sustainability was that annual yields for the entire 100-year period could not fall below 90% of the yield attained in the first year of the baseline scenario.[8] Results are summarized in Tables 4A-8 through 4A-10.

[8]Bellon (1995) and Marten (1988) have stated that sustainability implies no more than a 10% change in production capacity.

For the stable and neutral soils, the best solution to the constant consumption scenario was also the solution to the profit maximization scenario. The same did not hold for susceptible soils.

As previously noted, annual yields fell about 50% on the susceptible soils in the baseline scenarios. On the Minnesota susceptible soil (where annual yield was required to be at least 110.42 bushels), the depreciation of soil quality was greatly slowed by implementing soil conservation for 70 years, and reducing tillage intensity to no till. Fertilizer levels were also adjusted. As a result, the minimum yield attained on the Minnesota susceptible soil was 110.47 bushels. Although fertilizer leaching increased from 1.73 to 2.86 lbs over the 100-year period, it was drastically lower than under the two previous scenarios on this soil.

For the Iowa and Missouri susceptible soils, there was no optimal path of input mix that could maintain annual yields at 90% throughout the entire planning horizon. Presumably, this is because conservation practices were ineffective in keeping soil quality at levels needed to produce at least 108 bushels of corn on each soil every year.

4.4.4 Sustainability as Constant Resource Stock

The second definition of sustainability states that the stock of soil quality must be preserved in order for production to be sustainable. One option a producer might consider is to temporarily or permanently retire land from production. However, in this study, sustainability is examined under a production setting. Therefore, conservation measures, whether it be contouring, residue management, or terracing (depending on soil type), were fully implemented every year of the planning period. Given the differing levels of effectiveness for different conservation practices, each soil was examined first for its ability to maintain soil quality with the help of conservation and then for its impacts on other inputs, leaching, and profit.

As soil conservation practices were already implemented on the stable soils in the profit maximization and constant consumption scenarios, the soil management plan that met the requirements of the previous two scenarios also fulfilled the constant stock requirement. Although the constant stock and constant consumption definitions are often cited as having competing objectives, these objectives are compatible on stable soils.

When all conservation measures were applied to neutral soils, soil quality again increased from an average of 0.79 to 0.81. Annual yields increased and fertilizer leaching decreased.

However, increases in total output over the planning period did not offset the added cost brought on by 100 years of conservation practices. As a result, profit levels fell.

Conservation practices were unable to bring susceptible soils into a steady state with continuous cropping over the 100-year period. However, erosion decreased such that soil quality on average was only reduced to 0.63, compared to an average of 0.25 in previous scenarios. Fertilizer levels again initially increased and eventually declined (sharply in Missouri). Annual yields fell from an average of 120 bushels to 105 bushels. This is greatly improved over the profit maximization scenario where annual yields fell from 120 bushels to about 60 bushels. However, the high cost of conservation needed to improve soil quality and output greatly reduced the profit level when compared to the constant consumption scenario.

4.4.5 Sustainability as Intergenerational Equity—Reduced Leaching

The third definition of sustainability requires that the needs of the present are met without compromising the ability of future generations to meet their own needs. As mentioned in Chapter Three, there is no consensus regarding the appropriate measurement of intergenerational equity. Two requirements based on quality of life measures, leaching reduction and income potential, are explored here.

The first possibility considers human health issues. Groundwater contamination can result when fertilizer leaches through the soil. Society may implement a policy to reduce overall nitrate leaching. One way to achieve this is to set a tax on the price of fertilizer. This type of command and control policy that targets the source of the contamination is effective in reducing pollution (Baumol and Oates, 1990). Otherwise, if policy makers believe producers have free information concerning the interactions of fertilizer and leaching on their particular soil, producers may be left to choose the most appropriate means to reduce pollution from their activities.

Although command and control policies may reduce leaching, it is difficult to find the tax rate associated with the desired level of pollution. In this optimization run, a 10% tax was levied on the per pound cost of fertilizer. Interestingly, this tax rate was ineffective in reducing leaching at least 10% on all soils. Furthermore, output and profits were lower than under other sustainability requirements.

The second method undertaken required that leaching in any one year be no greater than 90% of the leaching in the baseline scenario. Under this method, where the producers were free

to choose their own means to meet the goal, the results were much improved. By reducing the amount of fertilizer applied in production and maintaining soil quality with soil conservation practices, all stable soils attained a reduction of at least 10% of overall leaching. For these soils, the solution that fulfills the requirements of the other two definitions of sustainability is also befitting to this intergenerational equity scenario. Even in Minnesota, where leaching initially worsened with improvements in soil quality, overall reductions in leaching were sufficient to fulfill the sustainability condition.

In all scenarios, the optimal input mixes changed most dramatically on the neutral soils. Fertilizer levels decreased as conservation measures were added to maintain soil quality. Leaching reductions were attained but overall production and profit levels fell compared to those that resulted in the constant consumption scenario. When all conservation measures are implemented over the entire planning period, as in the constant stock scenario, leaching is reduced more than 10%.

Management decisions on two of the susceptible soils (Iowa and Minnesota) were somewhat similar to those practiced on neutral soils. Soil conservation measures and reduced tillage were implemented early to maintain soil quality. When conservation practices ceased to be profitable (after about 10 years), fertilizer increased to offset soil quality losses and then decreased as it became complimentary to soil quality. Overall, leaching was reduced a little more than 10% on these soils. As with the neutral soils, the level of nitrogen leached over the 100 years was much less under the constant stock scenario. When leaching is reduced by the 10% minimum, profits are about 25% higher than under the constant stock scenario.

Given the direct relationship between leaching and soil quality on the Missouri susceptible soil, as well as the high cost of conservation, the best way to meet the leaching requirement was to let soil quality degrade. The input mix fluctuated greatly throughout the 100-year period and overall production fell compared to the constant stock scenario. However, on this soil, both profit and total leaching over the entire period were lower.

4.4.6 Sustainability as Intergenerational Equity—Income Potential

Income potential, proxied by greatest net discounted profits over the planning period, may also be used as a measure of intergenerational equity. The best solution to this intergenerational equity condition was already solved in the profit maximization scenario. This scenario, where

there was no minimum yield, no maximum leaching, no input tax, and no soil conservation requirements, is intuitively the most profitable of all scenarios no matter what soils are examined. Sustainability of any other kind usually results in some kind of economic, environmental, or social cost.

4.5 SCENARIO WRAP-UP

Table 4A-10 provides a summary of the compatibility of the definitions on the nine soils. In terms of the compatibility of different sustainability requirements, no conflicts arise on stable soils. The optimal resource management policy that satisfies the conditions for all three definitions generates many benefits such as stable high profits, output, and soil quality. It also allows for a stable input mix and limits negative externalities such as leaching. On neutral and susceptible soils, however, economic, social, and environmental consequences vary both by sustainability definition and by soil type. Furthermore, as soil degradation worsened, so did most of the consequences. On neutral soils, the goals of the constant consumption and intergenerational equity (income potential) definitions may be met with the same optimal path of soil quality degradation and input mix. The goals of the constant resource stock, reduced leaching and intergenerational equity definitions are also met, but each with its own optimal input mix, output, leaching, and profit.

Attaining sustainability on susceptible soils was difficult no matter what the definition. Susceptible soils tended to erode easily, leach, and lose their productive capabilities and profitability. Attempting to control any one of these factors (such as maintaining soil quality) led to negative impacts elsewhere (in this case, in profits and fluctuations in input demand).
No optimal mix of added inputs and soil quality was found that could even attain the conditions for the constant consumption definition of sustainability on two soils. The conditions of other definitions could be met with one exception (i.e., the two means to attain intergenerational equity on the Missouri susceptible soil were compatible).

4.5.1 Observations About Reversibility and Uncertainty

In the above scenario, soil quality on the stable and neutral soils reached a steady state over the 100-year planning period. Of concern, however, is the recognition that conservation measures (such as no till practices, residue management, and terracing) could be implemented to stabilize the level of soil quality above its natural steady state of reversibility and uncertainty.

The same possibilities do not hold for the susceptible soil. As shown in Figure 4-1, this soil erodes easily and cannot attain a steady state when continuously cropped for 100 years. However, as long as the endowment of soil quality is high, soil conservation measures, if undertaken immediately, may greatly slow degradation (i.e., elongate the shape of the degradation curve) and help minimize unforeseen circumstances. These conservation practices cannot slow this process forever. As shown in Figure 4-2, there is some level of soil quality below which even conservation practices cannot slow degradation. It is at this point that irreversibility becomes a reality. Therefore, in order to maintain quality of these soils, other types of conservation practices, such as set asides in grass cover, may be needed. However, this removes, at least temporarily, this land from the production process.

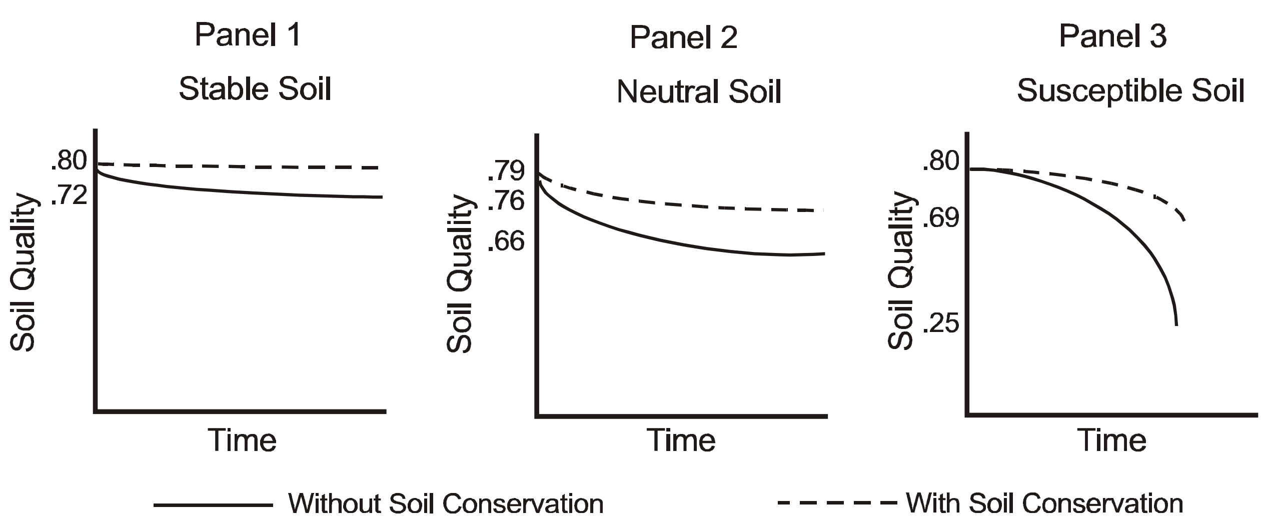

Figure 4-1. Paths of soil quality with and without soil conservation possibilities.

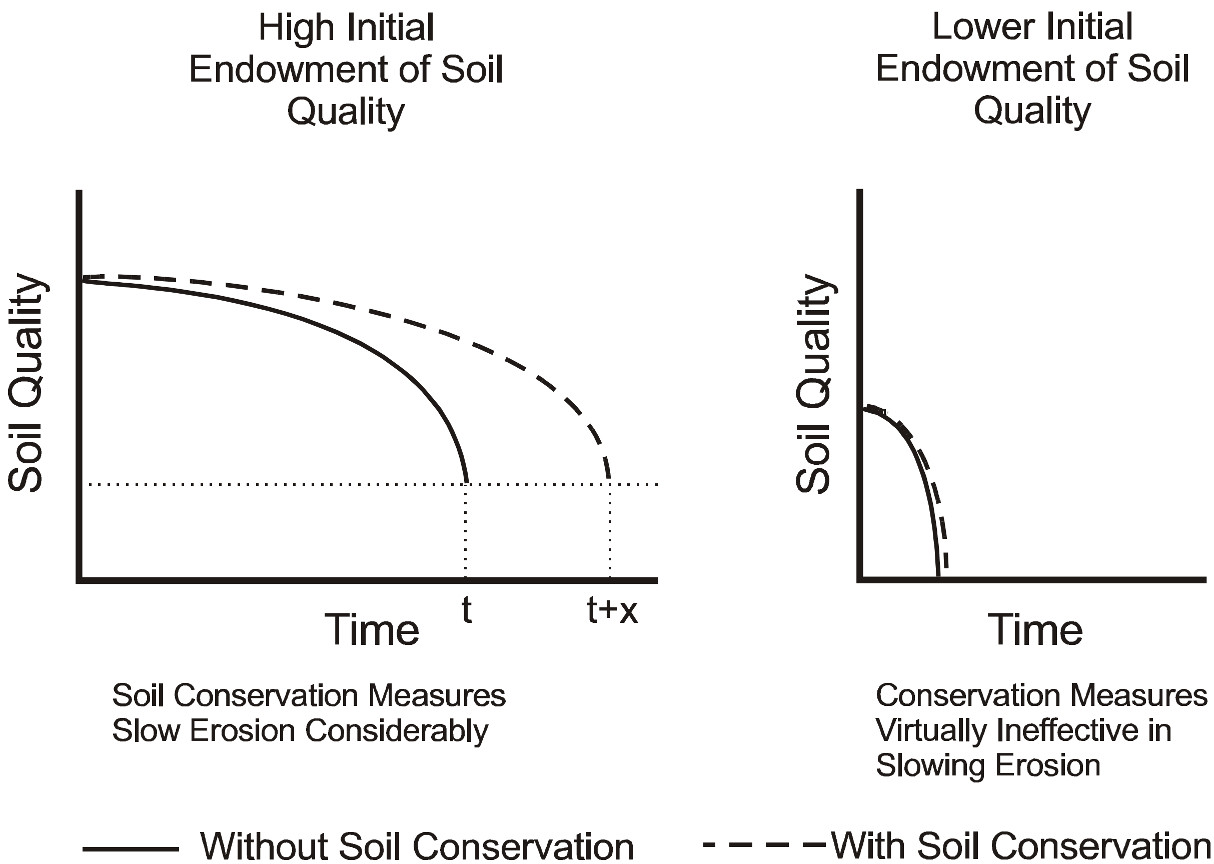

Figure 4-2. The impact of soil conservation on soil quality reversibility on susceptible soils.

APPENDIX 4A

TABLES FOR CHAPTER 4

TABLE 4A-1. SOIL AND MANAGEMENT FOR SIMULATION MODEL SCENARIOS

				Tillage Machinery[a]								
	Soil Type			Conventional		Conservation		No Till		Fertilizer[b] (pounds per acre)		
Region	Stable	Neutral	Susceptible	Tillage	Pesticide	Tillage	Pesticide	Tillage	Pesticide[c]	Low	Medium	High
Iowa	Tama	Dinsdale	Nordness	Tandem Disk; Field and row cultivators	Atrazine Lasso Furadan	Field and row cultivators	Atrazine Lasso Furadan	None	Atrazine Lasso Furadan	50	100	150
Missouri	Haymond	Mexico	Hartville	Tandem Disk; Field and row cultivators	Atrazine Lasso Furadan	Field and row cultivators	Atrazine Lasso Furadan	None	Atrazine Lasso Furadan	50	100	150
Minnesota	Port Byron	Kenyon	Rockton	Moldboard plow; Field and row cultivators	Banvel Dual	Chisel plow; Field and row cultivators	Banvel Dual	None	Banvel Dual 2,4-D Roundup	50	100	150

[a]Does not include machinery common to all practices such as pesticide and fertilizer applicators or combines.
[b]Actual pounds of nitrogen applied at low, medium, and high levels.
[c]Atrazine levels in Missouri and Minnesota increased under no-till practices compared to levels used under conventional and conservation practices.

TABLE 4A-2. SIMULATED SOIL QUALITY OVER 100 YEARS FOR THREE TILLAGE LEVELS

		Soil Quality Index					
		Conventional		Conservation		No-Till	
Region	Soil Type	High	Low	High	Low	High	Low
Iowa	Stable	0.80	0.73	0.80	0.77	0.82	0.80
	Neutral	0.80	0.66	0.80	0.68	0.80	0.70
	Susceptible	0.79	0.20	0.79	0.33	0.79	0.47
Missouri	Stable	0.80	0.72	0.80	0.79	0.80	0.80
	Neutral	0.80	0.66	0.80	0.67	0.80	0.70
	Susceptible	0.78	0.19	0.78	0.36	0.78	0.42
Minnesota	Stable	0.80	0.71	0.80	0.78	0.80	0.79
	Neutral	0.80	0.64	0.80	0.68	0.80	0.69
	Susceptible	0.79	0.07	0.79	0.18	0.79	0.31

TABLE 4A-3. SIMULATED YIELDS BY STATE AND SOIL TYPE FOR A 100-YEAR SIMULATION

		Yield (bushels per acre)		
Region	Soil Type	Low	High	Mean
Iowa	Stable	100.4	166.7	128.9
	Neutral	92.6	167.2	108.2
	Susceptible	63.9	168.5	76.8
Missouri	Stable	105.6	177.0	130.0
	Neutral	94.3	177.0	116.9
	Susceptible	46.9	159.0	57.3
Minnesota	Stable	103.0	164.7	131.0
	Neutral	94.1	197.4	101.8
	Susceptible	26.5	157.3	48.0

TABLE 4A-4. REGRESSION COEFFICIENT ESTIMATES IN THE PRODUCTION FUNCTION

Soil[a] Type/ Location	Variable Coefficients[b,c,]												
	A	L_a	L_b	W_a	W_b	N_a	N_b	SN_a	SN_b	P_a	P_b	SQ_a	SQ_b
Stable/IA	-6.47 ***	0.558 ***	-1.69 ***	1.115 ***	-0.036 ***	2.85 ***	-0.03 ***	0.146 ***	-0.001 ***	0.56 **	-0.316 **	0.65 ***	-0.316 **
Neutral/IA	-5.35 ***	0.558 ***	-1.69 ***	1.115 ***	-0.036 ***	2.51 ***	-0.026 ***	0.146 ***	-0.001 ***	0.56 **	-0.316 **	0.65 ***	-0.316 **
Susceptible/IA	-8.64 ***	0.558 ***	-1.69 ***	1.115 ***	-0.036 ***	3.48 ***	-0.039 ***	0.146 ***	-0.001 ***	0.56 **	-0.316 **	0.65 ***	-0.316 **
Stable\MO	-1.11 ***	0.558 ***	-1.69 ***	1.115 ***	-0.036 ***	1.48 ***	-0.013 ***	0.146 ***	-0.001 ***	0.56 **	-0.316 **	0.65 ***	-0.316 **
Neutral/MO	2.37 ***	0.558 ***	-1.69 ***	1.115 ***	-0.036 ***	0.311 ***	-0.0023 ***	0.146 ***	-0.001 ***	0.56 **	-0.316 **	0.65 ***	-0.316 **
Susceptible/MO	1.91 ***	0.558 ***	-1.69 ***	1.115 ***	-0.036 ***	0.448 ***	-0.005 ***	0.146 ***	-0.001 ***	0.56 **	-0.316 **	0.65 ***	-0.316 **
Stable/MN	-1.02 ***	0.558 ***	-1.69 ***	1.115 ***	-0.036 ***	1.23 ***	-0.01 ***	0.146 ***	-0.001 ***	0.56 **	-0.316 **	0.65 ***	-0.316 **
Neutral/MN	0.81 ***	0.558 ***	-1.69 ***	1.115 ***	-0.036 ***	0.727 ***	-0.0056 ***	0.146 ***	-0.001 ***	0.56 **	-0.316 **	0.65 ***	-0.316 **
Susceptible/MN	0.22 ***	0.558 ***	-1.69 ***	1.115 ***	-0.036 ***	0.883 ***	-0.0077 ***	0.146 ***	-0.001 ***	0.56 **	-0.316 **	0.65 ***	-0.316 **

[a]*IA*, *MO*, and *MN* represent Iowa, Missouri, and Minnesota, respectively. *A* is the intercept term, *L* is tillage, *W* is precipitation, *N* is applied fertilizer, *SN* is soil nitrogen, *P* is pesticide, and *SQ* is soil quality.

[b]The production function is the transcendental form: $y = Ax_1^{a_1} e^{b_1 x_1} x_2^{a_2} e^{b_2 x_2}$ and, therefore, there are two coefficients (a and b, respectively) assigned to each variable.

[c]These are the final values (after deviation from baseline values are accounted for in dummy variables) in the fixed effects model.

***Significant at the 1% level.

**Significant at the 5% level.

*Significant at the 10% level.

TABLE 4A-5. REGRESSION COEFFICIENTS IN THE SOIL QUALITY FUNCTION

Soil[a] Type/Location	Variable Coefficient[b, c]			
	SQ_{t-1}	SQ_{t-1}^2	$1/SQ_{t-1}$	L_{t-1}
Stable/IA	0.999 ***	0 ***	0 ***	-0.0001 **
Neutral/IA	1.0265 ***	-0.039 ***	0 ***	-0.0002 **
Susceptible/IA	0.9998 ***	0 ***	-0.0113 ***	-0.0021 **
Stable/MO	0.999 ***	0 ***	0 ***	-0.0001 **
Neutral/MO	1.0265 ***	-0.04 ***	0 ***	-0.0002 **
Susceptible/MO	1 ***	0 ***	-0.0112 ***	-0.0003 **
Stable/MN	0.999 ***	0 ***	0 ***	-0.0001 **
Neutral/MN	1.0265 ***	-0.04 ***	0 ***	-0.0002 **
Susceptible/MN	0.999 ***	0 ***	-0.0112 ***	-0.0003 ***

[a]IA, MO, and MN represent Iowa, Missouri, and Minnesota, respectively. *SQ* represents soil quality and *L* represents the estimated part of *M*, tillage.
[b]For stable and susceptible soils, the soil quality function takes on a linear form $Y = A + Bx$. The soil quality index for the neutral soils is of the quadratic form $y = A + b_x x + b_2 x^2$.
[c]These are the final values (after deviation from baseline values are accounted for in dummy variables) in the fixed effects model.
***Significant at the 1% level.
**Significant at the 5% level.
*Significant at the 10% level.

TABLE 4A-6. REGRESSION COEFFICIENTS IN THE SOIL NITROGEN FUNCTION FOR ALL SOILS

Soil[a] Type/Location	Variable Coefficient[b,c]						
	A	SN_{t-1}	N_{t-1}	W_{t-1}	LCH_{t-1}	L_{t-1}	Y_{t-1}
Stable/IA	1.32 ***	0.986 ***	0.057 **	-0.026 **	-0.062 ***	-0.784 **	-0.03 ***
Neutral/IA	1.32 ***	0.978 ***	0.057 **	-0.026 **	-0.062 ***	-0.784 **	-0.029 ***
Susceptible/IA	1.3 ***	0.965 ***	0.057 **	-0.026 **	-0.062 ***	-0.784 **	-0.028 ***
Stable/MO	0.283 ***	0.986 ***	0.057 **	-0.026 **	-0.062 ***	-0.784 **	-0.026 ***
Neutral/MO	-0.326 ***	0.976 ***	0.057 **	-0.026 **	-0.062 ***	-0.784 **	-0.022 ***
Susceptible/MO	-0.492 ***	0.981 ***	0.057 **	-0.026 **	-0.062 ***	-0.784 **	-0.02 ***
Stable/MN	0.393 ***	0.99 ***	0.057 **	-0.026 **	-0.062 ***	-0.784 **	-0.03 ***
Neutral/MN	0.308 ***	0.989 ***	0.057 **	-0.026 **	-0.062 ***	-0.784 **	-0.033 ***
Susceptible/MN	-1.065 ***	0.97 ***	0.057 ***	-0.026 **	-0.062 ***	-0.784 ***	-0.016 ***

[a]IA, MO, and MN represent Iowa, Missouri, and Minnesota, respectively. *A* represents the intercept term, *SN* is soil nitrogen, *W* is precipitation, *LCH* is leaching, and *L* is tillage.

[b]The soil nitrogen function takes on a linear form $y = A + b_i x_i$.

[c]These are the final values (after deviation from baseline values are accounted for in dummy variables).

***Significant at the 1% level.

**Significant at the 5% level.

*Significant at the 10% level.

TABLE 4A-7. REGRESSION COEFFICIENTS IN THE LEACHING FUNCTION FOR ALL SOILS

Soil[a] Type/Location	Variable Coefficient[b, c]						
	A	*L*	*W*	*N*	*SN*	*P*	*SQ*
Stable/IA	-7.31 ***	0.01 *	0.87 ***	0.29 ***	0.613 ***	0.02 NS[d]	-1.429 **
Neutral/IA	-10.02 ***	0.01 *	2.38 ***	0.29 ***	0.618 ***	0.02 NS	-1.68 **
Susceptible/IA	-5.9 NS	0.01 *	0.22 ***	0.29 ***	0.5477 ***	0.02 NS	-2.004 **
Stable/MO	-5.008 ***	0.01 *	0.807 ***	0.29 ***	0.4227 ***	0.02 NS	0.016 **
Neutral/MO	-5.68 ***	0.01 *	0.724 ***	0.29 ***	0.623 ***	0.02 NS	-1.426 **
Susceptible/MO	-5.45 ***	0.01 *	0.692 ***	0.29 ***	0.619 ***	0.02 NS	.7 **
Stable/MN	-7.56 ***	0.01 *	1.22 ***	0.29 ***	0.5623 ***	0.02 NS	0.0108 **
Neutral/MN	-7.82 ***	0.01 *	1.33 ***	0.29 ***	0.618 ***	0.02 NS	-1.495 **
Susceptible/MN	-5.6 ***	0.01 *	0.69 ***	0.29 ***	0.516 ***	0.02 NS	-1.845 **

[a]IA, MO, and MN represent Iowa, Missouri, and Minnesota, respectively. *A* is the intercept term, *L* is tillage, *W* is precipitation, *N* is nitrogen applied, *SN* is soil nitrogen, *P* is pesticide, and *SQ* is soil quality.
[b]The leaching function takes on a logarithmic form.
[c]These are the final values (after deviation from baseline values are accounted for in dummy variables).
[d]NS indicates that the variable is not significant at the 10% level.
***Significant at the 1% level.
**Significant at the 5% level.
*Significant at the 10% level.

TABLE 4A-8. SUMMARY OF THE CONDITIONS, RESULTS, AND IMPACTS OF THREE DEFINITIONS OF SUSTAINABILITY ON THREE STABLE SOILS

	SUSTAINABILITY SCENARIOS						
	Constant Consumption		Constant Stock		Equity as Reduced Leaching		
Soil	Annual Condition[a] and Result	Impacts[b] Over Time	Annual Condition and Result	Impacts Over Time	Final Condition and Result	Impacts Over Time	General Observations
	Condition	Profit = $7,266.34	Condition	Profit = $7,266.34	Condition	Profit = $7,266.34	The conditions of all three definitions were met using the same input management plan.
	Minimum yield = 126.82	Yield rose from 140.92 to 142.85	Full conservation every year	Yield rose from 140.92 to 142.85	Maximum leach = 0.783 lbs	Yield rose from 140.92 to 142.85	
		SQ rose from 0.80 to 0.808		SQ rose from 0.80 to 0.808		SQ rose from 0.80 to 0.808	
	Result	Conservation all years	Result	Conservation all years	Result	Conservation all years	
IA	Minimum yield = 140.92	Input mix steady	SQ rose from 0.80 to 0.808	Input mix steady	Leaching fell from 0.68 to 0.61	Input mix steady	
	Maximum yield = 142.82	Leach fell from 0.68 to 0.61		Leach fell from 0.68 to 0.61		Leach fell from 0.68 to 0.61	
	Condition	Profit = $7,268.27	Condition	Profit = $7,268.27	Condition	Profit = $7,268.27	The conditions of all three definitions were met using the same input management plan.
	Minimum yield = 125.05	Yield rose from 138.96 to 141.22	Full conservation every year	Yield rose from 138.96 to 141.22	Maximum leach = 1.97 lbs	Yield rose from 138.96 to 141.22	
		SQ rose from 0.80 to 0.809		SQ rose from 0.80 to 0.809		SQ rose from 0.80 to 0.809	
MO	Result	Conservation all years	Result	Conservation all years	Result	Conservation all years	
	Minimum yield = 138.96	Input mix steady	SQ rose from 0.80 to 0.809	Input mix steady	Leaching fell from 1.94 to 1.16	Input mix steady	
	Maximum yield = 141.22	Leach fell from 1.94 to 1.16		Leach fell from 1.94 to 1.16		Leach fell from 1.94 to 1.16	
	Condition	Profit = $7,252.73	Condition	Profit = $7,252.73	Condition	Profit = $7,252.73	The conditions of all three definitions were met using the same input management plan.
	Minimum yield = 129.05	Yield rose from 143.38 to 145.78	Full conservation every year	Yield rose from 143.38 to 145.78	Maximum Leach = 2.007 lbs	Yield rose from 143.38 to 145.78	
		SQ rose from 0.80 to 0.811		SQ rose from 0.80 to 0.811		SQ rose from 0.80 to 0.811	
MN	Result	100 years conservation	Result	Conservation all years	Result	Conservation all years	
	Minimum yield = 143.38	Input mix steady	SQ rose from 0.80 to 0.811	Input mix steady	Leaching fell from 1.93 to 1.64	Input mix steady	
	Maximum yield = 145.78	Leach fell from 1.93 to 1.64		Leach fell from 1.93 to 1.64		Leach fell from 1.93 to 1.64	

[a]Condition states the requirement for the relevant definition of sustainability; result states whether the condition has been met and provides the relevant statistics.
[b]Impacts presented over time are: net discounted profit; yield trend with first and final year statistics; soil quality trend over time and first and last year statistics; number of years conservation was implemented, whether input use was steady, had small changes over the 100 years or was volatile; leaching trend and first and last year statistics.

TABLE 4A-9. SUMMARY OF THE CONDITIONS, RESULTS, AND IMPACTS OF THREE DEFINITIONS OF SUSTAINABILITY ON THREE NEUTRAL SOILS

Soil	SUSTAINABILITY SCENARIOS						General Observations
	Constant Consumption		Constant Stock		Equity as Reduced Leaching		
	Annual Condition[a] and Result	Impacts[b] Over Time	Annual Condition and Result	Impacts Over Time	Final Condition and Result	Impacts Over Time	
IA	Condition Minimum yield = 120.14 Result Yield fell but minimum met Minimum yield = 128.41 Maximum yield = 133.49	Profit = $6,573.95 Yield fell from 133.49 to 128.41 SQ fell from 0.79 to 0.687 10 years conservation Small input mix changes Leach rose from 3.62 to 4.39	Condition Full conservation every year Result SQ rose from 0.79 to 0.805	Profit = $6,300.79 Yield rose from 134.18 to 139.79 SQ rose from 0.80 to 0.808 100 years conservation Small input mix changes Leach fell from 3.62 to 2.38	Condition Maximum leach = 4.0 lbs. Result Condition met but leach rose from 3.62 to 3.99	Profit = $6,555.19 Yield fell from 133.30 to 125.00 SQ fell from 0.79 to 0.699 13 years conservation Input mix volatile Leach rose from 3.62 to 3.99	The conditions of the definitions were met with different management plans.
MO	Condition Minimum yield = 119.97 Result Yield fell but minimum met Minimum yield = 126.47 Maximum yield = 133.30	Profit = $6,718.82 Yield down from 133.30 to 126.47 SQ down from 0.79 to 0.716 19 years conservation Small input mix changes Leach rose from 2.75 to 2.96	Condition Full conservation every year Result SQ rose from 0.790 to 0.808	Profit = $6,339.64 Yield rose from 133.34 to 140.57 SQ rose from 0.790 to 0.808 100 years conservation Small input mix changes Leach fell from 2.77 to 2.04	Condition Maximum leach = 2.943 lbs. Result Condition met but leach rose from 2.77 to 2.94	Profit = $6,608.62 Yield fell from 133.30 to 125.47 SQ fell from 0.79 to 0.72 24 years conservation Input mix volatile	The conditions of the definitions were met with different management plans.
MN	Condition Minimum yield = 121.97 Result Yield fell but minimum met Minimum yield = 127.06 Maximum yield = 135.51	Profit = $6,751.25, Yield fell from 135.51 to 127.06 SQ fell from 0.79 to 0.672 5 years conservation Small input mix changes Leach rose from 1.83 to 2.79	Condition Full conservation every year Result SQ rose from 0.79 to 0.808	Profit = $5,850.53 Yield rose from 135.54 to 140.19 SQ rose from 0.79 to 0.808 100 years conservation Small input mix changes Leach fell from 1.83 to 1.60	Condition Maximum leach = 2.54 lbs. Result Condition met but leach rose from 1.83 to 2.51	Profit = $6,048.32 Yield fell from 135.51 to 126.32 SQ fell from 0.79 to 0.685 11 years conservation Input mix volatile Leach rose from 1.83 to 2.51	The conditions of the definitions were met with different management plans.

[a]Condition states the requirement for the relevant definition of sustainability; result states whether the condition has been met and provides the relevant statistics.
[b]Impacts presented over time are: net discounted profit; yield trend with first and final year statistics; soil quality trend over time and first and last year statistics; number of years conservation was implemented, whether input use was steady, had small changes over the 100 years or was volatile; leaching trend and first and last year statistics.

TABLE 4A-10. SUMMARY OF THE CONDITIONS, RESULTS, AND IMPACTS OF THREE DEFINITIONS OF SUSTAINABILITY ON THREE SUSCEPTIBLE SOILS

Soil	SUSTAINABILITY SCENARIOS						General Observations
	Constant Consumption		Constant Stock		Intergenerational Equity		
	Annual Condition[a] and Result	Impacts[b] Over Time	Annual Condition and Result	Impacts Over Time	Final Condition and Result	Impacts Over Time	
IA	Condition Minimum yield = 108.14 Result Condition not met	No mix of inputs could maintain annual output at 108.14	Condition Full conservation every year Result SQ fell from .789 to .633	Profit = $3,790.37 Yield fell from 120.15 to 100.14 SQ fell from 0.789 to 0.633 100 years conservation Small input mix changes Leach rose from 1.37 to 2.97	Condition Maximum leach = 8.757 lbs. Result Condition met but leach rose from 1.37 to 8.68	Profit = $4,907.27 Yield fell from 120.14 to 66.32 SQ fell from 0.79 to 0.260 10 years conservation Inputs volatile Leach rose 1.37-8.68	Best minimum yield attainable is met with constant stock conditions (83% instead of 90%).
MO	Condition Minimum yield = 109.15 Result Condition not met	No mix of inputs could maintain annual output at 109.15	Condition Full conservation every year Result SQ fell from 0.790 to 0.58	Profit = $4,169.17 Yield fell from 121.30 to 103.07 SQ fell from 0.79 to 0.58 100 yrs conservation Input mix volatile Leach fell from 1.66 to 1.09	Condition Maximum leach= 1.49lbs Result Leaching fell from 1.49 to 0.58	Profit = $4,952.40 Yield fell from 116.79 to 60.03 SQ fell from 0.79 to 0.715 0 years conservation Input mix volatile Leach fell from 1.49 to 0.58	Best minimum yield attainable is met with constant stock conditions (85% instead of 90%).
MN	Condition Minimum yield = 110.42 Result Yield fell but minimum met Minimum yield = 110.47 Maximum yield = 122.71	Profit = $4,309.72 Yield fell from 122.71 to 110.47 over time SQ fell from 0.79 to 0.601 70 years conservation Small input mix changes Leach rose from 1.73 to 2.86	Condition Full conservation every year Result SQ fell from 0.79 to 0.672	Profit = $3,435.17 Yield fell from 122.69 to 109.10 SQ fell from 0.79 to 0.672 100 yrs conservation Small input mix changes Leach fell from 1.73 to 2.02	Condition Maximum leach = 10.66 lbs. Result Condition met but leach rose from 1.73 to 10.36	Profit = $4,695.47, Yield fell from 122.67 to 60.55 SQ fell from 0.79 to 0.258 11 years conservation Input mix volatile Leach rose from 1.73 to 10.36	Best minimum yield attainable is met with constant stock conditions (85% instead of 90%).

[a]Condition states the requirement for the relevant definition of sustainability; result states whether the condition has been met and provides the relevant statistics.
[b]Impacts presented over time are: net discounted profit; yield trend with first and final year statistics; soil quality trend over time and first and last year statistics; number of years conservation was implemented, whether input use was steady, had small changes over the 100 years or was volatile; leaching trend and first and last year statistics.

TABLE 4A-11. COMPATIBILITY OF SUSTAINABILITY DEFINITIONS ON DIFFERENT SOILS

	Sustainability Definitions Attained with the Same Soil Management Plan[a]			
Soil[b] Type/Location	Constant Consumption	Constant Soil Stock	Intergenerational Leaching	Equity Income
Stable/IA	X	X	X	X
Stable/MO	X	X	X	X
Stable/MN	X	X	X	X
Neutral/IA	X	-	-	X
Neutral/MO	X	-	-	X
Neutral/MN	X	-	-	X
Susceptible/IA	N/A[c]	-	-	-
Susceptible/Mo	N/A[c]	-	-	-

[a]An x is used to indicate all definitions that are compatible on the particular soil.
[b]IA, MO, and MN represent Iowa, Missouri, and Minnesota, respectively.
[c]On the Iowa and Missouri susceptible soils, the conditions for the constant consumption definition of sustainability could not be achieved.

5. CONCLUSIONS

Assessment of environmental condition is critical to wise management and policy decisions. However, it is difficult when there is so much dimensionality in objectives and complexity in defining, measuring, monitoring, and predicting environmental outcomes.

This research proposes a general method to examine the sustainability of resource management. For a unique production input, the endowment of a natural resource may be modeled as an index of quality. This index, consisting of the most important identifying characteristics of the resource, may be placed into a production setting where the benefits of economic use and preservation may be compared.

The methods used for soil conservation here provide one approach to assessing sustainability. Basic findings are summarized below. For simplicity, soil had one objective: crop production. This allowed an effective model, although other objectives such as leaching and soil quality were accounted for. Extrapolating this process to another environmental good, such as forest health, would require expanding to multiple outputs and would be more difficult to model. Therefore, the concepts that can be easily demonstrated by this relatively simple (but still very difficult) example can serve as a guide for how more complex systems might function and for future models with an expanded scope.

5.1 SELECTED FINDINGS

- As shown in the above scenarios, different definitions of sustainability have different impacts on soils. Management practices that fulfill the requirements (constant output, constant resource stock, and intergenerational equity) of one definition will not necessarily fulfill the requirements of another. Besides yielding different results across definitions, results varied by soil. On a stable soil, the optimal profit making strategy is the same as the constant consumption and constant resource stock; public intervention is not necessary and societal and private conflicts over sustainability are avoided. However, the pursuit of profits on a susceptible soil does not yield a constant output, nor does the constant output assure a constant

resource stock, and leaching also requires a different management scheme from any of the others.

- Soil conservation measures were implemented over the entire 100-year period in order to meet the conditions for the different definitions of sustainability on all stable soils. Therefore, one may conclude that a soil conservation policy would meet sustainability objectives on stable soils. However, policies are not needed since conservation is already the most profitable management scheme. Neutral and susceptible soils prove more of a challenge, since the most profitable management does not always satisfy the other versions of sustainability.
- All conservation measures were implemented on neutral and susceptible soils only when sustainability was defined as constant resource stock. When the condition for sustainability is constant consumption or intergenerational equity, conservation measures were used sporadically throughout the 100-year period, and in some cases, not at all. Therefore, in general, one may conclude that soil conservation measures do not meet sustainability objectives on neutral and susceptible soils.
- Reversibility is not a problem on stable soils, since it is already in the economic interest of the farmer to preserve soil quality. Neutral soils may be preserved longer, thus averting the problem of reversibility, but may also fall into the same trap as susceptible soils, depending on conservation costs and on whether it is closer to a stable or susceptible soil.
- Reversibility is not possible on some soils once a critical level has been surpassed. In this case, susceptible soils with an initial soil quality level below .8 (as is the case for many soils that have already been in production for years) will continue to be mined for their quality until their productivity is greatly reduced. However, when the initial endowment is above .8, conservation measures can greatly reduce the rate of degradation. The smaller the endowment of soil quality, the less effective and less profitable conservation measures are in preserving it.

5.2 FURTHER RESEARCH OPPORTUNITIES

This research is the first step in uncovering the relationship between the path of change for a natural resource and various definitions of sustainability. This concept is expected to hold across a wide range of soils and crops within the United States. However, further research is needed to support this claim. Management data for 17 additional crops on hundreds of soils

across 63 regions, soon to be released by the National Resources Conservation Services, can be utilized in a sensitivity analysis to examine the extent to which these relationships hold over other crops and other soils.

In addition, these results may be contingent on various assumptions of the research. The following assumptions could be examined in the future.

- *The Discount Rate*—Sensitivity analysis could be used to determine the rate which is needed for all objectives of sustainability to be met on one or all soils.
- *Relevant Time Frame*—Further study is needed to best determine the appropriate time frame for managing each resource in a sustainable manner.
- *Clear Definitions*—There is much discussion among those who support a particular definition as to its exact meaning. Research could help determine the degree of flexibility within each definition so that the same management plan remains acceptable.
- *Technological Advancements*—Inclusion of technological advancements could be modeled to improve the results of this study.
- *Conservation Cost Share*—Sensitivity analysis could help determine what percentage of conservation costs should be carried by society and by the producer in order to sustain a soil resources.
- *Improvements to Soil Quality Index*—This is the first soil quality index used for productivity purposes to include a sufficiency for soil organic matter. Further research could help identify what other purposes this index may be applied to.

6. REFERENCES

Acton, D. F.; Gregorich, L. J. (1995) Understanding soil health. In: Acton, D. F.; Gregorich, L. J. eds. The health of our soils: toward sustainable agriculture in Canada. Ottawa, Ontario, Canada: Center for Land and Biological Resources Research, Agriculture and Agri-Food Canada; pp. 1-5; publication 1906/E.

Baumol, W. J.; Oates, W. E. (1990) The theory of environmental policy. New York, NY: Cambridge University Press.

Beckerman, W. (1992) Economic growth and the environment. Whose growth? Whose environment? World Dev. 20: 481-496.

Bellon, M. R. (1995) Farmers' knowledge and sustainable agroecosystem management: an operational definition and an example from Chiapas, Mexico. Hum. Org. 54: 263-272.

Bishop, R. (1978) Endangered species and uncertainty: the economics of a safe minimum standard. Am. J. Agric. Econ. 60: 10-13.

Boulding, K. (1973) The economics of the coming of spaceship earth. In: Daly, H., ed. Toward a steady state economy. San Francisco, CA: W. H. Freeman Press.

Bowman, R.; Petersen, M. (1996) Soil organic matter levels in the central Great Plains. Department of Agriculture, Agricultural Research Service and Natural Resource Conservation Service; conservation tillage fact sheet no. 1-96.

Bowman, R. A.; Reeder, J. D.; Schuman, G. E. (1989) Evaluation of selected soil physical, chemical and biological parameters as indicators of soil productivity. In: Stewart, J. W. B., ed. Soil quality in semiarid agriculture: proceedings of an international conference as part of the first global agricultural technology exposition; June; Saskatoon, Saskatchewan, Canada.

Brooke, A.; Kendrick, D.; Meeraus, A. (1992) GAMS: a user's guide. Redwood City, CA: Scientific Press.

Buckman, H. O.; Brady, N. C. (1960) The nature and properties of soils: a college text of edaphology. 6th ed. New York, NY: The Macmillan Company.

Ceolla, D. (1997) Personal communication. USDA Natural Resource Conservation Service.

Cernea, M. (1993) The sociologist's approach to sustainable development. Finance Dev. 30: 11-13.

Clark, J. S.; Furtan, W. H. (1983) An economic model of soil conservation-depletion. J. Environ. Econ. Manage. 10: 356-370.

Daly, H. (1995) On Wilfred Beckerman's critique of sustainable development. Environ. Values 4: 49-55.

Dixit, A.; Hammond, P.; Hoel, M. (1980) On Hartwick's rule for regular maximin paths of capital accumulation and resource depletion. Rev. Econ. Stud. 47: 551-556.

Doran, J. W. Parkin, T. (1994) Defining and assessing soil quality. In: Doran, J. W.; Coleman, D. F.; Bezdicek, D. F.; Stewart, B. A., eds. Defining soil quality for a sustainable environment. Madison, WI: American Society of Agronomy, Inc.; Soil Science Society of America, Inc. special publication no. 35.

Doran, J. W.; Coleman, D. C.; Bezdicek, D. F.; Stewart, B. A. (1994) Defining soil quality for a sustainable environment: proceedings of a symposium sponsored by the Soil Science Society of America, American Society of Agronomy, and the North Central Region Committee on Soil Organic Matter; November 1992; Minneapolis, MN. Madison, WI: Soil Science Society of America, Inc.; American Society of Agronomy, Inc.; SSSA special publication no. 35.

Doran, J. W.; Sarrantonio, M.; Liebig, M. A. (1996) Soil health and sustainability. In: Sparks, D. L., ed. Advances in agronomy. San Diego, CA: Academic Press, Inc.; pp. 1-54.

DowElanco. (1994) What makes agriculture sustainable? The bottom line on agrichemical issues. Indianapolis, IN: Sustainable Agriculture Issue.

Dyke, P. T.; Heady, E. (1985) Assessment of soil erosion and crop productivity with economic models. In: Follett, R. F.; Stewart, B. A., eds. Soil erosion and crop productivity. Madison, WI: American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc.; 106-119.

Gold, M. (1994) Sustainable agriculture: definitions and terms. Beltsville, MD: U.S. Department of Agriculture; special reference brief no. 94-05.

Hartwick, J. M. (1977) Intergenerational equity and the investing of rents from exhaustible resources. Am. Econ. Rev. 67: 972-974.

Hartwick, J. (1978) Substitution among exhaustible resources and intergenerational equity. Rev. Econ. Stud. XLV-2: 347-354.

Helmers, G.; Hoag, D. (1993) Sustainable agriculture. In: Hallberg, M. C.; Spitze, R. F.; Ray, D. E., eds. Food, agriculture, and rural policy into the twenty-first century. Boulder, CO: Westview Press.

Hilgard, E. W. (1892) Agriculture weather bureau bulletin. Volume 3. Washington, DC: U.S. Department of Agriculture; pp. 1-59.

Hoag, D. (1997) The intertemporal impact of soil erosion on non-uniform soil profiles: a new direction in analyzing erosion impacts. Agric. Systems: forthcoming.

Hsiao, C. (1986) Analysis of panel data. New York, NY: Cambridge University Press. (Econometric Society monographs no. 11).

Jansson, A. M.; Hammer, M.; Folke, C.; Costanza, R., eds. (1994) Investing in natural capital: the ecological economics approach to sustainability. Washington, DC: Island Press.

Johnson, M. G.; Lammers, D. A.; Anderson, C. P.; Rygiewcz, P. T.; Stern, J. S. (1992) Sustaining soil quality by protecting the soil resource. In: Proceedings of the soil quality standards symposium; October 1990; San Antonio, TX. Washington, DC: U.S. Department of Agriculture; watershed and air management report no. WO-WSA-2.

Karlen, D. L.; Mausbach, M. J.; Doran, J. W.; Kine, R. G.; Harris, R. F.; Schuman, G. E. (1997) Soil quality: a concept, definition and framework for evaluation (a guest editorial). Soil Sci. Soc. Am. J. 61: 4-10.

Kennedy, A. C.; Papendick, R. I. (1995) Microbial characteristics of soil quality. J. Soil Water Conserv. 50: 243-248.

Kiniry, L. N.; Scrivner, C. L.; Keener, M. E. (1983) A soil productivity index based upon predicted water depletion and root growth. Columbia, MO: University of Missouri-Columbia, College of Agriculture; agricultural experiment station research bulletin no. 1051.

Larson, W. E.; Pierce, F. J. (1991) Conservation and enhancement of soil quality. In: Evaluation for sustainable management in the developing world: summaries of papers [from an] international workshop; September; Chlang Ral, Thailand. Bangkok, Thailand: Board for Soil Resources and Management; IBSRAM Proc. 12(2).

Larson, W. E.; Pierce, F. J. (1994) The dynamics of soil quality as a measure of sustainable management. In: Doran, J. W.; Coleman, D. C.; Bezdicek, D. F.; Stewart, B. A., eds. Defining soil quality for a sustainable environment. Madison, WI: American Society of Agronomy, Inc.; Soil Science Society of America special publication no. 35.

Lesser, J.; Zerbe, R. O., Jr. (1993) What can economic analysis contribute to the sustainability debate? Contemp. Econ. Policy 13: 88-100.

Maddala, G. S. (1993) The econometrics of panel data. Volumes 1-2. Brookfield, VT: Ashgate.

Marten, G. (1988) Productivity, stability, sustainability, equitability and autonomy as properties for agroecosystem assessment. Agric. Syst. 26: 291-316.

McConnell, K. (1983) An economic model of soil conservation. Am. J. Agric. Econ. 65: 83-89.

Mitchell, G.; Griggs, R. H.; Benson, V.; Williams, J. (1995) The EPIC model: environmental policy integrated climate (version 5300). Temple TX: Texas Agricultural Experiment Station, U.S. Department of Agriculture Agricultural Research Service and Natural Resource Conservation Service.

Munasinghe, M. (1993) The economist's approach to sustainable development. Finance Dev. 30: 16-19.

National Research Council. (1993) Soil and water quality: an agenda for agriculture. Washington, DC: National Academy Press.

Natural Resources Conservation Service. (1995) Soil quality. Washington, DC: U.S. Department of Agriculture; RCA/issue brief 5.

Olson, L. (1943) Columella and the beginning of soil science. Agric. Hist. 17: 65-72.

Olson, K. R.; Lal, R.; Norton, L. D. (1994) Evaluation of methods to study soil erosion-productivity relationships. J. Soil Water Conserv. 49: 586-590.

Page, J. (1977) Conservation and economic efficiency: an approach to materials policy. Baltimore, MD: Johns Hopkins University Press.

Parr, J. F.; Papendick, R. I.; Hornick, S. B.; Meyer, R. E. (1992) Soil quality: attributes and relationship to alternative agriculture. Am. J. Altern. Agric. 7: 5-11.

Pearce, D.; Atkinson, G. (1993) Capital theory and the measurement of sustainable development. Ecol. Econ. 8: 103-108.

Pearce, D.; Atkinson, G. (1995) Measuring sustainable development. In: Bromley, D., ed. The handbook of environmental economics. Cambridge, MA: Blackwell Publishers; pp. 166-181.

Pearce, D. W.; Warford, J. J. (1996) World without end economics: environment and sustainable development. 2nd ed. Oxford, United Kingdom: Oxford University Press for the World Bank.

Pezzey, J. (1992) Sustainability: an interdisciplinary guide. Environ. Values 1: 321-362.

Pierce, F. J.; Larson, W. E.; Dowdy, R. H.; Graham, W. A. P. (1983) Productivity of soils: assessing long-term changes due to erosion. J. Soil Water Conserv. 38: 39-44.

Pieri, C. (1995) Long term experiments on soil management in semi-arid Francophone Africa. In: Lal, R.; Stewart, B. A., eds. Soil management experimental basis for sustainability and environmental quality. Boca Raton, FL: Lewis Publishers; pp. 228-266.

Popp, J. H. (1997) In search of sustainability. Economic, social and environmental consequences of natural resource management: a case study of soil conservation in the United States [dissertation]. Fort Collins, CO: Colorado State University.

Rees, C. (1993) An ecologist's approach to sustainable development. Finance Dev. 30: 14-15.

Saliba, B. C. (1985) Soil productivity and farmers' erosion control incentives—a dynamic modeling approach. West. J. Agric. Econ. 10: 354-364.

Schuh, G. E.; Archibald, S. (1993) A methodological framework for the integration of environmental and sustainable development issues into agricultural planning and policy analysis in developing countries. Presented at: Food and Agricultural Organization of the United Nations seminar; Rome, Italy.

Segarra, E.; Taylor, D. B. (1987) Farm level dynamic analysis of soil conservation: an application to the piedmont area of Virginia. South. J. Agric. Econ. 19: 61-73.

Solow, R. (1974a) Intergenerational equity and exhaustible resources. Rev. Econ. Stud.: 29-45.

Solow, R. (1974b) The economics of resources or the resources of economics. Am. Econ. Rev. 64(2): 1-13.

Solow, R. (1991) Growth theory. In: Greenaway, D.; Bleamey, M.; Stewart, I., eds. Companion to economic thought. New York, NY: Rutledge Press; pp. 393-415.

Tammons, R. (1997) Personal communication. Columbus, MO: U.S. Department of Agriculture, Natural Resource Conservation Service.

U.S. Department of Agriculture. (1980) Report and recommendations on organic farming. Beltsville, MD: U.S. Department of Agriculture, Biological Waste Management and Organic Resources Laboratory.

U.S. Department of Agriculture. (1990-1995) Cropping practices survey. Unpublished data. Washington, DC: Economic Research Service.

U.S. Department of Agriculture. (1994) Agricultural statistics 1994. Washington, DC: U.S. Government Printing Office.

U.S. Department of Agriculture. (1996) Agricultural prices 1995 summary. Washington, DC: National Agricultural Statistics Service. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/price/zap-bb/agricultural_prices_annual_summary_07.16.96.

U.S. Department of Agriculture. (1997) Agricultural prices 1996 summary. Washington, DC: National Agricultural Statistics Service. Available online at: http://usda.mannlib.cornell.edu/reports/nassr/price/zap-bb/agricultural_prices_annual_summary_07.23.97.

Vickner, S. (1997) Personal communication. Colorado State University.

Walker, D. J.; Young, D. L. (1986) The effect of technical progress on erosion damage and economic incentives for soil conservation. Land Econ. 62: 83-93.

Warkentin, B. P. (1995) The changing concept of soil quality. J. Soil Water Conserv. 50: 226-228.

World Commission on Environment and Development. (1987) Our common future. Oxford, United Kingdom: Oxford University Press.